Crane safety in construction

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Executive summary

In Australia, 47 workers were killed in incidents involving cranes between 2003 and 2015 (Safe Work Australia, 2016a). Safe Work Australia (2019) also reports that there are, on average, around 240 serious injury claims arising from crane safety incidents every year.

The aim of this research project was twofold:

1. To identify causes and contributing factors associated with safety incidents involving cranes in the construction industry.
2. To explore strategies to reduce the risk of crane safety incidents in the construction industry.

The scope was further limited towards fixed and mobiles cranes used in the construction industry. In particular, the primary data collection focused on the construction industry in New South Wales.

Methods

The research was conducted in three parts:

1. a review of national and international academic and 'grey' literature (industry-based and government documents and reports) was undertaken
2. focus groups and interviews were organised with experts and informed workers from the industry

3. SafeWork New South Wales (NSW) data pertaining to crane-related safety activities were analysed.

Results

Literature review

Causes of crane safety incidents operate at different levels within a work system and include factors, such as:

- the regulatory environment
- prevailing levels of worker skill and competency
- industry supply issues
- site planning and management issues
- physical worksite conditions
- human errors and equipment failures.

In some instances, latent conditions are reported with the potential to cause serious crane safety incidents associated with design or manufacturing issues. Although such incidents are relatively rare, they show that not all crane safety incidents arise as a result of local site-based factors.

A range of different strategies was identified for preventing crane safety incidents in the construction industry. These relate to:

- the need for greater clarity relating to roles and responsibilities for crane-related activities at a worksite, and the involvement of suppliers and sub-contractors in equipment selection and site planning
- opportunities to increase training for people who plan, coordinate and supervise lifting operations
- licencing systems, and the importance of ensuring crane operators' competence in using a particular type or model of crane
- the adoption of new (and emerging) technologies to improve crane safety.

Focus groups and interviews

Cause-effect diagrams were developed reflecting five areas of crane safety incident causation: work environment issues, worksite conditions, human factor issues, equipment issues, and task/activity issues.

Factors and contributing factors were also classified as operating at one of three levels in the system of work involving the use of cranes in the construction industry: originating influences, shaping factors, and immediate circumstances.

A crane safety incident causation model was developed which reflects the operation of causal/contributing factors at these three levels. The model was tested successfully against documented crane safety incidents. A small number (n=6) of industry experts reviewed the crane safety incident causation model and confirmed its relevance both for understanding, and for investigating and preventing, crane safety incidents.

Industry experts consulted in focus groups/interviews also identified strategies that could assist in preventing safety incidents involving cranes. Suggested strategies fell into seven topic areas, as follows:

- training and competence
- development of a code of practice for crane operations
- communications and awareness raising
- the role of the regulator
- design and import issues
- technology use
- procurement and the management of commercial relationships.

SafeWork NSW quantitative data analysis

The analysis of the SafeWork NSW quantitative data revealed that:

- most crane safety incidents occur in the construction industry
- dangerous incidents occur most frequently when mobile and tower cranes are involved. Serious injuries occur most frequently for bridge/gantry cranes and mobile cranes
- the most common mechanism of crane safety incidents is a person being hit by the load being lifted. For incidents involving mobile cranes, the most common mechanism for incidents is the collapse of the crane

- between 2015 and 2018, there was a sharp increase in the number of dangerous incidents recorded per tower crane. However, the rate of serious injuries per tower crane was stable over this period
- when an immediate cause is identified for a crane safety incident, human error is most frequently cited. Faulty crane equipment is the next most frequent immediate cause identified
- crane crew experience is a significant risk factor for crane safety incidents. More experienced crane workers are less likely to be involved in crane safety incidents.

An agenda for preventing crane safety incidents

This research project identified four key areas of work with potential to prevent crane safety incidents. This agenda emerges from integrating findings from the literature review, focus groups and interviews with industry experts, and analysis of SafeWork NSW data.

Workforce competence

Human error was a frequently identified cause of crane safety incidents, and weaknesses were observed in the current High Risk Work training and licensing systems. Inexperience was also identified as a risk factor for crane safety incidents. Industry experts consulted in focus groups/interviews made suggestions to improve or better track the competency of the workforce, be it by recording the crane experience of workers, and/or introducing a tiered licensing system, and/or ensuring Verification of Competency (VOC) processes reflect machine-specific competence and/or providing specific training for those who make critical decisions with the potential to impact the safety of crane operations at construction sites.

Supply arrangements, communication and planning

Time pressures associated with the delivery of construction projects were found to negatively impact the time available for planning safe lifting activities. Commercial pressures and specific features of crane hire practices (such as the use of fixed price contracts) were also identified as risk factors for crane safety incidents. Fixed price contracts encourage work to be performed quickly, sometimes at the expense of safety, as delays are potentially costly for crane companies. Overly complex (and heavily paper-based) work health and safety (WHS) management systems were perceived to be ineffective for communicating site-specific risk factors and/or safe working practices to workers. Industry experts consulted in focus groups/interviews raised the importance of pre-deployment site visits to inform collaborative lift planning, as well as the need for standard clauses establishing safe operating requirements, and roles and responsibilities for safety, in commercial agreements between principal contractors and crane hire companies.

Industry and regulatory environment

Features of the industry and regulatory environment, including inspection practices, internationalisation of construction markets, and subcontracting practices, were identified as contributing to crane-related safety incidents in the construction industry. In particular, a history of non-compliance with WHS regulations was identified as a predictor of subsequent crane-related safety incidents among construction industry person[s] conducting a business or undertaking (PCBUs). Industry participants suggested safe working practices in using cranes could be improved through the regulator adopting an increased mentoring role and providing more detailed guidance on preventing crane safety incidents. Participants also suggested a more 'aggressive' inspection and enforcement regime could potentially produce improvements in the safe use of cranes in the construction industry.

Equipment design, maintenance and use

The operation of substandard cranes and structural/electrical failures were identified as immediate causal factors in crane safety incidents. These were traced back to deficiencies in manufacturers' information, inconsistent maintenance regimes, or modifications made to crane installations. Industry experts consulted in focus groups/interviews and identified the importance of third party crane assessment programs and suggested testing requirements should be based on functional age relative to a crane's design life (rather than determined by the age of a crane in years).

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General introduction

Background

The construction industry has developed into a highly mechanised working environment in which there is an increased dependency on mechanical material handling and lifting (Shapira et al., 2007). The dependence on cranes as the most prominent form of transportation on a construction site is linked to increasing industrialisation of construction processes and the off site manufacture of (often large and heavy) modular components (Raviv et al. 2017a). Cranes are therefore a critical feature of construction operations. They are also assessed as being one of the most dangerous items of equipment on a construction site (Sertyesilisik et al. 2010). The level of crane activity in major Australian cities is significant. The Rider Levett Bucknall (RLB) Crane Index measures the number of tower cranes standing as an indicator of construction activity. In the first quarter of 2019, this count was 310 for Sydney and 220 for Melbourne (RLB, 2019).

In Australia, 47 workers were killed in incidents involving cranes between 2003 and 2015 (Safe Work Australia, 2016a). Safe Work Australia (2019) also reports that there are, on average, around 240 serious injury claims arising from crane safety incidents every year.

Aims of the project

Safety incidents involving cranes can have dramatic consequences for workers, their families, and members of the public. Considering the large number of cranes being used in NSW, and Australia generally, it is critical to gain a better understanding of both the causes of crane safety incidents, and the solutions that can be successfully implemented to prevent them.

Since past research has shown that the circumstances of an incident likely differ as a function of the type of crane involved, the present study focused on two types of crane that are commonly found in mobile temporary workplaces such as construction sites: fixed cranes (tower cranes, self-erecting), and mobile cranes.

The present research aimed to answer two questions:

- What are the factors that cause or contribute to the occurrence of safety incidents involving fixed and mobile cranes used in the construction industry?
- What strategies, initiatives and technologies can be developed and implemented to reduce the risk of crane safety incidents in the construction industry?

A literature review was first conducted to synthesise the available published evidence and provide a frame of reference for the second and third components of the research. The second component was to analyse qualitative primary data relating to crane use and safety in the Australian construction industry – these data were collected through focus groups/interviews with industry experts. The third component of the research was to analyse data available to SafeWork NSW; for instance, crane safety incidents data, operational data, and High Risk Worker training and licensing data.

Structure of the report

The remainder of this report is structured as follows:

- the ‘Methods’ section presents a description of the research methods used for each of the three component parts of the work
- the ‘Results’ section presents the results of the analysis of the three component parts of the work
- the ‘Discussion’ section presents an overarching discussion of the findings of the three component parts of the work
- the ‘Appendix’ section presents supplementary material. This includes the tabulated focus group/interview data synthesis, causal maps used to inform the development of the crane incident causation model, as well as scenario crane incident cases used in the validation of the causation model
- the ‘References’ section presents a list of reference material used in this project.

Methods

Literature review

A review was undertaken of national and international academic and 'grey' literature (industry-based and government documents and reports).

The RMIT Library SearchIt database, Google Scholar, and relevant databases and journals, were searched, including the American Society of Civil Engineers database of conference and journal articles, Safety Science, and the *Journal of Safety Research*. Relevant industry websites (for example, 'Vertikal') were also searched, as were sites of international and Australian regulatory and health and safety policy-making bodies (for example, the UK Health and Safety Executive).

The document search used keywords including 'crane', 'crane accident/s', 'crane incident/s, 'crane + statistics', 'crane + statistics + construction', 'accident/s + approaches', 'accident/s + crane + construction', 'accident + construction + statistics', plus using previous combinations + [specific country] (US, UK, China, Japan, Asia more broadly).

The websites of the regulators across Australia (excluding SafeWork NSW) were also searched to develop a broad understanding of the material presented relevant to the subject of crane incident causation. Search terms included 'investigation', 'evaluation', 'cranes' and 'construction.' This search also included the web resources published by SafeWork Australia. The terms 'mobile' and 'fixed' were added to specify results on cranes. Further search parameters included 'investigation' or 'evaluation' (in title) and 'cranes' (in title) and 'construction'.

An exclusion criterion was also applied to exclude results relating to crane types outside the scope of the study, which focused on crane usage in the construction industry (for example, bridge or gantry cranes not ordinarily used at construction sites were excluded). Other materials excluded were those identified as being superseded or those that included information duplicated in multiple documents within the same jurisdiction (such as a news release and a safety alert referring to the same incident).

Identified materials were read and classified according to the type of information they presented; that is, whether the authors present an analysis of the causes or factors contributing to crane safety incidents in the construction industry, and/or the authors present information about strategies, initiatives or technologies (that were either implemented or recommended) to prevent crane safety incidents in the construction industry.

Information in the documents was synthesised and documented in the literature review under these general areas of analysis.

Interviews and focus groups

Procedure

Eight focus group sessions were organised by RMIT researchers in consultation with the Centre for Work Health and Safety (the Centre). Seven focus groups took place in Sydney, split between the Sydney CBD and Parramatta. This included a focus group specifically scheduled for employees of SafeWork NSW. One focus group was undertaken via Skype for regulator participants who could not attend a focus group session. The maximum duration of the focus group sessions was 90 minutes.

The majority of interviews were conducted via the telephone. However, two interviews were conducted on site at a crane company in Sydney. Interviews lasted for a maximum of 60 minutes.

The recruitment process started with the Centre putting together a contact list of known experts from the industry, crane workers, RTO representatives, and experts from the WHS regulator. The Centre then emailed an 'Eventbrite' invitation to these contacts. Prospective participants were able to 'opt in' to a focus group session that was convenient for them to attend. A limit of ten people per focus group was imposed to ensure group sizes remained manageable. For reasons of confidentiality, names of the registered participants were only known by the RMIT research team and were not shared with the Centre. The Centre also provided RMIT researchers with the names of people who could be approached to request an interview. People who were unable to attend a scheduled focus group session were offered the opportunity to be interviewed. In one case, a focus group participant introduced the research team to two members of his work team in order for them to be invited to participate in an interview. In keeping with confidentiality requirements, the Centre was not advised as to the identity of the individuals who registered and participated in focus groups or who were interviewed. In total, 35 people participated in a focus group and nine people participated in interviews.

Focus group/interview participants included crane owners, crane operators, construction managers, supervisors and workers, consultants, and people from relevant industry associations and organisations. The focus group sessions were held on 8, 14, 15 and 24 May 2019. One interview was conducted prior to the commencement of the focus groups due to the participant's preference and time constraints. The remaining eight interviews were conducted in the two weeks after the focus groups.

The focus groups were conducted using a pre-agreed data collection process. Participants were asked to share their thoughts and experiences relating to the factors causing or contributing to crane safety incidents in four main areas: site conditions, the work environment, human factors, and site safety management.

Participants were first asked to address each of the four areas in relation to the cause of incidents involving both fixed and mobile cranes. They were then asked to group and rank the top causal/contributing factors (relating to fixed and mobile cranes). Finally, they were asked to identify strategies or interventions that could help to reduce the incidence of crane safety incidents, with particular relevance to the factors they identified. See Appendix 9 for semi-structured interview questions and focus group approach.

Data collected during the first round of focus groups and interviews were audio-recorded (with participants' informed consent) and transcribed verbatim in preparation for analysis (Gale et al. 2013).

Following analysis of the first round of focus group/interview data, five further interviews were conducted with selected industry representatives to evaluate the validity/usefulness of the outputs from the initial data analysis (in particular, a crane safety incident causation model). The purpose of these interviews was to:

- examine whether the crane safety incident causation model developed following the first round of data collection/analysis is useful in helping to identify causal/contributing factors in example crane safety incidents
- examine whether the content of the crane safety incident causation model is applicable to both mobile and fixed (tower) cranes
- elicit industry participants' views regarding the practical usefulness of the crane safety incident causation model.

Interview participants were provided with an example case scenario describing either a mobile crane or a tower crane incident. Participants were randomly assigned to the mobile and tower crane incident descriptions. The interviews were not sufficiently long enough for both scenarios to be considered by all participants.

Participants were asked to read through the incident description/scenario and then identify immediate circumstances, shaping factors, and originating influences, that contributed to the incidents. For the purposes of this exercise, three groups were provided with the tower crane scenario and two groups were provided with the mobile crane scenario.

Participants in the second round of consultation (validation) were also asked:

- whether factors in the model reflected their opinion as to the causal/contributing factors in crane safety incidents, and
- whether they would find the model useful in analysing incidents and/or understanding crane-related safety risks in their workplaces.

Data analysis

In total, 444 pages of transcribed data were generated from the initial focus groups/interviews. These data were analysed using a systematic method of analysis that is well suited to applied policy research (Gale et al. 2013). The 'framework method' of qualitative data analysis is useful because, while it captures key concepts, ideas and themes from the original accounts and observations of participants, it is also focused on meeting pre-set aims and objectives of funders and researchers (Pope et al. 2000). Data collection tends to be more structured compared to other qualitative research approaches, and the analytical process is made explicit (and is often informed by) research questions or *a priori* theoretical positions (Pope et al. 2000).

The framework method can be used for diagnostic and strategic purposes and is designed to meet specific information requirements in a limited timeframe (Ritchie & Spencer, 1994). In this case, the information requirements to be met were both diagnostic and strategic, and related to identifying and understanding two domains: first, the causes of safety incidents involving cranes (mobile and fixed) in the Australian construction industry (diagnostic); and second, participants' viewpoints about what could or should be done to prevent crane safety incidents in the construction industry context (strategic).

The framework method of analysis offers several advantages. It provides a systematic model for managing and mapping large qualitative datasets. The matrix format used in the framework also provides a structured overview of summarised data, making it easy to comprehend and interpret. Finally, the step-by-step process of analysis makes it is suitable for interdisciplinary and collaborative research projects (Gale et al. 2013).

The steps followed in the framework method of analysis are those prescribed by Ritchie and Spencer (1994):

1. Familiarisation with data – gaining an overview of the material to be analysed. All the transcripts were read by one analyst. The analyst did not participate in data collection.

2. Identifying a thematic framework – once familiar with the data, key issues, concepts and themes could be identified, according to which the data can then be examined in detail and referenced. In this case, the analyst used a balance of deductive processes (deriving themes from the theories of incident causation that informed questions posed by the focus group facilitator/interviewer), and inductive processes (identifying themes emerging from participants' discussion). Combining inductive and deductive analytical processes is accepted practice in qualitative data analysis (Fereday & Muir-Cochrane, 2006). Gale et al. (2013) argue that the framework method can accommodate both inductive and deductive thematic analysis, or reflect a combination of both approaches.

In developing a framework for subsequent coding and classifying data, it is useful to test the framework for completeness, to ensure it is reasonably inclusive of the data, reproducible, and credible to the people who provided the data (Patton, 2002). The construction industry experience of the data analyst was critical in ensuring the thematic framework developed in this step met these criteria for completeness.

3. Indexing – the framework was applied to the whole dataset in its text form. During this stage, the analyst read the focus group/interview transcripts in detail and highlighted core meanings, themes and concepts contained in the narratives and responses of participants (that is, the transcripts). Content analysis of this type describes 'qualitative data reduction and sense-making effort that takes a volume of qualitative material and attempts to identify core consistencies and meanings' (Patton, 2002, p. 453). Relevant themes and concepts identified in the data were systematically cross-referenced with the framework developed in step 2. By systematically identifying meaning, themes and patterns, and linking these back to specific quotes or passages in the transcribed data, the process of indexing is made visible and accessible. This is an important feature of applied policy research. A portion of the data was also reviewed by two researchers to test the reliability of the thematic framework and coding process. To ensure the coding process was consistent and reproducible, disagreements were discussed until consensus was reached.

4. Charting – relevant portions of data (those illustrative of core meanings, themes and concepts identified in step 3) were then 'lifted' from the original source documents (in this case transcripts) and incorporated into a matrix/spreadsheet format. This was done for each focus group transcript, prior to creating an overall table containing all relevant themes/concepts, their description and example quotations (traceable back to the transcripts from which they were drawn). This table is presented in Appendix 5 of this report. The table organises causal factors identified by the focus group/interview participants into three levels of causation included in the ConAC model: that is, immediate circumstances, shaping factors, and originating influences.

5. Mapping and interpretation – when all the data has been sifted and incorporated into the framework according to core themes/concepts, the analyst then interpreted and mapped the entire dataset. During mapping and interpretation, the meaning of the data is explored in relation to the research aims, patterns of association, explanations, and linkages between diagnosed issues and preventive strategies. At this stage, findings are judged in terms of their substantive significance. This involved considering how coherent and solid the evidence is in support of the findings, to what extent the findings increase

understanding of the phenomena being studied, to what extent the findings are consistent with other knowledge relating to the phenomena, and to what extent the findings are useful for their intended purpose (Patton, 2002). The data were then further examined to identify causal links between factors operating at different levels in the ConAC causation framework. Cause-effect maps were developed to show the relationship between factors operating at different levels in the 'hierarchy' of causal factors. These cause-effect diagrams are provided in Appendix 6.

These cause-effect diagrams were developed for five broad areas of crane incident causation: work environment issues, worksite conditions, human factor issues, equipment issues, and task/activity issues.

These broad areas referred back to the way in which the focus group questions were posed. However, due to the richness of data and detailed responses provided, the site management factor was broken down into two separate cause-effect diagrams (reflecting equipment issues and task/activity issues). The diagrams can be found in Appendix 6 of this report.

6. In step 5 of the analysis of qualitative data, 'cause-effect' trees (logic diagrams) were developed, representing linkages between contributing factors to crane safety incidents. These trees are useful in representing knowledge that is subjective and interrelated to other issues that need to be considered simultaneously, as is the case in understanding the factors that influence construction WHS (Cooke et al. 2008). The cause-effect trees represent actual or potential causal pathways between distal and site-level causes/contributing factors identified by focus group/interview participants. Where possible, causal inferences (pathways) were developed based upon the explanations provided by focus group/interview participants. Some of these pathways were explicitly identified by participants, while others were implied in their comments and explanations of the causes of crane safety incidents. However, some pathways incorporated into the trees were inferred by the analyst, drawing on extensive industry knowledge and experience. The cause-effect tree diagrams provided an understanding of actual or potential pathways through which managerial/organisational decisions and actions contribute to unsafe physical conditions, and/or human error, in relation to crane usage.

On the basis of the qualitative data analysis, a crane safety incident causation model was developed based upon the nodes in the cause-effect diagrams. This model is based on the ConAC incident causation framework. The ConAC framework was developed by Haslam et al. (2003) based on a study of 100 construction safety incidents, categorising causal factors as immediate circumstances, shaping factors and originating influences. In the US, Behm and Schneller (2013) used the ConAC framework to analyse the causes of 27 construction safety incidents of varying degrees of severity. In Australia, Cooke and Lingard (2011) used the same framework to analyse the causes of fatal incidents in an analysis of coronial investigation reports. The ConAC framework has been extended and adapted by Harvey et al. (2018). The model is applicable to the construction industry and useful in facilitating an understanding of the causes of serious (fatal) incidents, as well as less serious incidents and near misses (Gibb et al. 2014). Consequently, this model was used as a framework to structure the results of the qualitative focus group/interview data analysis.

The resulting crane safety incident causation model thus provides an evidence-informed analysis of the causal/contributing factors, as identified by focus group/interview participants, operating at each of the three levels of causation: immediate circumstances, shaping factors, and originating influences.

SafeWork NSW data

The following issues were examined in the quantitative analysis of SafeWork NSW data:

- Crane safety incident rates were compared across industries in NSW. Crane safety incidents were analysed according to a number of variables, including injuries, near misses, the type of crane involved, the mechanism by which the incident occurred and the victim type
- time series analysis was performed to understand how the frequency of crane safety incidents has changed over time
- causal factors that could be extracted from incident reports were analysed
- geographical analysis was performed to map the regions in NSW where crane safety incidents occur
- licensing and training data for High Risk Work licence holders: that is, operators, riggers and dogmen, was analysed to identify the population of high-risk workers most at risk of being involved in a crane safety incident. The characteristics (for example, age and experience level) of these workers were compared to those of the general population of High-Risk Work licence holders
- the size of a High-Risk Work training organisation was analysed for its potential as a risk factor for crane safety incidents
- the person[s] conducting a business or undertaking (PCBU) most at risk of experiencing a crane safety incident were identified by analysing their WHS compliance history.

Data sources

Several datasets captured and managed by SafeWork NSW were used to support the quantitative analysis. These are described below.

The workplace incident database

The workplace incident dataset was extracted from the Workplace Services Management System (WSMS). It provides details regarding 75,215 workplace incidents that have occurred between 01/01/2002 and 01/02/2019 in NSW. Eighty variables were documented for each incident (for example, incident date, incident type), and a further 30 quantitative variables were created relating to crane safety incidents (see Appendix 7 for a list of extracted variables and Section 2.2.3 for the procedure by which they were created).

The High-Risk Work (HRW) Licence database

The HRW Licence database consists of all HRW licences issued between 29/04/1996 and 01/02/2019 by the Government Licensing Service (GLS). It holds details for a total of 151,715 licences across 14 variables which provide details about the licences and licensees (for example, reference number, licence issue date, licence expiry date, age, class).

The HRW training database

The HRW training database details training records for each individual who has received RTO training for a HRW Licence. It consists of 75,021 licences active on 1 February 2019. The dataset includes variables which provide details about licences and licensees (for example, issue date, expiry date, class, training).

Inspector compliance notices issued to PCBUs

The compliance notice database was extracted from WSMS. It consists of 72,504 notices issued by inspectors to PCBUs between 1 January 2007 and 1 January 2019. It records 75 variables which provide information about the circumstances of the notice issued (for example, type of notice, date issued, status, ABN, name, postcode).

The crane registration database

Crane registration data was extracted from WSMS and consists of registered mobile and tower cranes in NSW. A total of 3,213 cranes were listed as registered on 1 February 2019, with 14 variables providing information about each registered crane (for example, registration number, issue date, owner ABN, industry).

Data cleansing and analysis

Figure 1 illustrates the procedure followed to narrow the WSMS workplace incident dataset down to crane safety incidents only, and to extract causal information from the accident reports.

Automated data filtering

To identify safety incidents that were crane-related, the WSMS workplace incident dataset was initially filtered for the keyword ‘crane’ in the ‘Incident Description’ and ‘Action Taken’ fields. The ‘Incident Description’ field describes the incident in question, usually reported by the PCBU. The ‘Action Taken’ field contains a complete SafeWork NSW inspector’s report and was highly likely to contain the word ‘crane’ for crane safety incidents. The initial screening resulted in 1,461 incidents that contained the word ‘crane’ in either field, out of a total of 10,026 incidents.

Workplace incidents are categorised by SafeWork NSW into several groups: dangerous incident, serious injury, injury, serious illness, fatal injury, fatal illness, pollution, or other. The crane safety incidents were further filtered to only include fatal injuries (n = 72), serious injuries (n = 605), and dangerous incidents (n = 799). Definitions of serious injuries and dangerous incidents are taken directly from the *Work Health and Safety Act 2011*, Section 37. Incident type definitions are provided in Appendix 8.

Manual review

All dangerous incidents, serious injuries and fatal injuries that included the text string ‘crane’ in the ‘Incident Description’ and ‘Action Taken’ fields were manually reviewed to confirm that the incidents were in fact crane related. This procedure was required because there are many instances where the word ‘crane’ is mentioned in the incident database, but a crane was not directly involved in the incident in question. The ‘Incident Description’ and ‘Action Taken’ fields were individually reviewed and incidents where a crane was not involved were filtered out. A total of 1075 crane safety incidents remained after this filtering process was applied, including 15 incidents resulting in a fatality (fatal injuries), 344 incidents resulting in serious injuries, and 731 incidents categorised as dangerous (Figure 1).

Extracting further quantitative information from the workplace incident database

The ‘Incident Description’ and ‘Action Taken’ fields contained additional information in plain text. A procedure was established to convert the plain text into a set of new quantitative variables. The procedure taken was as follows. Three analysts reviewed 80 random records. Each analyst defined a set of quantitative variables they deemed relevant to the analysis of crane safety incidents. A final set of 30 quantitative variables was settled upon by consensus. These variables provided information about the crane (for example, type of crane, action of crane at time of incident), and further details surrounding the incident (for example, fall from crane, hit by load), the victim of the incident, weather conditions, causal factors, and many more. A complete list of all 30 quantitative variables can be found in Appendix 7.

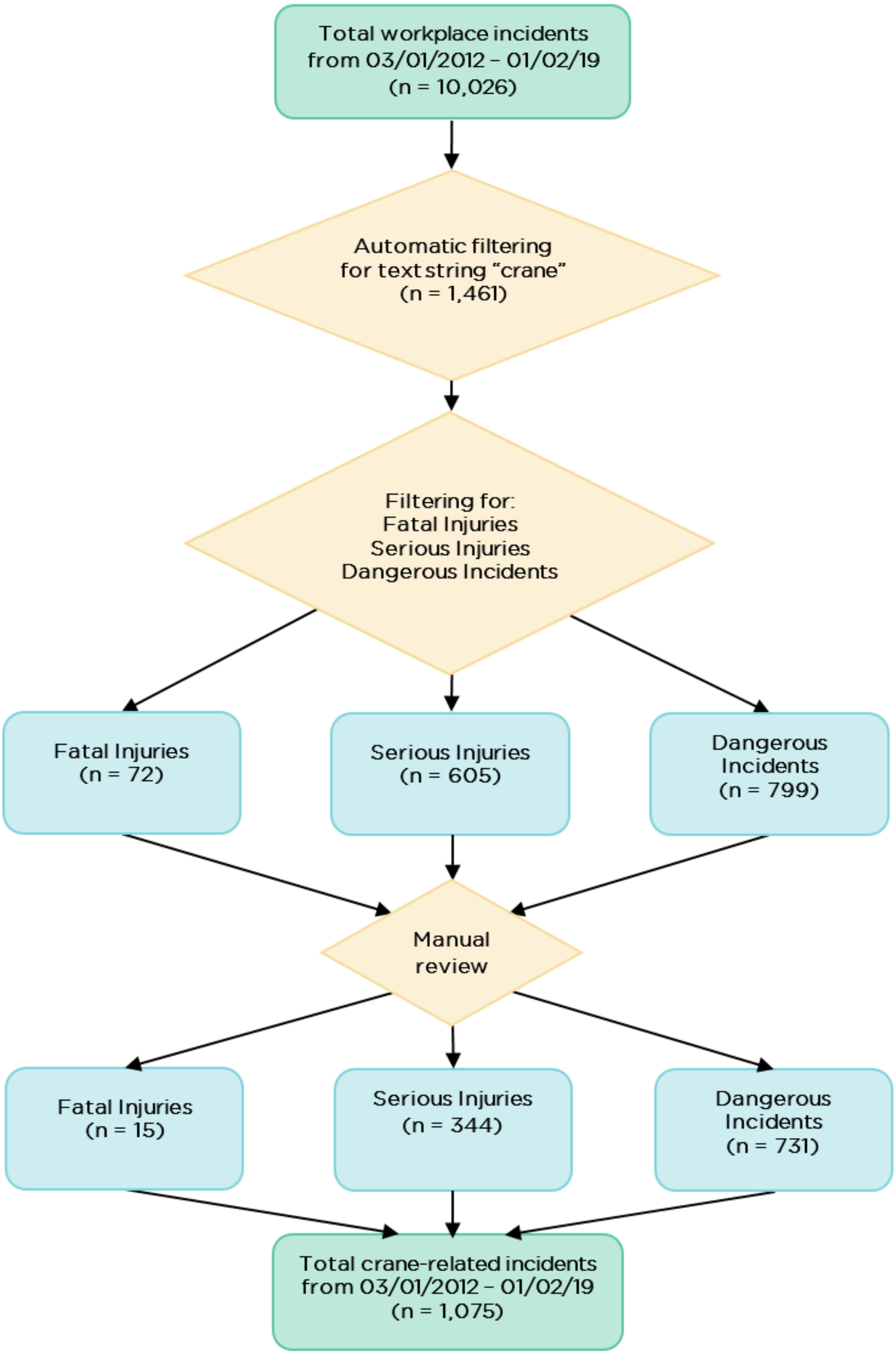

Figure 1. Flowchart describing the filtering procedure of the WSMS workplace incident database for crane safety incidents.

PCBU crane ownership and compliance notice history

The list of registered cranes was transformed to provide a list of PCBUs currently owning at least one registered crane. The number and the type(s) of crane owned by each business were examined, as well as the average and the maximum time a registered crane had been owned. The

WSMS compliance notice dataset was then used to inform about the history of compliance notices issued to each PCBU.

HRW licensing and training

- List of licensed HRW involved in crane safety incidents. By combining information collected from the workplace incident database and from the investigation files, d a list 280 of identifiable HRW found to be involved in crane safety incidents as riggers, dogmen or crane operators was created.
- Licensing and training dataset preparation. There are multiple licence types for each of the three main roles of working with or around a crane (that is, rigger, dogman, operator). The licence types were categorised under three main roles: rigging (licences for basic, intermediate, and advanced rigging), dogging (licences for dogging), and operating (licences for operating: non-slewing mobile cranes greater than 3 tonnes; slewing mobile cranes up to 20 tonnes, up to 60 tonnes, up to 100 tonnes, and over 100 tonnes; self-erecting tower cranes; tower cranes; bridge and gantry cranes; and vehicle loading cranes).
- Characteristics of crane crew and PCBUs operating cranes. The extent to which characteristics of those HRW involved in workplace incidents differ from the population at large was examined. The populations examined were riggers, dogmen, crane operators, and PCBUs owning cranes.

Statistical analysis

A chi-squared test was used to determine the independence between two or more groups. Results are presented as ($\chi 2(a) = b$, $p < c$), where a is the number of degrees of freedom, b is the value of the test statistic, and c is the p-value. A p-value of <0.05 was deemed to be significant.

Linear models were fitted to time series data to determine trends over time. A F-test was used to determine the statistical significance of the trend: that is, whether the slope of the linear fit significantly differed from zero. Results are presented as ($F_{a,b} = c$, $p < d$), where *a* and *b* are the of degrees of freedom, c is the value of the test statistic, and *d* is the p-value. A p-value of <0.05 was deemed to be significant.

Further analysis examined whether independent trends in the data were significantly different. The values and errors of the slopes of linear models were compared, creating a z-score and associated probability (p-value). Results are presented as ($z = a$, $p = b$) where *a* is the z-score and *b* is the calculated p-value. A p-value of <0.05 was deemed to be significant.

Results

Literature review

The literature review is structured to respond to the two research aims. First, the literature relating to the causes of crane safety incidents in the construction industry is synthesised and discussed. Second, strategies recommended in the literature for the prevention of crane safety incidents in the construction industry are described. The literature review is structured as follows:

- information comparing the different types of safety incidents involving fixed and mobile cranes is presented
- literature examining the causes of tower crane safety incidents is presented
- literature examining the causes of mobile crane safety incidents is presented
- commentary on the role played by human error in crane safety incident causation is discussed
- the potential for crane safety incidents to be caused by latent conditions is considered
- research undertaken to quantify the risk of crane safety incidents is described
- risk reduction strategies and initiatives (identified in the literature) are described, including the application of advanced technologies to support crane safety in the construction industry
- key findings and limitations inherent in the literature review are summarised.

Comparison of incidents involving mobile and fixed cranes

Shepherd et al. (2000) analysed crane fatalities occurring in the US construction industry between 1985 and 1995, on the basis of the damaging energy involved. The crane type was specified in 67% of the incident records. Of these 65% of incidents involved mobile cranes, 20% involved aerial lifts, and 6% involved tower cranes.

The fatal incidents involving cranes were classified depending on whether the fatality occurred as a result of:

- electrical energy – electrocution (217 cases)
- gravitational energy (268 cases)
- machine energy (34 cases)
- other forms of energy (6 cases).

Each energy form was further subdivided into incident type. For example, gravitational energy incidents were subdivided into:

- falls of objects (144 cases)
- falls of people (88 cases)
- falls of crane – overturning (36 cases).

Where data about the crane type are incorporated into the analysis of crane safety incident data, the evidence suggests that mobile and fixed cranes are involved in different types of safety incident (Neitzel et al., 2001)[1]. Beavers et al. (2006) analysed 125 cases of crane safety incidents resulting in 127 fatalities occurring in the US between 1997 and 2003. They report the majority of these incidents to involve mobile cranes (88%), with 56% involving lattice boom type mobile cranes.

Beavers et al. (2006) examined proximal causes and contributing factors to the fatal crane incidents. However, in this analysis, the proximal cause is better described as the incident type (for example, struck by load, electrocution) and contributing factor describes the *immediate* cause of the incident (for example, rigging failure, unbalanced load, boom contact with source of electricity). The most frequent proximal causes identified are shown in Table 1.

Table 1. Tower crane safety incident causation (Beavers et al. 2006).

Causes	Number of cases	Percentage
Struck by load (other than failure of boo m/cable)	40	32.0%
Electrocution	34	27.2%
Crushed during assembly/disassembly	15	12.0%
Failure of boom/cable	15	12.0%
Crane tip over	14	11.2%
Struck by cab/counterweight	4	3.2%
Falls	3	2.4%
Total	125	100.0%

Beavers et al. (2006) observe that electrocution and crane tip-over cases exclusively involved mobile cranes. Electrocutions predominantly involved failure to maintain clearance in relation to overhead powerlines in accordance with specified guidelines. Tip-over incidents were mainly caused by overloading, loss of centre of gravity, and/or outrigger failure. While contact with

1 Gantry, overhead and ship-to-shore cargo cranes were excluded from this analysis. Thus fixed cranes refer to tower cranes utilised at construction sites. These include flat top, high top and luffing jib tower cranes.

overhead powerlines is found to be a major cause of fatal incidents involving mobile cranes, Shapira et al. (2008) argue that the presence of power lines has only a moderate impact on safety in the use of tower cranes.

Differences in incident type between mobile and tower cranes are shown in Figure 2 which is taken from an analysis of 937 crane safety incidents occurring worldwide from 2011-2015 (Milazzo et al. 2016).

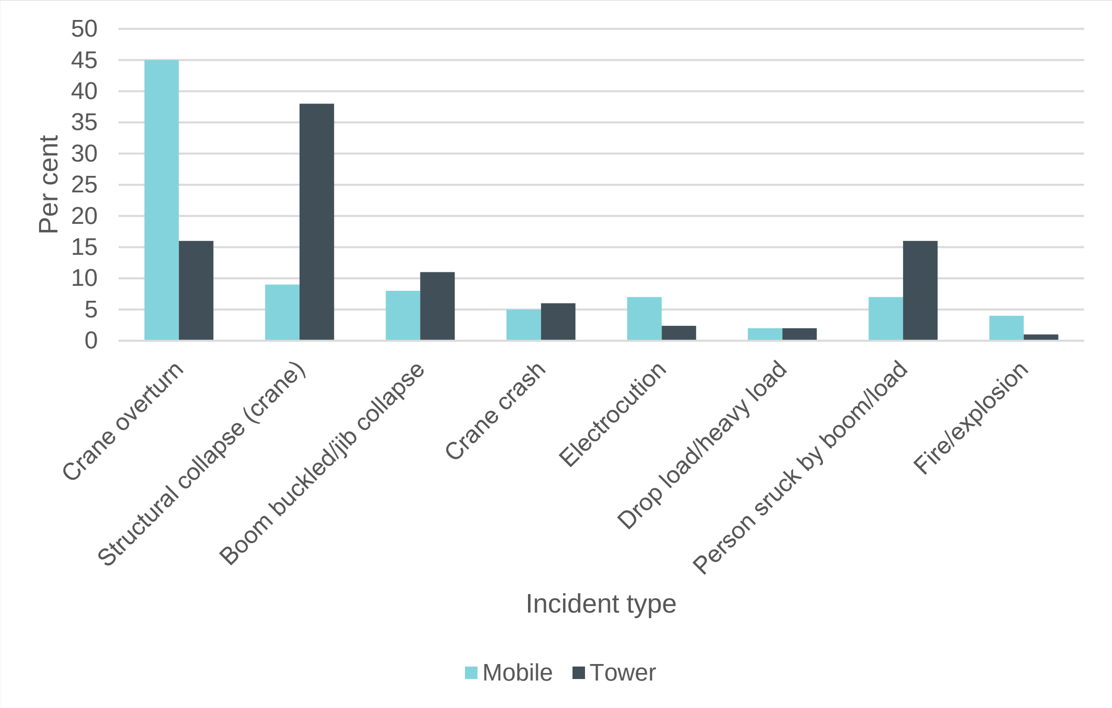

Figure 2. Main incident types for mobile and tower cranes. Adapted from Milazzo et al. 2016.

Some writers argue that human error is more likely to be a factor in mobile crane safety incidents than it is in tower crane safety incidents (Shapiro et al. 2000), potentially because tower crane operation is more heavily automated than the operation of a mobile crane (Raviv et al. 2017a). Another factor in this difference may be that tower cranes, once in position, have limited range of movement and operational parameters do not change to a great extent. However, the circumstances in which mobile cranes operate are constantly changing and therefore it is much more difficult to rely on automation and safety instrumentation that may not determine safety-relevant changes in the operating environment; for example, changing ground conditions (Kan et al. 2018).

Crane safety incident causes

Some of the literature that examines crane safety incident causation does not differentiate between factors causing/contributing to safety incidents involving fixed and mobile cranes. For example, in a study of High Risk Construction Operations (HRCO) conducted in the US, a crane safety investigation team found evidence of improper rigging and lifting practices as contributing to crane safety incidents irrespective of crane type. Improper rigging and lifting practices observed were:

- hoisting over people
- load insufficiently attached to crane
- danger of losing all or part of the load
- load striking other objects during hoisting
- slings and other rigging instruments in a deteriorated condition.

It is noteworthy that a fatal crane incident that occurred in Melbourne in 2018 was believed to be caused by the failure or malfunction of the hoist rope termination assembly. A concrete kibble fell causing fatal injury to a worker working beneath the lift route. WorkSafe Victoria also points out that work should be planned to avoid lifting of loads over areas at which work is being performed (WorkSafe Victoria, 2018). In New York, the HRCO investigation team attributed unsafe rigging practices to human error, reporting that the rigging equipment is generally inspected and within sufficient load ratings (Smith & Corley, 2009).

In Australia, Gharaie et al. (2015) identified the most frequent types of crane incident in the National Coroners' Information System (NCIS) database to be electrocutions and persons being struck by moving objects. However, they did not specify the types of crane involved in these incidents. The incidents reported in the NCIS database were reported to be caused mostly by site layout issues which were traced back to space constraints in the site environment and aspects of the work design. Site constraints were related to poor risk management and failure to adequately design construction processes. Work design factors were traced back to inadequate attention to safety in the design of the product being constructed (that is, the building or structure) and the processes of construction.

Sertyesilisik et al. (2010) examined the safety of lifting operations at three case study construction sites in the UK and identified a number of site management issues with the potential to impact the safety of cranes operations. These included:

- time pressure and tight deadlines which encourage unqualified workers to act as a slinger/signaller to speed up operations
- construction contractors, particularly smaller firms, using specialist equipment providers as a way to overlook their safety responsibilities
- construction contractors lack of awareness of their safety responsibilities, believing (incorrectly) that contract lift hiring removes their responsibility
- too much emphasis on paperwork

- a shortage of industry-based inspectors with in- depth knowledge of crane safety issues
- the need for more rigorous requirements and processes for planning lifting operations
- deficiencies in the level of training for lift supervisors and slingers/signallers (Sertyesilisik et al. 2010).

Safety incidents involving tower cranes

In the UK, the Health and Safety Executive (HSE) commissioned an investigation of tower crane incidents occurring between 1989 and 2009 worldwide. Isherwood (2010) considered 85 tower crane incidents and placed each of these into one of seven categories. Twenty-eight incidents were attributed to an 'unknown cause' group[2]. Of the remaining 57, the categories and percentage distributions are shown in Table 2.

Table 2. Tower crane safety incident causation (Isherwood, 2010).

Categories	Number of incidents	Percentage
Erection/dismantling/extending the crane	29	51.0%
Extreme weather	15	26.0%
Foundation issues	2	4.0%
Mechanical/structural issues	4	7.0%
Misuse	6	10.0%
Electrical/control system issues	1	2.0%
Total	57	100.0%[3]

Erection/dismantling/extending (climbing) a tower crane was the most common category of the tower crane incidents considered in the HSE analysis. Isherwood (2010) suggests that the process of lifting, manoeuvring and fitting together large components at height is physically demanding and hazardous. Further, workers engaged in this work are often required to work long/non-standard hours. Shin (2015) similarly identifies that the majority (68.4%) of fatal incidents involving

2 The number of incidents attributed to 'unknown' factors is indicative of informational limitations in understanding crane incident causation, including in large scale international studies.

3 This classification system confounds incident cause (for example, extreme weather, misuse and issues associated with the crane foundation, mechanical/structural performance or electrical/control systems) with an on-site activity of phase of use (that is, the erection/dismantling/extension of the crane). These are not necessarily mutually exclusive, for example extreme weather could combine with misuse in the erection/dismantling/extension of the crane to produce a safety incident. This hypothetical example highlights the need for a more nuanced way of understanding causation than the use of simple classification systems such as this.

tower cranes occurring in Korea between 2001 and 2011 occurred during installing/dismantling, while 18.4% took place during normal operation of the crane.

Focus groups conducted with construction professionals/crane operators in Korea identified dangers for safety incidents during tower crane installation/dismantling (see Table 3; Shin, 2015).

Table 3. Dangers when erecting/dismantling tower cranes (Shin, 2015).

Activity	Risk factors
Erecting	Asymmetric load caused by wrong setting of the foundation anchor, which inclined to one side Insufficient installation of a telescopic shoe (incomplete of fixing or mounting) Poor supporting/fastening of a brace/block to a mast Not using safety belts Working without a scaffold and work plates
Climbing	Imbalance of each jib while telescoping by not using a counterweight[4] Unlocking or missing of fixing pins at both ends of the sides (not clapping and fastening all bolts) Insufficient loading conditions in the mast bogie rails Derailment of a mast from bogie rails Imbalance due to failure to use a balance mast Buckling of a telescopic cage Fracture of clamped bolts supporting a circle ring
Dismantling	Unsafe removal of pins on the telescopic supporter Jib fracture/inappropriate selection of the position for raising the main jib Fracture of a wire rope during dismantling Imbalance due to failure to use a balance mast
General	Abrasion (wear and tear of components such as bolts, nuts, or pins) Incorrect stability of the slewing platform by not completing the connection or omitting bolts on the surrounding circle ring Inappropriate sling work or operation (incompetence of slingers) Errors of a crane operation or malfunction of a tower crane

Shin (2015) identified causal factors (see Table 4) for 38 fatal incidents occurring during the erection/dismantling of a tower crane.

4 This wording is quoted directly from Shin (2015). The use of the word 'telescoping' in relation to tower cranes suggests that this refers to self-erecting tower cranes sometimes used at small to medium building sites (Safe Work Australia, 2016).

Table 4. Causal factors for fatal incidents occurring during erection/dismantling of a tower crane, in descending order of frequency (Shin, 2015).

Causal factors	Number of incidents	Percentage
Violation of work procedure	12	31.6%
Insufficient safety procedure	9	23.7%
Lack of inspection or deterioration of components	4	10.5%
Unsafe operation of tower crane	3	7.9%
Signalling error	2	5.3%
Intrusion into a danger zone	2	5.3%
Loosening of fastening objects	2	5.3%
Not wearing fall protection gear	2	5.3%
Excessive action of the worker	2	5.3%
Total	38	100.0%

It is noteworthy that most of these causal factors attribute the incident to human error. Human error is a frequently identified causal factor in tower crane safety incidents. For example, Tam and Fung (2011) examined 12 safety incidents involving tower cranes in Hong Kong between 1998 and 2005, concluding that these events largely occurred due to unsafe practices of tower crane operation which were attributed to:

- 'indolent' performance of requirements or responsibilities of practitioners
- inadequate training
- fatigue (p. 208).

However, Shin (2015) acknowledges that behavioural causes of safety incidents involving cranes can, in most cases, be explained by organisational issues, including poor communication between principal contractors and crane hire companies, competition and cost pressures inherent in multi-layered subcontracting, inadequate pre-planning of crane installation activities on site, and inconsistent maintenance regimes.

Organisational factors have been identified in a number of safety incidents involving tower cranes. For example, Marquez et al. (2014) examined a tower crane collapse in Argentina and found that the crane foundation/supporting structure failed because:

- information was not transferred between the crane designer/manufacturer and the construction team (user of the crane), and thus, load conditions considered during design were not well understood by users
- early warning signs of failure were misinterpreted or ignored, meaning no proper mitigation measures were taken
- site-based tests were performed but these did not follow pre-established or approved testing procedures (Marquez et al. 2014).

Marquez et al. (2014) argue that the human errors involved in the incident arose because the construction company, at whose site the crane was working, did not have a good understanding of the impact of variable loads and cyclic stresses on crane foundation structures. Involving crane manufacturers in the design or approval of crane foundation systems was identified as a strategy that could have prevented the collapse. Questions were also raised about the allocation of responsibilities in the lease or sale of tower cranes. Marquez et al. (2014) note that crane manufacturers are required to specify the maximum load and moments the foundation must sustain. Yet, once a crane is on the market, Marquez et al. (2014) argue there is no systematic process to capture information about the design of crane foundation systems, including defects and incidents, so that this can be shared with construction companies.

The case example below provides another example of how communication failure (in this case between the principal contractor and the designer of the tower crane foundation/support system) contributed to the collapse of a tower crane in the US.

Case example: Poor communication and change of construction process leads to tower crane collapse

> A communication failure between a crane foundation/support system designer and the construction contractor was identified as a causal factor in the collapse of a tower crane in the US in 2006 (McDonald et al. 2011). In this incident a change to the timing of construction work made by the construction contractor was not communicated to the structural engineer responsible for designing the tower crane foundation/support system. As a result, the design relied on a structural tie between the building core and the crane tower. This tie would have resisted forces due to the crane's overturning moment. However, due to the delay of the core construction, the structural ties were eliminated from the construction plans. This change was not effectively communicated to the designer with the result that the crane base was substantially under-designed. When exposed to repeated load reversals due to operation and winds, fatigue cracks developed, causing a catastrophic collapse (McDonald et al. 2011). This example shows how immediate mechanical causes (that

is, fatigue-related cracking) can be traced back to a poor design decision which, in turn, can be traced back to a failure in communication between important players involved in the set-up and operation of the tower crane.

Consistent with the finding of Marquez et al. (2014) factors causing or contributing to safety incidents in tower cranes have been identified at different levels within a system of work. Zhou et al. (2018) used a qualitative (AcciMap) technique to identify factors contributing to tower crane safety incidents (occurring in China) at the following levels:

- the workers involved in crane assembly/dismantling or lifting operations, including individual workers' attitudes, competencies and behaviours
- the equipment being used, including the selection of crane type, structural reliability and safety devices
- the worksite environment, including site supervision, layout and work planning
- environmental conditions, including wind conditions and visibility
- the regulatory environment, including preventive WHS legislation and certification requirements for crane usage (Zhou et al. 2018)[5].

Fifty-six causal factors were identified by Zhou et al. (2018) following a literature review and interviews with 12 industry experts. Further interviews with experts were used to identify the level at which each factor operated, and the causal links with other factors, to develop a model of tower crane safety incident causation applicable to the construction industry in China. At a government/regulatory level, Zhou et al. (2018) identify features of the regulatory environment as contributing to tower crane safety incidents, including deficiencies in safety regulation and supervision, operator certification, and crane registration requirements.

At the 'tower crane stakeholder' level, the attitudes and safety management systems of principal contractors, manufacturers' qualifications and subcontractors' input (defined as funding/resourcing) into tower crane activities were identified as contributing factors.

At the site management level, communication was identified as a contributing factor, including the quality of principal contractor and subcontractors' safety briefings, the principal contractors' safety knowledge and training of subcontractors' personnel, the quality of principal and subcontractor safety management planning, work schedule pressures implicit in project programs, and crane inspection and maintenance regimes.

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5 These levels are ordered in terms of their increasing distance (separation) from the immediate circumstances of the safety incident.

In relation to the on site tower crane staff, the competence and behaviour of supervisors, crane operators, and riggers and signallers, were identified as factors that could contribute to safety incidents involving tower cranes. It was also recognised that behaviours are shaped by the commitment to safety (particularly of supervisory personnel), workers' safety values, and job stress.

At the environment/equipment level, contributory factors identified included features of the construction site and prevailing environment, including overlapping crane operations, congested sites with obstructions, and weather conditions (for example, wind). The reliability of the tower crane components and foundation system, the ergonomic characteristics of the crane cabin, and availability of operator aids and auxiliary systems, were also identified as potential contributing factors at this level of analysis.

Importantly, Zhou et al. (2018) report linkages between causal factors within and between the different levels of the AcciMap model. For example, decisions made by tower crane stakeholders can affect construction site management practices and aspects of the work environment and equipment used. More specifically, principal contractors' selection decisions have the potential to impact subcontractors' crane-related safety practices. Principal contractors' behaviours can determine the on site safety management practices within which subcontracted crane workers perform their work. Subcontractors' safety activities also determine maintenance, which has the potential to impact safety and the reliability of equipment. The model also showed that factors related to the regulator's behaviour have a direct impact on tower crane stakeholders and site management practices. Regulatory requirements establish responsibilities and obligations for various tower crane stakeholders in relation to workplace safety, and site safety management practices are subject to inspection and compliance monitoring.

Subcontracting practices, and in particular the way crane operators are engaged by principal contractors, are frequently identified as relevant factors contributing to safety standards in tower crane use in the construction industry (Tam and Fung, 2011; Shin, 205). It is noted that constructors typically do not own their own tower cranes but lease them from a lessor for the required duration. Competitive pressures inherent in the subcontracting system (including awarding work to the lowest bidder) are reported to negatively impact the extent to which equipment is safely stored, maintained and installed (Shin, 2015). These subcontracting arrangements also create conditions in which crane operators work across multiple jobs/sites, experience low levels of control, and have time pressures imposed upon them by principal contractors' construction programs/schedules. Shin (2015) also observes that principal contractors do not always provide appropriately prepared sites to support crane erection and dismantling activities, increasing the risk of safety incidents. Safe installation/erection requires pre-preparation and planning to ensure that issues, such as ground conditions, access roads, and other controls, are properly considered and implemented. Communication between the principal contractor and the crane company is of great importance to ensure site preparation and safety.

A forensic analysis of the cause of tower crane incidents in the US revealed that the tower crane safety incidents investigated were caused by:

- poor lifting practices, specifically the use of soft (nylon) slings, during climbing or 'jumping' a crane
- under-design of foundation system (and lack of approval by crane manufacturer)
- poor quality maintenance/repair of crane components
- deficiencies in the inspection regime (Peraza & Travis, 2009).

These causal factors are similar to some of the staff and equipment level factors identified in the analysis by Zhou et al. (2018), suggesting commonalities in tower crane safety incident causation in different countries. It is also noteworthy that only one of the causal factors identified by Peraza and Travis (2009) relates to immediate circumstances of an incident (the use of soft slings). The other causes identified are separated from the incident in time, as well as level of responsibility of persons involved (that is, they are regulatory or managerial failures, rather than frontline worker errors).

Tam and Fung (2011) conducted a survey of construction industry representatives in Hong Kong to examine causal factors in tower crane safety incidents. Participants to this survey reported the following causal factors for tower crane safety incidents:

- a widespread failure to comply with an industry Code of Practice relating to the safe use of tower cranes
- problems inherent in the existing certification system for operators and other workers involved in the use of tower cranes
- deficiencies in work practices, including ineffective communication between crane operators and signallers in situations in which the operator has a restricted view of the lift path
- a failure to follow manufacturers' instructions during erection/dismantling (Tam & Fung, 2011).

These factors also reflect failures related to the operation of regulation, as well as poor site-level management practices relating to the use of tower cranes.

Technical failures and tower crane safety

Raviv et al. (2017b) examined the relationship between human errors and technical failures in tower crane incidents and report that technical failures are present in tower crane safety incidents linked to the highest levels of risk and outcome severity. Further, an inverse relationship was found between the incidence of human error failure types (for example, communication failure or inattention) and the risk potential of a tower crane incident (Raviv et al. 2017b). Thus, tower crane safety incidents with the most serious consequence potential are likely to involve some form of technical failure.

Further, the literature review reveals that not all tower crane safety incidents are caused by unsafe acts, and some incidents are caused by underlying design or technical issues. This observation draws upon a distinction, made by James Reason (1990), between active errors and latent conditions. Active errors are most likely to be made by frontline workers and have an immediate effect; for example, omitting a step in a process or applying a rule incorrectly (Gordon et al, 1998). Latent conditions are removed from the 'sharp end' of work and have a delayed consequence. Reason states that such conditions 'arise from decisions made by designers, builders, procedure writers, and top-level management. Such decisions may be mistaken, but they need not be' (Reason, 2000, p. 395). Latent conditions can lie dormant for long periods of time until they combine with other triggers to produce a safety incident opportunity.

According to Reason (2000), latent conditions produce two kinds of undesirable outcome:

- they can create the conditions in which people are more likely to make active errors – for example, by creating time pressures, fatigue, under-resourcing, or specifying the use of inappropriate equipment for a task, or
- they can produce deficiencies in system defences – for example, by providing unreliable warning systems, poorly designed facilities, or unworkable procedures.

The following two case examples reflect situations in which: (i) a tower crane collapse was attributed to a latent condition; and (ii) the design characteristics and performance of a luffing jib type tower crane could (under certain circumstances) produce a safety incident, irrespective of operator behaviour.

Case example: Latent condition in tower crane incident causation

Swuste (2013) analysed a fatal tower crane collapse that occurred in Rotterdam in 2008. The tower crane was being used in construction of a 24-storey apartment block when it fell, killing the operator and causing substantial damage. An investigation conducted by the Dutch Safety Board (OVV) investigated the incident to determine its cause. The weather was good on the day of the incident and conditions were favourable for the lifting activity. A balcony slab was being lifted and, including the balancing device, the total load burden was 12.8 tons. When the load was in place, workers on the balcony communicated to the crane driver that the load should be moved inwards after they observed the trolley of the crane moving outwards towards the end of the jib. The driver replied, denying he had moved the control command. The load then swayed away from the workers on the balcony and the crane collapsed. The detailed technical investigation found that the crane had reached its maximum load for the 27-metre outreach position. However, the load moment protection device was switched on. Chemical analysis and tensile tests revealed the steel structure of the crane was built according to design specifications and fracture surfaces were indicative of overload rather than material defects. Weather conditions were good and it was unlikely wind would have been a factor. Neither had there been quick or abrupt movements of the trolley causing the load to swing. It was considered plausible that the operator did not command the trolley to move outwards towards the end of the jib immediately prior to the collapse. Other factors considered were malfunction of the control motor system impacting the functionality of the electric trolley braking system and bending of the jib (beyond that estimated by the manufacturer (Swuste, 2013). Swuste argues that this incident should be considered a 'normal accident' (see Perrow, 1984) because the mass of the load, height of operation, poorly understood dynamics, critically narrow limits of safety, intrinsic weakness in the safety monitoring and control system, and unobservable failure process, combined to provide minimal redundancy and little time for recovery from failure.

The same incident was considered in an analysis of tower crane incidents worldwide. Isherwood (2010) categorised it as having electrical/control system causes and, in his report, also identified an example of a similar problem associated with a tower crane in the UK that did not result in major structural failure of the crane. Isherwood expresses the view that 'this scenario has the potential for becoming more prominent in crane incidents as newer cranes having ever more sophisticated control systems come on the market and enter service. Much depends on the training/competence of individuals setting up this type of control system during erection of the crane and replacement of spare parts once the crane is in service to ensure that the internal settings of all motor drives are correct for the application' (p. 27).

Case example: The impact of wind loading on the safety of luffing jib type tower crane

Following a crane collapse incident in Liverpool, Isherwood and Richardson (2012) were commissioned by the UK's Health and Safety Executive to undertake an analysis of the effect of wind loading on the operation of luffing type tower cranes.

A luffing type tower crane was acquired, fitted with instrumentation to measure wind speeds at the outer end of the jib and on top of the crane's A frame, as well as tension in the luffing system. The crane was set up in an experimental testing location. Under testing, the jib of the crane was found to be susceptible to uncontrolled movement when exposed to wind loading below the maximum in-service wind speed, and at jib elevations within the normal maximum and minimum radius specified by the manufacturer. During testing, the jib of the crane was 'blown back' against a spring buffer mounted on the A frame, at which time the luffing system lost tension and the luffing rope came out of the grooves of one of the A frame pulleys. Uncontrolled movement of the jib was observed to occur when the wind speed approached the maximum in-service wind speed specified by the manufacturer, and when the jib was close to maximum elevation and minimum radius. In such circumstances, a serious safety incident could occur with little or no warning, and little opportunity for recovery.

Isherwood and Richardson also note that, because luffing cranes raise and lower their jibs to place the load on the hook at the required distance from the crane mast, it is common for the height above ground of the jib to be significantly greater than the height above ground of the A frame. On the crane used for testing, this difference could be as great at 33 metres and occasions were found at which wind speeds measured by instruments positioned on the A frame and the end of the jib recorded significantly different measurements. It is common for the anemometer (to measure wind conditions) to be fitted on top of the A frame which can be a concern if the crane control setting relies on these measurements to determine the safe working limits of the crane and triggering an alarm or warning. Isherwood and Richardson note that it is possible that, unknown to an operator, wind speeds in excess of maximum in-service wind speed could be reached before any warning is triggered. The examples (and evidence) provided by Isherwood and Richardson

(2012) provides further support to the argument that latent conditions (as defined by Reason) may – in albeit rare conditions – cause serious crane safety incidents.

In relation to wind loading, authors of a High Risk Construction Oversight Study undertaken in the US recommended that actual wind speeds in urban areas densely built with many high rise buildings should be monitored to assess the appropriateness of current crane designs in relation to wind speed (Smith & Corley, 2009).

These examples suggest that not all tower crane safety incidents necessarily involve human error. Albeit relatively rare, tower crane safety incidents may be caused by latent condition pathways (for example, associated with design characteristics or technical failures) irrespective of operator behaviour.

Safety incidents involving mobile cranes

There are many types of mobile crane. Mobile cranes use principles of leverage to lift heavy loads, with the weight of the crane balanced against the load being hoisted at the tipping point or tipping axis (NIOSH, 2006). Mobile cranes are able to lift heavy loads, swing them in multiple directions and raise them overhead. However, these features contribute to the risk of tipping over if the crane is not set up correctly or the manufacturer's instructions are not followed.

In the US:

- the North Carolina Department of Labor estimates that one mobile crane tips over during every 10,000 hours of crane use in the US
- nearly 80% of all mobile crane tip-overs are attributed to operators exceeding the crane's operational capacity
- approximately 54% of these incidents are the result of swinging the boom or making a lift without the outriggers fully extended (NIOSH, 2006).

NIOSH utilised the US Bureau of Labor Statistics' multi-source database, the Census of Fatal Occupational Injuries (CFOI), to identify 719 work-related deaths that occurred between 1992 and 2002 and which involved a mobile crane. Of these deaths, 290 (40.3%) involved a construction worker being struck by falling objects, including an uncontrolled hoisted load or part(s) of a mobile crane. Of these 'struck by' fatalities, 153 (52.8%) occurred in the construction industry. The breakdown of types of fatal safety incidents involving mobile cranes is provided in Figure 3.

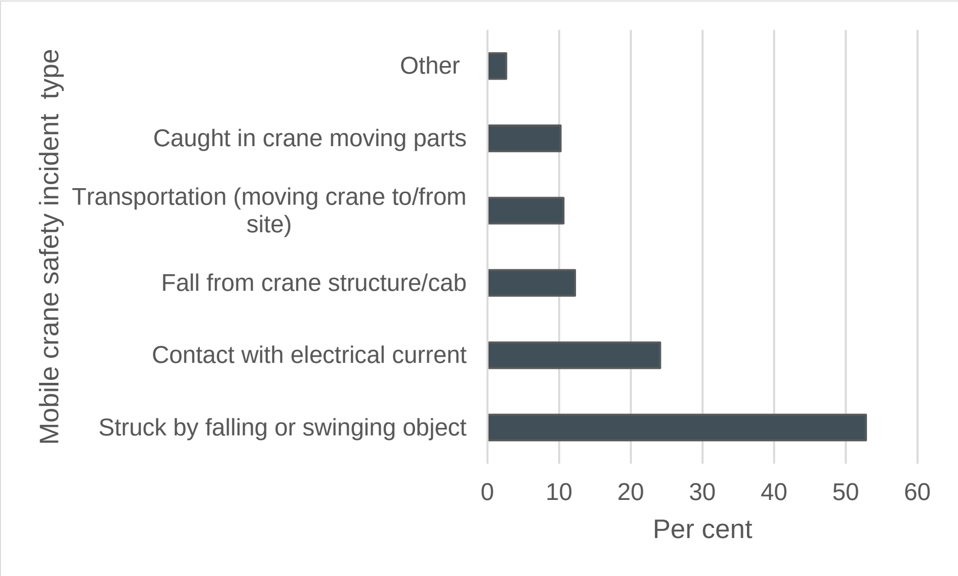

Figure 3. Fatal incidents involving mobile cranes in the US, 1992-2002. Adapted from NIOSH, 2006.

The NIOSH alert also examines several mobile crane safety incidents (all involving over-tipping and resulting in fatalities). These incidents and their identified causes are summarised in Table 5.

Table 5. Causes of case study incidents involving mobile cranes (adapted from NIOSH, 2006).

Case circumstances	Causes/contributing factors
A suspended personnel platform was struck by an uncontrolled load (a roof section) while being lifted by a large mobile crane. The roof section was being lifted in windy conditions. The roof section was being lowered into place when the crane began to tip-over and the roof section collided with the personnel platform, knocking it to the ground. The three workers in the platform were fatally injured as a result of the incident.	The crane was found to have tipped as a result of the combination of: • the weight of the hoisted load • side loads from wind • out-of-level ground conditions • the swinging motion of the hoisted load as the crane moved sideways.
A carpenter who was removing formwork was struck by a loaded concrete bucket during a crane tip-over. Concrete was being hoisted using a crawler-mounted crane. A rooftop spotter was directing the lifting/carrying of concrete. As the crane operator hoisted the bucket of concrete, swung it over the roof and towards the empty forms, the crane lost stability and tipped. The concrete bucket struck the worker on the head and shoulder.	Investigation of the crane configuration, the distance of the intended landing site from the crane's centre pin, and the manufacturer's load chart indicated that the crane's recommended capacity had been exceeded. Prior to the incident, the crane's LMI had been reported to indicate false readings in the past and had not been repaired/recalibrated. Thus, the LMI may have provided the operator with false information.

A truck driver was crushed when a crane tipped over and the crane's boom landed on the cab of a dump truck. The all-terrain crane was preparing to unload components of a tower crane to be installed at the construction site. The crane operator had fully extended the crane's left outriggers. The right outriggers were only partially extended, as they would have blocked truck access to the site. This set-up was intended to be temporary. The crane operator began to clear the area by lifting an empty concrete bucket over the rear of the crane. The operator swung the bucket over the right side of the crane. As the crane's boom swung to the right, the operator also began to "boom down" to extend the load radius. When the bucket reached the area near the dump truck, the operator lowered it to the ground. The crane tipped toward the load. The operator was unable to drop the load to regain stability and the crane's boom hit the truck cab.	An investigation showed that the crane's load lift capacity had been exceeded for the boom length and angle used.

Kan et al. (2018) used fault tree analysis to understand the causal factors contributing to falling object incidents in mobile crane use. Using deductive reasoning, and drawing on historical incident data and experts' knowledge, falling object incidents were attributed to defective crane parts, rigging failures, overloading, and environmental factors. Each of these causes was further decomposed to understand the intermediate and basic events that can create them. Thus, the use of a crane with defective parts can arise because of poor maintenance and/or a failure to perform pre-operation checks. Overloading can be caused by load indicator failure and/or operator error. By tracing back incident causes to understand the lowest level basic events, Kan et al. (2018) argue that causes/contributing factors can be grouped to determine whether they predominantly relate to technical/mechanical issues, human factors or managerial issues.

As with tower crane safety incidents, the factors contributing to mobile crane safety incidents include human error, as well as mechanical/managerial issues. For example, Kan et al (2018) decompose the causes of overloading of mobile cranes, suggesting that overloading can occur as a result of human error or the failure of a load indicator device. Further operator error (in relation to overloading) can be traced back to poor safety management, improper operation, and/or inadequate pre-planning. The role played by human error in crane safety incident causation is further discussed below. It is also evident from the case examples provided in Table 2 that environmental conditions can also contribute to safety incidents involving mobile cranes.

Human error and crane safety incident causation

Human error is often cited as a prominent causal factor in construction safety incidents, including those involving cranes (Garrett & Teizer, 2009; Milazzo et al. 2016). Milazzo et al. (2016) report human error to be the most recurring initial cause of crane safety incidents (drawing on a dataset including mobile, tower and gantry crane incidents). They identify the following errors as occurring most frequently:

- weight underestimation of the loads being lifted, causing boom buckling or crane overturning
- over-extension of boom of mobile crane leading to contact with obstacles, such as powerlines.

Despite the frequency with which crane safety incidents are attributed to human error, the nature of the error is often not reported, which potentially limits the lessons learned from these analyses.

Reason (1991) categorised errors in terms of whether they are skill-based slips and lapses, rule-based mistakes or knowledge-based mistakes. This classification system has been adopted in guidance on human factors and error reduction (HSE, 1999). Violations are distinct from error and are defined as 'deliberate departures from rules that describe the safe or approved methods of performing a particular task or job' (Lawton, 1998, p. 78).

According to this classification system, skill-based errors can occur when people are distracted or preoccupied with things other than the task, leading to slips or lapses. Slips and lapses generally occur when people are performing very familiar tasks (for example, driving a car), which are carried out without much need for conscious attention. Even very skilled and experienced workers are prone to slips and lapses if their attention is diverted from the task they are performing.

Slips are 'actions-not-as-planned'; for example, omitting a step in a work sequence. But lapses occur when someone forgets to carry out an action, loses their place when performing a task, or perhaps forgets what they intended to do.

Rule- and knowledge-based errors are also referred to as mistakes. These are deliberate actions taken by people who do the wrong thing believing it to be right (HSE, 1999). Mistakes differ from slips and lapses in that they are not necessarily related to inattention or distraction but reflect a failure in mental processes. A rule-based mistake can occur, for example, when a set of rules is remembered but wrongly applied to a situation. A knowledge-based mistake occurs when a problem or situation is unfamiliar, misdiagnosed and the wrong action is applied.

The underlying reason for human errors depends on the type of error that has occurred. Leah (2013) points out, in relation to the operation of construction plant and machinery, that different error/failure types imply the need for different preventive measures. Thus, slips and lapses could potentially be reduced by modifying the ergonomic design of the crane cabin and man-machine interface, whereas rule and knowledge-based mistakes may be reduced through improved training and/or supervision (Leah, 2013). Further investigation to 'unpack' and better understand the kinds of human error involved in crane safety incidents is therefore warranted.

Perhaps a more fundamental problem associated with the attribution of safety incident causation to human error was observed by Rasmussen (1982), who commented that:

Frequently they (human errors) are identified after the fact: If a system performs less satisfactorily than it normally does – due to a human act or to a disturbance which could have been counteracted by a reasonable human act – the cause will very likely be identified as a human error (Rasmussen, 1982, p. 313).

The premise that 'What You Look for is What You Find' has also been observed in incident investigation; that is, if human errors are sought they will likely be found (Lundberg et al. 2009).

Attributing incidents to human error has been referred to as 'judgement in hindsight' (Hollnagel & Almaberti, 2001). Dekker (2002) is particularly critical of 'after the fact' methods for classifying human errors, arguing that they:

- are highly subject to hindsight bias
- are based on judgement rather than analysis
- do little to explain why people acted as they did, given the circumstances in which they found themselves (Dekker, 2002).

In relation to the latter point, the circumstances surrounding the error are often much more complex than error classification systems suggest. They can include, for example:

- competing organisational priorities and conflicting goals
- resource and time constraints
- limitations associated with equipment or technologies
- information overload
- communication breakdowns
- inter-personal or coordination failures among team members.

Previous analyses of crane safety incident causes suggest that many of these underlying factors are at play. Thus, the underlying reasons for human error made in relation to crane operation may lie at deeper levels of an organisational environment or system of work than the immediate circumstances of an incident.

The need to understand the root cause of crane-related safety incidents in order to improve prevention activities has been noted (Kan et al. 2018). It is acknowledged that the factors that cause or contribute to safety incidents in the construction industry operate at different levels within a system of work or organisational environment and are linked through 'cause-effect' chains. Identifying the underlying or root causes of crane safety incidents is valuable as it can inform the development of effective preventative strategies. Marquez et al. (2014) similarly argue that it is necessary to look beyond the immediate, visible causes of an incident to identify factors (events, conditions or exceeded barriers) that created the immediate causal factors, and thus contributed to crane safety incidents. However, Swuste (2013) argues that the identification of root causes can only be achieved once the immediate causes of an incident are well understood.

Quantification of safety risk related to crane use

A number of techniques have been used to quantify the risks associated with the use of cranes. These include:

- cluster analysis based on crane incident stories (Raviv et al., 2017a)
- analytic hierarchy process, which uses experts to order risk factors by their priority or importance (Shapira & Lyachin, 2009; Raviv et al. 2017b)
- 'bowtie' analysis (Aneziris et al. 2008)
- development of risk factor scales with expert weighting to create a crane safety index (Shapira et al. 2012).

In the Netherlands, the Workgroup Occupational Risk Model project sought to identify dominant paths to crane safety incidents so that this information could be used to direct risk reduction activities (Aneziris et al. 2008). Risk logic models were developed starting with a 'top' event representing an adverse consequence of undertaking a work action. This event is decomposed into simpler events, the probability of which can be quantified. The 'bowtie' model positions the adverse event at the centre. Events to the left of the centre represent causes, or necessary prerequisites for the event to occur. Events to the right describe mitigation failures and dose/response factors that contribute to the consequence of the centre event. This technique was used to model and quantify the risk of crane safety incidents based upon engineering principles, existing information about crane safety rules and regulations, and historical incident data. According to Aneziris et al. (2008) the resulting models can be used to determine the probability of the occurrence of four levels of consequence associated with crane incidents of particular types (for example, falling loads/loads overturning and collapsing cranes). However, the bowtie models developed by Aneziris address single hazards and do not enable an integrated assessment of crane-related risk associated with construction site operations. This limits their usefulness to inform site-based risk assessment activities.

New and evidence-informed ways to undertake site-specific risk assessments of crane-related safety are being developed that have the potential to improve project-level risk management activities. An example of this is a model developed by Shapira et al. (2012). This model is based on experts' identification of risk factors associated with the use of tower cranes and systematic weighting of the importance of these factors for the likelihood of safety incidents involving tower cranes (Shapira & Lyachin, 2009). Based on the expert judgements, factors included in the risk quantification model are shown in Table 6.

Table 6. Safety factors associated with tower cranes (Shapira et al. 2012).

Factor family	Description	Risk	Weighting (%)
Project conditions	Blind lifts – partial view/obstruction of work zone	Operator has no line of sight with load Complete reliance on signalperson Potential communication failure	5.63
	Overlapping cranes – work zones shared by more than one crane	Danger of job, loads or cables colliding	7.02
	Length of operator work shift	Long often monotonous work can cause physical/mental fatigue and error	3.96
	Type of load – dimensions, weight, configuration, packaging, rigging methods etc make some loads more hazardous	When properly rigged loads should not vary in safety risk but combined with factors such as tight workspaces, winds etc, some loads can present increased risk	4.69
Environment	Wind – intensity varies according to site location, topography and geography	Tower cranes are designed to sustain wind up to specified intensities, but sudden wind gusts or high winds combined with other factors (for example, sail-like loads) can be dangerous.	9.50
Human factors	Operator proficiency – experience and competence, training and certification.	Operator proficiency can impact errors, recognising and preventing dangerous situations before they develop: 'feeling the crane'	12.90

Factor family	Description	Risk	Weighting (%)
	Operator character – behavioural patterns and mental capacity	Argued to have a bearing on chance of safety incidents	6.27
	Operator employment source – on the company permanent payroll or outsourced from a staffing company (project duration only)	Outsourced operators can be discriminated against, experience job security etc, that can impact their work	4.52
	Superintendent character – behavioural patterns and mental capacity	Argued to have a bearing on quality of supervision and chance of safety incidents	9.16
	Signalperson experience – training and experience	Potential untrained/inexperienced signalpersons increase chances of safety incidents, particularly in blind lifts	5.98
Safety management	Site safety management – actions to increase awareness, training, prevention, monitoring and compliance with procedures	Driven by superintendent. Impact on crane work and reduces chance of crane safety incidents	14.18
	Company safety management – policy, and processes for consultation, training, planning etc	Determine way in which company manages projects and people	7.41
	Maintenance management – cranes and lifting accessories, resource allocation, planning and scheduling maintenance	Underserviced cranes and lifting accessories increase chance of safety incidents	8.88

Each of the factors listed in Table 6 has a weighting (an expression of how important the factor was considered to be by industry experts), as well as a specified method of measurement. Some of these measures are objective and easily quantifiable (for example, the length of the work shift), while others are more subjective and harder to quantify (for example, operator proficiency). Shapira et al. (2012) acknowledge that some of the measurement methods they developed need further testing and refinement.

The risk quantification model uses site-specific data relating to each of these factors (which needs to be input by persons knowledgeable about site-specific conditions and crane operation arrangements) to create a cumulative weighted risk value for the site. This cumulative weighted risk value is the sum of each of the individual weighted risk values for each of the 13 factors in Table 6.

However, the cumulative weighted risk value is further transformed by multiplying it with other site-specific values that reflect:

- the extent to which the tower crane activities 'oversail' areas beyond the site boundary (indicating risk exposure to the public)
- the number of workers who will work in the vicinity of the tower crane (indicating on site risk exposure)
- the extent of the crane use (indicating hours/duration of daily exposure)
- intensiveness of operation (indicating the number of tasks/lifting cycles to be performed in a given time).

All of these factors are combined to produce a single quantitative site-specific risk rating associated with the use of tower cranes. This model was developed in the construction industry in Israel and, therefore, the risk factors and their respective weighting may not apply to other countries or contexts. However, the approach taken to modelling risk is potentially very useful because it provides an evidence-informed and integrated method for understanding site-specific risk factors relating to the use of tower cranes. The use of weighted risk factors based on expert judgement is likely to produce a more defensible assessment of risk than the types of semi-quantitative (and highly subjective) risk matrices that are currently in widespread use in the construction industry. Further, the incorporation of factors that capture exposure in terms of public safety, numbers of workers, duration and intensity of crane use also add important elements above and beyond two-dimensional estimations of risk based solely on likelihood and consequence.

Raviv et al. (2017a) developed a database of incident stories, using construction industry representatives in Israel to capture data about safety incidents that involved tower cranes, and resulted in a range of outcomes (from near misses and fatalities).

The circumstances of each incident were coded and incorporated into the database. Incident characteristics were qualitative in nature but were assigned parallel quantitative descriptors which enabled cluster analysis to be used to calculate the potential for each incident within a certain group in the database to produce a given outcome severity level. This provided a statistical basis for linking groups of incidents with certain characteristics to less severe and more severe outcomes. Five distinct clusters of incidents were identified. Every incident in the cluster with the highest risk potential for fatalities or severe injuries involved a technical failure. Technical failure occurred in 100% of cases in this cluster, but in only 15% of occurrences in the whole database.

These results indicate that technical failures are typically linked to high severity outcomes in safety incidents involving tower cranes, highlighting the importance of enforcing daily inspection of cranes by competent persons, and ensuring effective repair and maintenance procedures are in place (Raviv et al. 2017b).

Incidents in the high risk cluster for serious safety outcomes also frequently involved falling objects and tended to happen during normal crane operation, rather than during erection and dismantling. The latter finding appears to be inconsistent with previous research that suggests the majority of fatal tower crane safety incidents occur during erection/dismantling (Shin, 2015). One potential reason for this difference could be the different industry settings in which the analysis took place. It is possible that the construction industry context in Korea is significantly different from that of Israel and that these differences reflect this (Raviv et al. 2017a). The potential for variation between countries also reflects inherent limitations associated with the generalisability of quantitative risk models to industry contexts other than the context in which they were developed.

Raviv et al. (2017b) found the cluster of incidents with the highest potential for low severity outcomes involves a broader range of failure types than the 'high severity' incident cluster. Incidents with high potential for low severity outcomes involved:

- operator error, which occurred in 39% of incidents in this cluster compared with only 13% in the entire database
- technical failure, which accounted for 30% in this cluster compared with 15% in the entire database
- other types of failure that were distributed similarly to the distribution across the entire database.

Incidents in the cluster with high potential for low severity outcomes were divided evenly between routine work (for example, normal operation of the crane) and non-routine work (for example, dismantling and erection activities).

Risk reduction strategies and initiatives

Planning, supervision and management of lifting operations

A common theme in the literature is the important role and responsibility of multiple stakeholders in relation to maintaining crane safety. Responsibilities are borne by designers, manufacturers, suppliers, principal contractors, and subcontractors.

In some jurisdictions, specific duties are established for the planning and management of lifting operations. For example, in the UK, crane-related safety matters are regulated under the *Lifting Operations and Lifting Equipment Regulations* (1998). These regulations establish requirements so that lifting operations be properly planned by a competent person, appropriately supervised, and carried out in a safe manner.

Effective lift planning, communication and coordination are identified as being critical in the prevention of crane safety incidents in construction projects (Wiethorn, 2018). Lifting operations involve a range of people including lift planners/directors, crane operators, supervisors, riggers, and signal persons.

Weithorn (2018) argues that the roles and responsibilities of all parties need to be clear and well understood. In accordance with US guidelines developed by the American Society of Mechanical Engineers (*P30.1-2014 Planning for load handling activities*) a competent person should be appointed with responsibility for planning lifting operations at construction projects. Weithorn (2018) developed a theoretical lift plan document that establishes who should take primary and secondary responsibility for all activities related to the management of safety in lifting operations. This is presented in the form of a responsibility matrix and identifies persons responsible for the following:

- ensuring the crane meets relevant design requirements
- ensuring the crane is inspected and appropriately certified
- identification of site-specific hazards
- provision of ingress and egress of the crane
- development of a lift plan
- determining how a load should be rigged
- determining what rigging is required
- assigning a designated signal person
- providing appropriate crane signals
- load movement and placement.

The role of lift director is formally acknowledged in the responsibility matrix developed by Weithorn (2018). In the US, the National Commission for the Certification of Crane Operators has developed a formal training and certification program for lift directors. This certification requires demonstration of competency in the following areas:

- site control and evaluation
- roles, responsibilities of parties and required qualifications of lifting personnel

- lifting operations
- lifting plans
- rigging
- signalling
- load chart content and comprehension
- use of different types of crane.

US guidance also recommends lift directors hold pre-lift meetings with relevant parties to establish clear roles and responsibilities for a particular lifting task. A list of topics to be covered at the pre-lift meeting is provided in the American Society of Mechanical Engineers, *P30.1-2014 Planning for load handling activities.* Wiethorn (2018) analysed 701 crane safety incidents and determined that a pre-lift meeting did not occur in 62% of these incidents but would have addressed factors that initiated or contributed to the majority of incidents. Consistent with this emphasis on consultation and lift planning, Sertyesilisik et al. (2010) report team-based selection of equipment (involving subcontractors) helps to ensure the most suitable equipment is selected. Further, at some worksites rigorous planning was undertaken for lifting operations and, every two weeks, the success of lifting plans and suitability of lifting equipment was reviewed to ensure continued safety and effectiveness (Sertyesilisik et al. 2010).

In the Australian context, Smith (2018) recommends closer collaboration between crane companies and principal contractors, particularly when contractors are opting to maximise the use of pre-fabricated components and designing for efficient and safe on site assembly of these components. Smith (2018) argues that crane companies can contribute to improved safety in design and construction outcomes by collaborating with principal contractors (engaged in Design and Construct projects) in planning for constructability in the design stage of construction projects.

Operator competency

The question of whether certification is indicative of competency in crane operation is currently being debated in the US, where a national certification scheme for crane operators has reportedly stalled due to disagreements as to whether certification should be based on crane type or crane type and capacity (Vertikal, 2018). In Australia, a person who holds a High Risk Work Licence (HRWL) can operate a crane. HRWL training is provided by public and private RTOs but industry reports indicate that the quality of training is not consistent (Lifting Matters, 2018a). Experience in crane operations is not a mandated requirement. Instead, many construction companies and projects require Verification of Competency (VOC) in relation to crane operation. However, the content for VOC has been poorly defined, unregulated and inconsistent. Further, because sites have preferred VOC providers, operators are required to complete multiple VOCs relating to the same crane type for different worksites (Lifting Matters, 2018). The CrewSafe initiative (implemented by the Crane Industry Council of Australia) sought to increase safety in the use of cranes by introducing a standardised machine-specific assessment program to confirm and document individual operators' competency in the operation of a specific make and model of crane. Thus, it captures an operator's understanding of the unique functions of specific crane types. The CrewSafe assessment is impartial and undertaken by a peer assessor. Operator assessments are also filmed, documented and accessible on a CrewSafe digital app, providing site supervisors with easy access to operator competency data (Vertikal, 2018).

Recommended tracking system for major structural or mechanical components

Regular maintenance is important to maintain the safe operation of cranes. Monitoring repairs to critical components and keeping comprehensive maintenance records was recommended by the US High Risk Construction Operations Study (HRCOS) (Smith & Cowley, 2009). The HRCOS crane team also recommended registering and tracking all key crane components (for example, the boom and tower mast sections, A-frame, turntable, climbing section, machine platform, operator's cab, counter jib, and the movable counter mechanism if applicable) throughout their life. A national registration and tracking system was recommended following the collapse of a tower crane in New York in 2008. The incident was found to be the result of a weld along the circumference of the turntable, made as a repair to the crane (Peraza & Travis, 2009). The HRCOS team also identified a number of websites that sell crane components that are not manufactured or approved by the Original Equipment Manufacturer (OEM), despite being advertised as such. These parts may be inferior to OEM parts and component tracking could prevent the purchase and use of such components (Smith & Crowley, 2009).

Voluntary crane safety assessment programs

The US HROCS crane team also emphasised the importance of annual third party crane inspections, as well as more regular inspections and maintenance procedures implemented by crane owners (Smith & Cowley, 2009). However, the HRCOS investigation team noted that an increase in variety of crane manufacturers and models in use and increasing technological complexity of crane equipment[6] requires constant training for inspectors. Smith and Cowley

6 For example, most modern large cranes are controlled via Programmable Logic Controller technology (see, for example, https://www.designworldonline.com/safety-plc-ensures-safe-crane-operation/).

(2009) also note that the inspector should be impartial (that is, not be employed by entities owning or operating the crane being inspected).

In Australia, the crane industry has initiated a voluntary third party crane assessment program. The CraneSafe program was developed by the Crane Industry Council of Australia (CICA) in consultation with industry stakeholders. The CraneSafe program aims to supplement existing workplace safety requirements with annual assessments of mobile cranes, providing crane owners and operators with:

- a process for third party assessment of safety aspects of their cranes
- a common, industry-wide system for assessment of their cranes single method by which crane operators, owners, manufacturers, suppliers, designers, and importers, can fulfil their obligations under state WHS legislation.

CraneSafe also publish data relating to the top ten faults identified for each type of crane covered by their inspection/assessment program (CraneSafe, 2019).

Safety-enhancing technologies

Many safety-enhancing technologies are available and have been adopted by crane and component manufacturers; for example, slow 'cut out' mechanisms that slow down a crane before stopping when it is approaching the limits of safe operation. Some international research is also focused on developing additional technologies that have the potential to improve the safe use of tower cranes and mobile cranes. Many of these technologies are still under development and/or not yet in widespread use within the construction industry. Some examples are described in Table 7.

Table 7. Safety enhancing technologies.

Intention of technology application	Focus	Details	Reference
Technology to support lift planning	Planning collision-free mobile crane operations in modular-based (off site) construction	A methodology which applies dynamic graphical description of three-dimensional (3D) visualisation to simulate various scenarios with different crane models and types The methodology helps to select the most effective and efficient crane operation and avoid collisions and spatial conflicts The methodology also assists with the design of support system.	Han et al. (2015)
Technology to support lift planning	Developing / approving safe lifting plans	Linking simulation/visualisation tools with 3D CAD models The approach allows simulating tower crane lifting activities to examine the safety of lifting operations and approving lifting plans	Al-Hussein et al. (2006)
Technology to support lift planning	Automated lift planning for mobile cranes	An approach to develop plans for lifting large prefabricated components into position using mobile cranes The process incorporates design and site layout with mobile crane capacity and configuration data (maximum and minimum lift radii)	Lei et al. (2013)
Technology to support automated lift planning and tracking	A lifting path tracking system as part of a robotic tower crane system for high-rise construction	A robotic tower crane system equipped with a laser-technology-based lifting path tracking system The system is proposed to improve productivity and resolve problems with blind spots, long lifting distance and material swing	Lee et al. (2009)
Technology to support crane operation	Safe load rotation and manoeuvring by tower cranes	Under-hook devices: for example, the Verton R-Series and the Buildvation 'Rigger Assist' devices These technologies help the crew to safely lift and rotate the load and minimise load swing	Smith (2018)

Intention of technology application	Focus	Details	Reference
Technology to support crane operation	Improved visibility, anti-collision monitoring	Video-based systems These systems use waterproof, vibration-proof compact cameras fitted at one or more locations on a crane to provide improved vision to reduce the risk of collision and help with blind lifts	LSM Technologies, (2019)
Technology to support crane operation	Anti-collision	SMIE anti-collision system It is a semi-autonomous system that allows a crane operator to anticipate the risk of collision between the moving parts of their crane and those of a neighbouring crane The system automatically stops hazardous movements	SMIE (2019)
Technology to support crane operation	Anti-collision	A prototype system combining sensors with a game engine to monitor the safety of mobile crane lifting operations in real time Sensors are used to monitor the movement of the major crane parts and the suspended load The system generates a visual representation of the crane in relation to objects in the surrounding environment The system sends warnings if the crane gets too close to surrounding objects	Fang et al. (2016; 2018)
Technology to support crane operation	Anti-collision	A system combining sensors and video cameras to collect and represent information about the location of a tower crane jib and lifted load The data is incorporated in a 3D BIM model of the site to help seeing the location of a lifted load in the context of the building and surroundings in real time during lifting operations	Lee et al. (2012)

Intention of technology application	Focus	Details	Reference
Technology to support crane operation	Design of mobile crane supporting system	An automated system to assist in calculating the mobile crane's support reactions and in designing the supporting system This system can generate a 2D reaction influence chart which shows the reactions for each outrigger at varying horizontal swing angles and vertical boom angles to the ground	Hasan et al. (2010)
Technology to support crane operation	Vibration control during fast crane operation	A simple vibration control method for fast crane operation The proposed method maintains a small sway angle in fast crane operation. It uses piece-wise acceleration and deceleration to reduce the sway angle and vibration frequency Therefore, the method helps to achieve higher productivity (faster operation) while ensuring safety.	Kuo & Kang (2014)
Technology to support crane operation	Monitoring safety performance of mobile cranes, avoiding electrocution near power lines	A graphical fuzzy-set model to determine the performance of a crane and its operation to avoid electrocution The model can be used to simulate the safety assessment of a crane operation, especially when operating near power lines	Al-Humaidi & Tan (2009)
Technology to support crane operation	Crane safe operation monitoring	A prototype of advanced tower crane equipped with wireless video control and Radio Frequency Identification (RFID) – video sent back from cameras enables the crane operator to see the situations around the crane and under the trolley	Lee et al. (2006)
Technology to support crane operation	Anti-collision monitoring of tower crane	A distance measurement method based on using ultrasonic sensor for tower crane obstacle Using multiple sensors, the proposed method enables monitoring of surrounding obstacles of tower cranes and detect accurate distance between crane and obstacle	Lichen et al. (2012)

Intention of technology application	Focus	Details	Reference
Technology to support training	Safety training of construction plant operators	A game technology-based safety training platform to assist in the safety training of operatives working with construction plant (mobile cranes, tower cranes and excavators) The platform allows trainees to study and practice the operating methods or sequences of plant operations in a virtual environment	Guo et al. (2012)
Technology to support safety training	Crane operation training	A crane simulator known as SimCrane 3D^{+} The system provides a realistic simulation with improved depth perception	Juang et al. (2013)
Technology to support training	Training of crane operators	A framework for developing as-built virtual environments for advance training of crane operators The framework integrates Building Information Modelling (BIM) and real-time location tracking technology in a virtual environment It can be used to construct as-built work scenarios for assessing and improving operator skills in a virtual training environment	Fang et al. (2014)
Technology to support training	Training of crane crew, improving cooperation between crane operators and ground personnel during blind lifts	An approach for developing a virtual training environment that allows multiple users to participate in lifting operations cooperatively Using a 3D real-time immersive visualisation interface, users can perform hands-on tasks such as operating cranes and directing blind lifts	Fang & Teizer (2014)

Technologies to support lift planning

The use of three-dimensional visualisation tools to analyse different site context-specific lifting scenarios. Linking simulation/visualisation tools with 3D CAD models allows tower crane lifting activities to be reproduced digitally in a realistic and detailed way. This information can be used to examine the safety of lifting operations and as a mechanism for approving a lifting plan (Al-

Hussein et al. 2006). Automated lift planning processes have also been developed for the use of mobile cranes in heavy industrial construction projects. These processes incorporate design and site layout with mobile crane capacity and configuration data (maximum and minimum lift radii) to develop plans for lifting large pre-fabricated components into position using mobile cranes (Lei et al. 2013).

Technologies to support crane operation

Crane load indicators and various types of limiting devices are installed in cranes as required by Australian Standards[7]. However, there have been recent developments in the deployment of technology to make crane operations safer. For example, Smith (2018) describes the development of under-hook devices, such as the Verton R-Series and the Buildvation 'Rigger Assist' devices. The Verton R-series is a remote-controlled electromechanical under-hook load rotation system. It uses a gyrocopter, controlled electronically and remotely, to rotate the load suspended under the crane hook. This allows a load to be rotated without the need for tag lines, held by riggers to guide a load (see the case example below). Similarly, the Rigger Assist technology is attached to the crane hook and measures angle deviation from the vertical of the hook in real time. This helps the operator to ensure that the boom tip is directly over the centre of gravity of the load to reduce load swing at the point of lifting. The information generated is provided to the operator in the crane cabin but can also be made available to the rigger via the use of smart glasses.

Under-hook load rotation system

> A condenser unit was to be removed and replaced in a hotel in inner city Brisbane. The work was carried out at a height of 90m and the new unit needed to be placed in a narrow access point in the roof cavity of the hotel. The location of the hotel, at a busy CBD intersection, required the work be performed in a tight timeframe to avoid lengthy road closure. The Verton R-Series enabled the lifting to be performed without need for taglines, which would have been very difficult to achieve at the 90m height of the work. Using the technology, the load was lifted and placed with precision, using global satellite positioning coordinates. This prevented workers from working under the load, as well as leaning out of the workspace at height to guide the load into place. It also reduced the duration of the lift and the space within which the road needed to be closed. The shorter lifting cycle time and ease of placement also reduces operator fatigue.

7 AS 1418.5: Cranes, hoists and winches – Mobile cranes.

Lifting Matters, 2018b, p.9

Technologies to support crane operation have included the development of video-based systems that utilise waterproof, vibration-proof compact cameras fitted at one or more locations on a crane to provide improved vision to reduce the risks associated with collision of crane components with workers, equipment, or adjacent structures. One provider of camera-based systems, LSM Technologies, reports the successful deployment of the technology on luffing cranes in the Australian construction industry. This technology is claimed to reduce the risks associated with undertaking 'blind lifts' (LSM Technologies, 2019). Camera-based systems provide operators with raw video which helps operators to make decisions, using their knowledge and experience. This is in contrast with autonomous monitoring systems (some examples of which are described below).

Proximity safety management systems have also been developed which use slewing, trolley and travelling sensors to capture data that is then used to model the crane's movement using polar coordinate systems. These movements are then compared with pre-established zones defined by arcs and lines (Luo et al. 2014). An example of such a system is the SMIE anti-collision system which is a semi-autonomous system that allows a crane operator to anticipate the risk of collision between the moving parts of their crane and those of a neighbouring crane. If the risk of collision is detected, the SMIE system automatically 'intervenes' to stop the hazardous movements (SMIE, 2019).

Other technologies deployed (in combination with a variety of sensors) to aid the safe operation of cranes are game technologies and building information model (BIM) technologies which allow visualisation of lifting operations. For example, Fang et al. (2016) developed a prototype system combining sensors with a game engine to monitor the safety of mobile crane lifting operations in real time. This system combines a system of sensors to monitor the movement of the major crane parts as well as the suspended load. Data is collected about the physical worksite topography and site conditions (captured using a terrestrial laser scanner) and game engine technology is used to create a visual representation of the crane in relation to objects in the surrounding environment (for example, trees, buildings). These objects are marked as bounding box objects in the game engine. Proximity thresholds and severity levels can be set for objects and structures in the work environment. If the movement sensors determine that the mobile crane (or its load) comes within a pre-determined distance of one of the site obstructions, a visual or auditory warning is given to the operator. Fang et al. (2018) evaluated the impact of the use of this system on crane operators' situation awareness and performance. This assessment involved five crane operators undertaking two different lifting tasks (of varying levels of complexity) using a telescopic mobile boom type crane. Situation awareness is defined as 'a person's perception of the elements of the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future' (Endsley, 1988). Situation awareness is linked to safety in the performance of complex and/or hazardous work tasks (Stanton et al. 2001; Sneddon et al. 2013). Following the field test, Fang et al. (2018) concluded:

- the operator assistance system enhanced operators' situation awareness in terms of the timeliness with which they responded to questions about their environment and the correctness of their responses – the improvement in situation awareness was also more evident when operators were undertaking demanding lifting tasks
- operators' situation awareness and their lift performance were positively correlated – that is, increased situation awareness improved the performance of a lift
- the operator assistance system was more effective in improving safety than in improving efficiency performance
- the complexity level of a lift task directly affected the operator's workload, especially in relation to mental demands – higher workload reduces situation awareness that potentially compromises safety performance in lifting.

Lee et al. (2012) developed a combined sensor and video system to collect and represent information about the location of a tower crane jib and lifted load. This system was linked to a three-dimensional building information model (BIM) representing the physical design and construction details of the building under construction. Tower crane operators were able to see the location of a lifted load in the context of the building and surroundings in real time during lifting operations. The ease of use and usefulness of the BIM-enabled navigation system were assessed to be high in field trials by tower crane operators, particularly in 'blind lift' situations. The possibility of using localisation technologies, such as global positioning system (GPS) and radio frequency (RFID), to directly capture crane position data in relation to other objects, equipment or personnel is also under experimental development. These have advantages in their ability to capture data relating to objects temporarily located in a position that may block a crane operator's field of view (for example, items of mobile plant), and/or in identifying when workers enter blind spots or exclusion zones during lifting operations (Cheng & Teizer, 2014). However, error rates associated with the use of GPS and RFID have been reported to impact the performance of autonomous safety systems reliant on these technologies (Luo et al. 2014; Lee et al. 2012). Finally, the use of camera-equipped unmanned aerial vehicles (UAVs) and object detection technologies is being explored as a means of monitoring crane movements and identifying safety hazards in real time (Roberts et al. 2017).

Smith (2018) argues that the automation of crane operations is inevitable and, in his opinion, will relieve pressure from crane operators and other field workers enabling them to focus their attention on critical lift decisions. Smith comments: ‘We have to approach smart technology and automation capabilities as an opportunity to improve the way we do things, including our safety outcomes’ (p.6). For example, he describes the E-Fence technology developed by CAT which automatically stops an excavator’s movements within defined boundaries beside, below and above the machine. The opportunity to use similar technology to prevent crane boom collisions at multi-crane sites, or accidental slewing into power lines, is noted (Smith, 2018).

The extent to which advanced technologies produce improvements in crane safety will, in part, be affected by the extent to which the technologies are perceived to be useful by crane operators. To this end, Fang et al. (2017) recommend that these technologies should be rigorously evaluated to ensure that the safety benefits associated with their use are objectively demonstrated. Also, because the work of a crane operator requires the simultaneous processing of information from multiple sources, including environmental changes, crew communication and crane performance feedback, any new safety systems should be carefully designed to reduce the cognitive load experienced by operators as a result of their use (Fang et al. 2017).

Ergonomic cabin design for tower cranes

The need to pay attention to human factors in crane design also applies to the design of crane cabin interiors. Crane operators work long hours (Fang et al. 2017) and spend most of the working day in the crane cabin. Work is performed in a static, sedentary position with hands held on operating handles. The work requires frequent bending or body twisting and also involves exposure to vibration and noise (Brkic et al., 2015). Tam and Fung (2011) report tower crane operators work in cramped conditions and frequently feel physical and thermal discomfort. Crane operators are also reported to be a high risk group for low back pain (Burdorf & Zondervan, 1990). Brkic et al. (2015) considered the design of crane cabins as a feature that could improve working conditions, reduce fatigue, and improve safety in the construction industry. They suggest that manufacturers often refer to subjective and arbitrary historical guidelines to inform the design of crane cabins, rather than use anthropometric data to inform design decisions. Brkic et al. (2015) developed a method of assessment of the needs of crane operators (in Serbia) based on anthropometric data and kinematic modelling.

Data logger installation

Singapore has established a legislative requirement to fit cranes with data loggers that are automatically switched on whenever the crane is in operation. This requirement applied to all cranes registered with the Singapore Government’s Ministry of Manpower after August 1 2015. Cranes registered before this date had to be retrofitted with data loggers by 1 August 2018. The following crane types were included in this requirement:

- truck mounted variable boom length type
- truck mounted fixed boom length type
- crawler mounted variable boom length type
- crawler mounted fixed boom length type
- wheel mounted (w/o prime mover) variable boom length type
- wheel mounted (w/o prime mover) fixed boom length type
- tower crane (horizontal boom)
- tower crane (luffing boom).

The data logger is required to:

- detect and record any override key activation for the cranes' safety devices, including derricking limiter, over-hoisting limiter, and rated capacity limiter
- detect and record overloading occurrences (that is, when load reaches and exceeds 100% of the crane's rated capacity)
- detect and record status of limit switches, including derricking limiter and over-hoisting limiter
- be equipped with data security and anti-tampering feature
- download recorded data
- generate reports.

The data logger also needs to record the following operational parameters:

- date and time
- crane configuration
- permitted load, actual load, percentage of usage of rated capacity (for main hook and auxiliary hook)
- radius of load
- slew angle (applicable to cranes with safe working load that varies according to the slewing angle)
- main boom angle, fly jib angle (if applicable)
- boom length, fly jib length (if applicable)
- sequence of extension (for telescopic cranes)
- status of limit switches
- status of override key activation (for over-derricking limiter, over-hoisting limiter, and rated capacity limiter).

Funding was provided by the Singaporean Work Safety and Health Council to fund up to 50% of the costs of installing data loggers.

The rationale for this requirement was to collect data that can be used to take proactive measures to prevent unsafe operation of cranes, and also aid in the investigation of crane safety incidents. In Australia, it has been argued that installing crane data logging systems can help crane owners comply with Australian Standards (relating to determining the required frequency of Major Inspections), and can maximise the asset life of cranes (Cranes and Lifting, 2018). Authors of a HRCOS prepared for the New York City Buildings Commissioner in 2009 observed that the airline industry has, for many years, recognised the importance of applying stricter maintenance and repair systems on ageing aircraft. Thus, operational data, including detailed flight information, is available from which to identify an age threshold at which planes might be at risk. The HRCOS team observe that similar operational data, which could be used to establish the functional age of cranes and crane components, is not currently available (Smith & Corley, 2009). In Australia, CICA argues that 'crane usage is a more important indicator of potential wear to crane components than the age of the crane alone', and 'the usage of years to define when a crane has reached its design life is not granular enough to relate to the time of operation.' CICA recommends alternative methods for crane condition monitoring, potentially including the use of data logging (CICA, 2017).

Guidance materials for crane usage in a globalised construction industry

In an increasingly globalised construction industry, Shapira et al. (2012) note the 'gradual disappearance of traditional borderlines between equipment cultures' (p. 1281). Factors contributing to crane safety incidents can arise as a result of the internationalisation of construction markets and engagement of resources (equipment as well as personnel) from different countries. In the European Union, this has been identified as a factor impacting competition in the markets for cranes and lifting equipment, and increasing the risk of crane-related safety incidents. In particular, concerns about importation and use of cranes in the European Union or European Economic Area construction markets led the Committee for European Construction Equipment (CECE) to collaborate with leading crane manufacturers to produce a pictorial guide highlighting the most easily recognisable non-compliant elements of a tower crane (Cranes Today, 2011). The guide identifies the most frequently encountered examples of non-compliance as being:

- incorrect markings, instructions and documents
- the wrong combination of modular components being used
- excessive noise emission levels

- a lack of additional safety equipment, warnings, and correct labelling (CECE, 2011).

In 2013, the European Materials Handling Federation Product Group (Cranes and Lifting Equipment) developed a similar guide for identifying non-compliant mobile cranes. Both guides are intended to be early warning tools for crane buyers and users (who may have limited technical knowledge). If one or more items are out of line with the specified criteria then it is probable that the crane is non-compliant with European Union standards and regulations (FEM, 2013).

Risk-specific guidance materials

In the UK, specific guidance has been developed for the use of both tower cranes and mobile cranes alongside railways. This guidance material was developed by the UK Construction Plant-hire Association's (CPA) Crane Interest Group and was produced in cooperation with the UK railway network operator, Network Rail.

The guidance addresses specific risk to railway operations associated with the use of cranes (for example, if a crane or its load falls onto the track) and establishes good practice measures for risk elimination and reduction. The guidance provides detailed requirements for crane configuration, setting up, and lift planning, in close proximity to an operating railway. Sample documents and pro formas are also provided, for example, a foundation pre-rigging inspection report form (Vertikal, 2019).

Information limitations

Analysis of the extant literature reveals the absence of a consistent classification method/taxonomy or framework previously used in the analysis of causal or contributing factors for crane safety incidents. Analysis of patterns/trends is therefore difficult because factors involved are inconsistently recorded. Further, in many cases, little information is available upon which to identify with any certainty causes or contributing factors in crane safety incidents. Classifying crane incident by type provides some indication of how crane incidents occur. However, the incident datasets on which this classification is usually based do not adequately address causation, and do not provide reliable incident data to understand why these incidents occur (Wiethorn, 2018).

Other limitations to historical analyses of crane safety incidents include a heavy emphasis on fatal incident data (few studies of crane incidents in construction include non-fatal incident or 'near miss' incident data), and the aggregation of incident data relating to all types of cranes into a single dataset.

Relatively few crane safety incidents have been subjected to detailed investigation and reporting that is available in the public domain. Those incidents for which detailed causal information is available tend to be very serious incidents. The heavy emphasis on analysing data relating to fatal incidents ignores a significant component of safety risk associated with crane usage and reduces opportunities to learn from a much larger body of non-fatal or near miss cases (Raviv et al. 2017a). Near miss incidents involving cranes may not be fully reported, limiting opportunities to learn from these events. Also, because high-consequence crane incidents (associated with tower cranes and large mobile cranes) have a low probability of occurrence, there may also be a low probability of repetition of cause (especially when considered within a single jurisdiction).

Aggregating crane incident data into a single dataset (without differentiating by crane type) assumes that the factors associated with safety incidents apply equally to all types of crane, and limits opportunities to understand important differences relating to the safety risks (and control measures) relevant to different types of crane.

Focus groups/interviews

Framework analysis

The analysis of the first round of focus group/interview data led to the development of a crane incident causation table. This table, presented as Appendix 5 to this report, collates factors identified by participants as causes/contributing factors to crane safety incidents in the Australian construction industry. Each of these factors was described – drawing on the meanings derived from participants' comments or explanations of each factor. Example quotations are also linked these factors to the focus group/interview transcripts.

The factors extracted were also classified using the ConAC causation framework as a guide. Factors were grouped according to their proximity to/distance from an incident. Thus, factors were grouped as originating influences, shaping factors, and immediate circumstances.

Originating influences identified aspects of the general industry and regulatory environment, including:

- adequacy of regulatory training requirements
- a disconnect between industry standards and regulatory requirements
- an increase in foreign workers in the construction industry
- a resource shortage
- an overheated construction market.

Other originating influences related to the ways in which construction projects are delivered and managed, including:

- client demands and expectations
- the procurement method selected
- poor communication between the principal contractor and crane operator
- a lack of adequate planning by the principal contractor and/or crane operator.

Shaping factors identified as relevant to crane safety incident causation described site management practices or workforce characteristics that increased the risk of crane safety incidents. These included:

- long working hours
- workforce fatigue and mental health
- a ‘tick and flick’ approach to safety-related documentation
- inadequate supervision
- site-specific physical constraints and conditions
- the development of safe work method statements (SWMSs) in isolation (not considering other site activities)
- inadequate/incorrect information provided to crane operators
- poor safety in design or change in work planning/sequencing.

Immediate circumstances identified by participants as causing crane safety incidents in the construction industry included worker factors, site factors, and material/equipment factors.

Worker factors included:

- failure to follow manufacturers’ instructions and/or SWMSs
- lack of familiarity with crane being used
- overriding safety technology
- lapses in concentration.

Site factors included:

- changes to ground conditions
- inadequate supporting structures
- lighting/visibility
- interaction with adjacent activities/adjoining properties.

Material/equipment factors included:

- loads too heavy for a lift
- crane too small for tasks being performed

- use of substandard cranes or lifting equipment
- structural/electrical failures of cranes.

Further details, and the full set of causal/contributing factors identified following analysis of the first round of focus groups/interviews, are described and evidenced in Appendix 5.

It is important to note that these factors do not occur in isolation and their effects are likely to be highly interrelated – both between and within levels of causation/contribution. Thus, the overheated procurement environment (an originating influence), combined with clients' demands and expectations (originating influences), could contribute to crane company over-commitments, long working hours, and fatigue (shaping factors). In turn, these factors could contribute to a crane being used that is too small for a task being performed, operators taking shortcuts, hazards not being properly identified, and safety technology being overridden (immediate circumstances).

Cause-effect trees

Each of the causal/contributing factors identified in steps 1-4 of the framework analysis was then incorporated into one of five 'cause-effect' trees to identify potential pathways of causation between factors identified at different levels. These trees are reproduced as Appendix 6 to this report and reflect the following areas of causation:

- work environment issues
- worksite conditions
- human factor issues
- equipment issues
- task/activity issues.

The trees show how immediate circumstances of crane safety incidents can be traced back to causal/contributing factors in the site, organisational and industry environments. For example, in the human factors cause-effect tree an operator's unfamiliarity with the crane/plant being operated can be traced back to inadequate onboarding and induction of foreign workers, selection of dry versus wet hire arrangements, transient workforce, and a crane company's over-commitment to work. These factors, in turn, can be traced back to an increase in use of foreign workers in the construction industry due to resource shortages and an overheated procurement environment. They can also be traced back to crane company management arrangements, planning and experience.

It is not possible to 'unpack' each of the trees in this section of the report as they are very detailed. However, they are included in Appendix 6 and show interrelationships between causal/contributing factors within and between levels within the crane safety incident causation model that was developed as an output of the framework analysis of focus group/interview data.

Crane safety incident causation model

A crane safety incident causation model was developed as an output of the analysis of focus group/interview data. This model is presented in Figure 4. The model is based upon the ConAC model of causation but is specific to crane safety incident causation in the Australian construction industry. The model arranges causal/contributing factors identified in the framework analysis in a graphic representation of originating influences, shaping factors, and immediate circumstances, identified by participants as relevant to crane safety incident causation in the construction industry. This model presents the synthesis and primary output of the qualitative data analysis presented in this report. The application of the model taxonomy in identifying causal factors was indicated in case examples which can be found at Appendix 1-4.

Validation of the crane safety incident causation model

The validity of the crane safety incident causation model was subsequently evaluated in a second round of industry consultation. This involved applying the model to case study crane safety incident scenarios. The results of this validation are presented briefly below.

The frequency with which immediate circumstances, shaping factors, and originating influences, were identified as relevant to the two scenarios (one involving a tower crane safety incident, another involving a mobile crane safety incident) are presented in Appendix 3 and 4. The frequency with which causal/contributing factors were identified as relevant to the crane safety incident scenarios used in the validation can be found in Table 12 at the end of Appendix 6.

While a small number of people/groups participated in this exercise (n=5), this validation round showed a reasonably high level of consistency between the three experts tasked to identify the causes involved in the tower crane incident (factors systematically picked are denoted by a grey bar showing a frequency count of three), and the two experts tasked to identify the causes involved in the mobile crane incident (factors systematically picked are denoted by a blue bar showing a frequency count of two). It also showed that the causal/contributing factors identified at the three levels (immediate circumstances, shaping factors, and originating influences) were relevant to both mobile and tower crane incidents (as indicated by a spread of grey and blue lines across all three levels).

A small number of factors not included in the original crane safety incident causation model were identified by participants in the second round of consultation. These were subsequently included in an updated model.

Participants also indicated that the crane incident causation model would be useful in planning for crane-related activities and in investigating and understanding the causal/contributing factors in crane safety incidents.

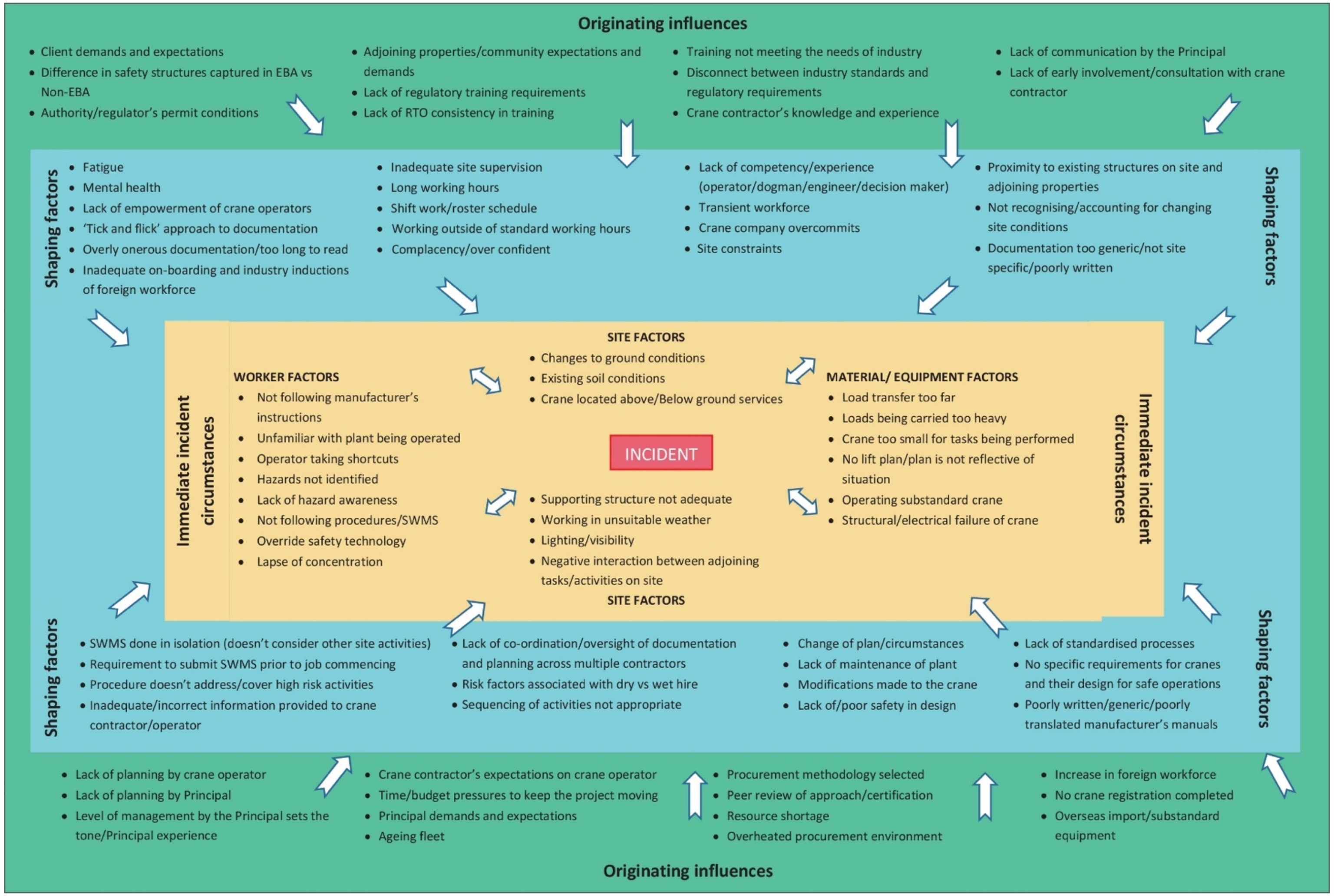

Figure 4. Crane safety incident causation model.

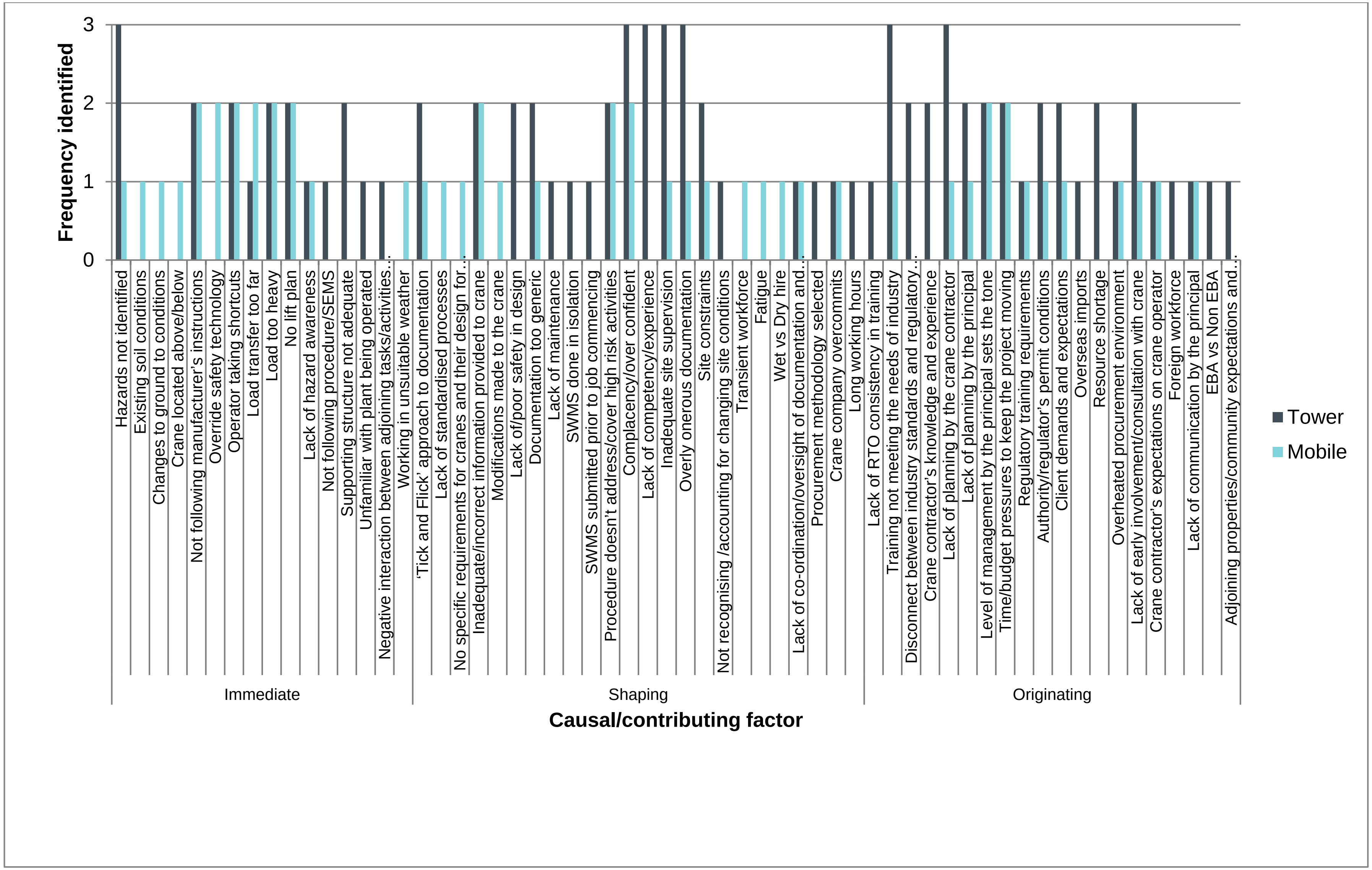

Figure 5. Causal/contributing factors identified in the scenario analysis.

Potential strategies/solutions for crane safety incident reduction

Participants in the initial focus groups/interviews were asked to provide suggestions for preventing safety incidents involving cranes. All propositions were broadly grouped into seven topic areas: training and competence, development of a code of practice for crane operations, communications and awareness raising, the role of the regulator, design and import issues, use of technology, and procurement and the management of commercial relationships[8].

In the following section of the report, suggestions made under each topic area are 'unpacked' to provide:

- a statement about the problem identified and/or need for preventive strategies
- an explanation of each suggestion made in relation to this problem/need
- a description of what the suggestion might mean in practice
- potential benefits associated with each suggestion
- anticipated outcomes
- possible performance measures related to each suggestion.

Topic area 1: Training and competence

Suggestion 1.1	Implement a tiered licensing system
Problem/need	Competence is understood to develop with experience over time. The current licensing system does not currently reflect 'gradations' in workers' experience levels. Understanding the site-based work experience level of operators (and other workers who perform specific crane-related activities) can help employers to allocate tasks and manage workers more effectively, based on their experience levels.
Action	Introduction of different categories (levels) of licences for dogmen, riggers, and crane operators.
Description	Similar to road vehicle legislation, a specific licence would be required before a person was allowed to operate a crane or undertake dogman activities. Upon completing a recognised training course, a person would be issued with a licence, subject to restrictions during a probationary period.
Key benefits	Workers could be assigned tasks commensurate with their level of competency and experience. Safe operating capabilities could be better monitored and assessed, particularly in newcomers to the industry.
Desirable outcomes	More consistent approach to developing and managing critical skills required to operate and work safely with cranes.

8 These topic areas and subsequent suggestions have not been ranked and are presented in the order in which they were raised by participants, not in order of priority or importance.

Performance measures	Training records and licences quantify and reflect the progressive development of knowledge, skills and experience related to crane operation, direction of crane operations, and rigging practices.

Suggestion 1.2	Introduction of ‘logbooks’ documenting crane operation experience
Problem/need	Related to Suggestion 1.1, workers’ experience in operating a particular type of crane is not consistently documented and recorded. Relatively inexperienced workers could potentially engage in high risk work. Participants identified a need for improved ‘visibility’ relating to the experience level of crane operators.
Action	Introduction of a ‘logbook’ system to record experience operating particular types of crane. To be linked to licensing (see Suggestion 1.1).
Description	Logbooks and record keeping were seen to assist in evaluating and managing crane operators’ experience in working with particular crane types. They provide information about their levels of relevant experience to crane operation companies, and construction contractors who engage crane crews or operators. Experience data can be recorded using commercially available digital/web-based tools.
Key benefits	Formal recording of work experience provides a record and evidence of work history in relation to particular crane/equipment types. Employers and contractors can make selection decisions based on relevance of prior work experience. Workers can be assigned tasks better suited to their previous employment experience. A more systematic approach to developing skills and competencies linked to experience could be implemented.
Desirable outcomes	If adopted as an industry requirement, this would provide a consistent approach to managing skill development and experience in relation to crane operations.
Performance measures	Reliable records kept to quantify and evidence workers’ experience related to the operation of different types of crane.

Suggestion 1.3	Periodic testing/assessment for crane operators
Problem/need	Experience is an important contributor to operators’ competence. However, participants also commented that safe working practices may be forgotten over time, and/or new technology or changes to industry guidelines may require that training be updated periodically to ensure knowledge, skills and abilities reflect current ‘best practice.’
Action	Participants commented that periodic testing for crane operators could also be beneficial.
Description	These participants observed that operators should keep up to date with new technologies and legislative changes.

Key benefits	Refresher training was considered a means of ensuring crane operators' knowledge remains current, and safe operating practices remain 'front of mind', throughout the industry. Potentially, refresher training could be linked to the logbook suggestion made in 1.1.
Desirable outcomes	Refresher training undertaken to ensure currency of knowledge.
Performance measures	Records are retained regarding crane safety refresher training.

Suggestion 1.4	Establish Verification of Competence (VOC) requirements related to specific crane types
Problem/need	Participants observed that current licensing arrangement reflect broad categories of crane type and capacity. However, crane operating features vary considerably by make and model. They identified a need to capture machine-specific competence in industry VOC practices.
Action	Participants suggested there is a need to ensure VOC processes more consistently capture crane operators' competence in operating specific types of crane (that is, including make and model).
Description	Participants commented that the content of VOCs is ill-defined and can vary from provider to provider. The goal of VOC is to ensure crane operators are assessed in terms of their competence to use a particular type of equipment (CICA, 2018). However, the use of different VOC providers means operators often have to complete multiple VOCs to work on different sites. A standardised, machine-specific assessment program, such as the CICA CrewSafe system, can help to overcome these challenges.
Key benefits	Operators are assessed using consistent criteria and through demonstrating competence in relation to a specific make and model of crane. Familiarity with unique features of a crane is assessed.
Desirable outcomes	More consistent, efficient, verifiable and traceable assessment of competence to operate a specific crane.
Performance measures	Consistency in VOC assessment requirements and increased crane-specific knowledge.

Suggestion 1.5	Establish specific training (and potentially licensing/registration) for other workers whose activities could impact the safety of crane operations
Problem/need	Participants commented that the safety of crane activities in the construction industry is affected by the competence of different parties, not just operators, dogmen, and riggers. Other parties involved in making safety-critical decisions about planning, managing and coordinating crane activities do not need specific training in crane-related safety. This represents an important gap in management of workforce capability.

Action	Participants suggested two other groups of workers whose activities could impact the safety of crane operations. These were: • engineers who oversee work activities involving cranes • people responsible for coordinating crane-related activities on construction sites.
Description	It was suggested that to be able to carry out their work competently, engineers who oversee work involving cranes should receive specific training in crane-related safety issues, and that this be reflected in a registration system. It was also suggested that a new category of crane worker be established (that is, a crane activity coordinator). Participants believed people acting in this role should have specific training, and potentially also be licensed. Prior to initiating lifting operations, a person filling a crane coordinator role could, for example, conduct pre-lift meetings to discuss and plan lifting procedures, rigging methods, signalling systems, load movement and placement, and the responsibilities and roles of all parties.
Key benefits	Greater certainty for crane operators that site personnel have properly analysed, planned and prepared for lifting activities to take place.
Anticipated outcomes	More careful and coordinated approach to planning lifting operations in a particular worksite context.
Performance measures	Clear allocation of roles and responsibilities for lifting operations. Decisions concerning lift planning and preparation made by people with requisite knowledge and experience, with decisions communicated to and well understood by all involved in lifting operations.

Topic area 2: Develop a Code of Practice for crane operations

Suggestion 2.1	Develop a Code of Practice (CoP) for crane activities
Problem/need	Participants observed there is a level of inconsistency in knowledge and adoption of 'best practices' in relation to crane-related safety activities in the construction industry. In NSW there is no specific Code of Practice related to use of cranes. Participants identified a need for clear and comprehensive guidance for all relevant industry participants relating to the practices required for compliance with WHS regulation in relation to crane use at construction sites.
Action	Participants suggested a CoP should be developed for crane activities in NSW. This could be similar to CoPs in place in Queensland for Tower Cranes (2017) and Mobile Cranes (2006). The current NSW CoP, 'Managing the risks of plant in the workplace code of practice', is not specific to cranes.

Description	The CoP would contain guidance on managing risks associated with specific types of cranes. Topics identified by participants as areas that could potentially be incorporated into a crane-specific CoP are listed below. Roles and responsibilities of all participants involved in, or whose actions could have an impact on, the safety of crane-related activities, including clients, principal contractors, crane manufacturers, crane owners/operators, site engineers and crane coordinators (see 1.5), maintenance personnel, riggers, dogmen, site supervisors, and others. Providing specific guidance on coordination of lifting activities, as well as communication and consultation between participants in planning, design, and conduct of lifting operations. Nomination of a coordination role to ensure pre-planning is undertaken effectively before lifting operations commence (see 1.5). Alignment of training and crane usage requirements with manufacturers' guidelines. Establishing testing, inspection, and maintenance, regimes and ensuring these are aligned with crane manufacturers' guidelines. Guidance on ensuring fitness for work of people engaged in operating cranes or lifting activities. Specific suggestions made in relation to this topic were medical assessments, drug and alcohol testing, and fatigue management processes. Specific guidance for identifying hazards in a specific work environment, and implementation of appropriate controls and parameters for lifting operations in particular conditions (for example, heat, wind, spatial restrictions, underground/overhead services, geotechnical conditions, adjacent structures, roads or railways). Requirements for the registration of cranes and notification of use at a particular worksite/location.
Key benefits	A detailed set of guidelines specific to crane usage as a reference point for all parties involved in work involving cranes in the construction industry.
Desirable outcomes	More consistent approach to accessing and understanding practical guidance to help industry participants better meet their legislative responsibilities when using cranes at construction sites. Guidance material describing good practice for using cranes at construction sites.
Performance measures	Code of Practice development and widespread industry use. Increased industry knowledge of good practice in managing crane activities at construction sites, and compliance with legislative requirements relevant to crane use and lifting operations.

Topic area 3: Communication and awareness-raising

Suggestion 3.1	Implement more effective communication and awareness raising
Problem/need	Related to Suggestion 2.1, participants perceived there is a gap in the communication of 'best practice' information and guidance material relating to the safe use of cranes in the construction industry.
Action	Participants identified several areas in which more effective communication and awareness-raising activity relating to crane safety could be implemented.

Description	Specific areas where information/awareness-raising was identified as being beneficial are listed below. To provide timely and detailed information about causation following a crane incident. Detailed incident investigation data is not widely or readily available in the public domain, potentially reducing the ability to use incident investigation findings for prevention. While confidentiality of information is important during an investigation, releasing certain information that could be used to inform timely prevention activity was considered beneficial. The availability of more detailed investigation reports, once investigations are complete, can also facilitate learning as these incidents can be used in toolbox meetings etc to communicate safety risks associated with crane usage. The US Occupational Safety and Health Administration, for example, produces and makes publicly available detailed engineering reports describing outcomes of selected significant incidents involving machinery failures. To collate and disseminate international best practice information on crane safety. Examples provided by participants included UK-based practices of assessing crane drivers' fitness for work, and ISO standards relating to crane design, operation, and inspection. Industry organisations, such as CICA, potentially could play a role in collecting and disseminating safety-related information about crane use in the construction industry. To explore the use of social marketing approaches to 'push out' important messages about crane safety to target audiences. To ensure industry participants are aware of important tools available to them, such as anonymous reporting 'hotlines' for safety-related concerns or to report instances of non-compliance.
Key benefits	Construction organisations, crane operators, and other stakeholders, would have easy access to the best available information upon which to manage the safety of crane-related activities.
Desirable outcomes	Management of crane-related activities in the construction industry would be evidence-informed. All parties would have access to up-to-date information about incident causation, prevention, and best practice, in the safe use of cranes.
Performance measures	Increased knowledge and awareness of crane-related safety issues across the construction industry. Better risk management and decision-making in relation to preventing incidents involving cranes.

Topic area 4: The role of the regulator

Suggestion 4.1	Implement a more proactive inspection approach
Problem/need	Participants commented that worksite inspections are sometimes announced prior to their occurrence and the operations of smaller crane operators (particularly in the case of mobile cranes) may not be subject to inspection. Potentially this creates a 'gap' in which cases of non-compliance may not be identified.
Action	Increase surveillance and enforcement of crane-related safety requirements.

Description	Participants suggested the level of enforcement of crane-related safety requirements could be increased. In particular, participants made the suggestions listed below. Use more proactive inspection processes, potentially using registration of crane usage and location information to identify sites for unannounced inspections. Introduce a campaign for smaller crane operators and sites to ensure the focus is not always on large companies and construction worksites. Consider using fines and penalties for operators found to be in breach of safety regulations, similar to traffic penalties.
Key benefits	Participants suggested a proactive enforcement approach could potentially improve compliance levels.
Desirable outcomes	Industry expectation that sites could be visited at any time without prior notification.
Performance measures	More frequent unannounced inspections. Improved levels of compliance and, in the medium to long term, fewer instances of non-compliance.

Suggestion 4.2	Provide a strong advisory/mentoring role
Problem/need	Participants described inconsistencies in the level of knowledge about safety of crane operations in the construction industry. The need was identified for a reliable source of up to date information about crane safety incident causation, incident prevention, and best practice recommendations.
Action	Provide a more comprehensive advisory/mentoring role for crane-related safety issues.
Description	Participants also suggested the regulator could provide more comprehensive guidance and advisory services to industry on crane safety. Related to this was an expressed concern about engineering expertise related to crane safety.
Key benefits	The regulator can play an important role, both in enforcing safety-related statutory requirements, and in providing advice and guidance about how to prevent safety-related incidents involving cranes. The model of crane incident causation developed in this report – which is based on evidence and opinions collected from experienced Australian crane industry representatives – is one mechanism the regulator can potentially use to leverage the advice provided about the factors to consider when managing risks associated with crane use at construction sites.
Desirable outcomes	Better informed industry stakeholders in relation to managing safety risks relevant to crane use and lifting operations.
Performance measures	Increased frequency of interactions between regulator and industry in which advice is provided on managing safety risks relating to cranes. Information sharing in joint investigations of crane safety incidents (including near miss incidents) using the model of crane incident causation.

Topic area 5: Design and import issues

Suggestion 5.1	Review design and import requirements for cranes
Problem/need	Participants identified difficulties in ensuring compliance of imported cranes and components with Australian Standards requirements. There is a perceived lack of 'visibility' on testing procedures undertaken, maintenance records, and quality of information provided by importers and suppliers.
Action	Participants commented that, in relation to new or secondhand cranes imported into Australia from overseas, closer attention could be paid to design and import requirements for cranes.
Description	Current NSW WHS Regulations (2017) (Part 5.1) establish extensive duties for persons conducting businesses or undertakings that design, manufacture, import, or supply items of plant. However, participants still perceived WHS issues associated with the way design and import requirements are currently monitored. Concerns were raised, in particular, about maintenance records and the quality of information provided about cranes that are supplied or imported. The magnitude of this problem is not known and cannot easily be discerned from information available to the research team. However, it is important that imported cranes are reviewed to ensure they comply with relevant Australian Standards requirements (AS 1418 and AS 2550 sets of standards).
Key benefits	Ensuring imported cranes meet design, maintenance and inspection requirements in accordance with Australian legislation and standards. Ensuring information provided about imported cranes meets Australian requirements (for example, load chart content requirements).
Desirable outcomes	Industry-level consistency in applying design and import requirements for imported cranes.
Performance measures	Reduction in safety-related issues/non-conformances associated with imported cranes.

Topic area 6: Technology

Suggestion 6.1	Incorporate new technology
Problem/need	Human error is frequently identified as a causal factor in crane safety incidents. Technologies are increasingly available that reduce the likelihood (or impact) of human error. However, participants observed that these are not consistently fitted by crane manufacturers and are less likely to be in place in older cranes.
Action	Incorporate new technologies in cranes to ensure they are equipped with the latest devices to maximise safe working and prevent incidents.
Description	Participants referenced technologies including, limiters, cameras and real time data logging, monitoring and sensor equipment. Participants were in favour of remote monitoring of plant (back-to-base) which companies can use to monitor how plant is being used. The use of existing and emerging technologies to improve crane safety was extensively described in the literature review section of this report. Some technologies are now commercially available and in use by crane manufacture, supply and operation companies. Examples of these are given in the literature review. Other technologies are still under development. With advances in sensor technology and autonomous machinery, technology-based safety systems are likely to grow in use over time.
Key benefits	Potential to increase reliability of crane operation and reduce the impact of human error.
Desirable outcomes	Technologies proven to be reliable and effective are adopted for use in mobile and fixed (tower) cranes. Crane operators would potentially have objective data to support decisions taken not to perform unsafe lifting operations.
Performance measures	Potential reduction in crane incidents attributed to human error. Improved accuracy and efficiency of crane operation (load movement and placement).

Topic area 7: Procurement and the management of commercial relationships

Suggestion 7.1	Improve management of safety in the procurement of crane services
Problem/need	Crane contractors (typically subcontracted to principal contractors) may be subject to commercial pressures arising as a result of competitive practices, tight project timelines, and their position in the construction industry supply network. Participants commented that crane supply arrangements can sometimes have a negative impact upon safety.
Action	Participants suggested that actions taken to improve the procurement of crane services (both wet and dry hire) could be improved by introducing standard clauses into contract documents relating to providing these services.

Description	The commercial contracts under which crane services are procured can impact the way risks and responsibilities for safe operation are borne and experienced by crane operators, and other workers involved in lifting operations. Clear, industry-accepted standard agreements were suggested as a means to ensure crane operators are not subject to pressures to continue working in situations in which crane operation may not be safe. In particular, participants made two suggestions. First, standard clauses be included in contracts between principal contractors and crane hire companies identifying responsibilities for safe operation of cranes at a worksite. Second, crane hire companies establish operating requirements in tender documents relating to providing crane services. These could include, for example, requirements related to maintenance and the specification of safe limits of a crane's operation. Related to this latter point, participants also suggested standard templates be developed by which crane operators could document situations in which work should be ceased (for example, poor weather). This could also refer to data collected via objective (back-to-base) monitoring systems which could be used to ensure lifting activities remain within specified safe parameters for a crane's operation.
Key benefits	Clarity relating to roles and responsibilities for safety of crane operations at a construction worksite. Commercial relationships between principal contractors and crane operators that respect crane operators' safety responsibilities and knowledge of safe working practices relating to the use of cranes.
Desirable outcomes	Risks and responsibilities are appropriately allocated and commercial mechanisms are in place, enabling crane operators to establish and maintain safe working practices at all times.
Performance measures	Standard practices for procurement of crane services that reflect the need for safe operation.

Limitations

The suggestions made by participants reflect the ideas of a relatively small sample of industry informants who participated in the initial focus groups/interviews. As such, they cannot be read as being broadly representative of industry views. With this limitation in mind, it is recommended that participants' suggestions be considered further within broader industry consultative processes to determine their feasibility, and the likely benefits they would produce in terms of improved crane safety and incident reduction.

SafeWork NSW data

Crane safety incidents by industry

Figure 6 shows the two industries with the highest number of crane safety incidents are construction (59%) and manufacturing (17%) The three industries that exhibit a higher proportion of crane safety incidents when compared to non-crane safety incidents were construction, manufacturing, and transport/storage. A chi-squared analysis showed that the type of industry is a significant risk factor for crane safety incidents, with the industry most at risk of experiencing crane safety incidents being construction ($\chi 2(9) = 717.11$, $p < 0.001$).

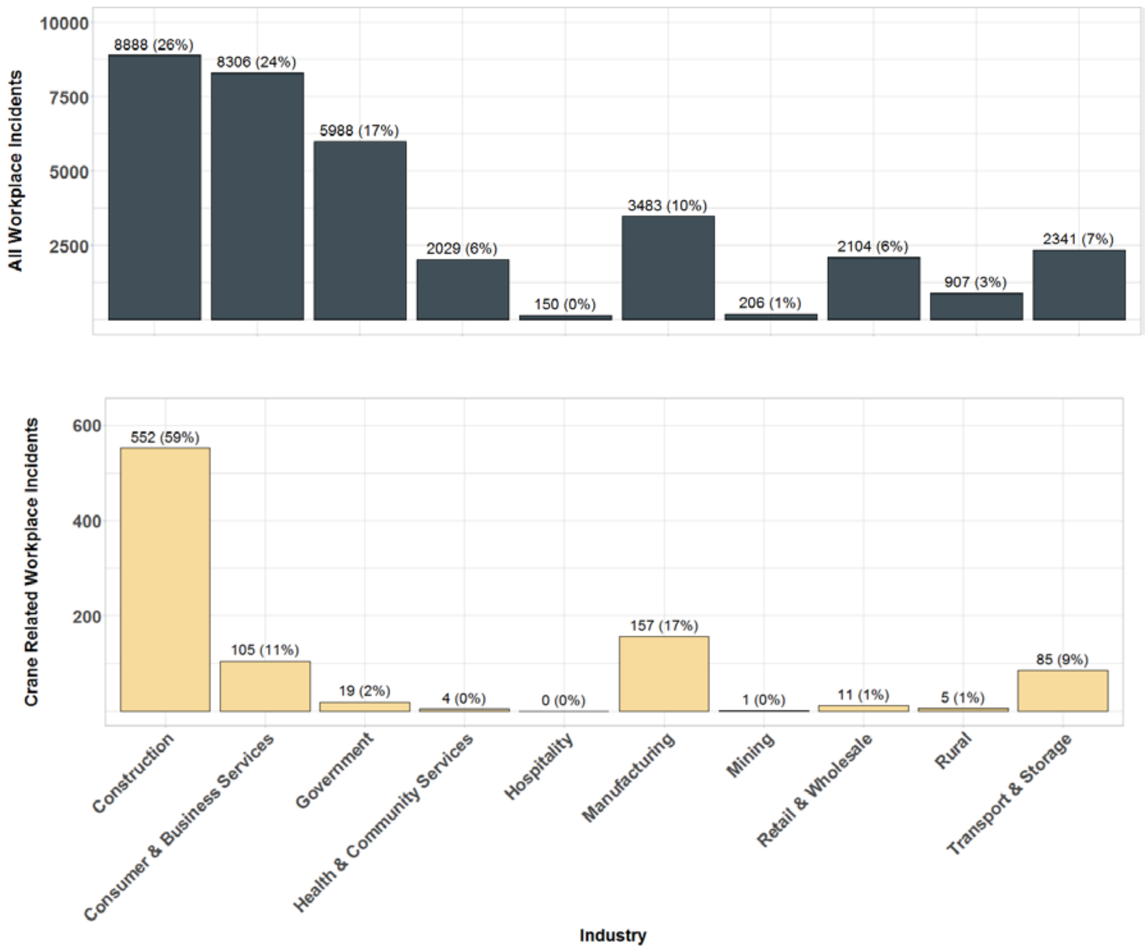

Figure 6. Proportions of crane and safety incidents and all workplace safety incidents by industry.

Incident type vs. type of crane

The information for the type of crane involved in the incident was missing from a significant number of records (36%, or 391 records out of 1075). From those records where the type of crane involved was recorded, the top three crane types involved in safety incidents were mobile cranes (36%), tower cranes (26%), and gantry cranes (17%).

Figure 7 shows the relationship between crane type and incident type for the five cranes exhibiting the highest frequency of workplace incidents. Workplace incidents are grouped into three categories: dangerous incidents, serious injuries, and fatal injuries (see Appendix 8 for definitions).

Mobile cranes accounted for 67 (or 33%) of all serious injuries. Tower cranes accounted for only 31 (or 15%) of serious injuries.

Dangerous incidents occurred most frequently for mobile cranes (176 or 37%), tower cranes (146 or 30%), and gantry cranes (60 or 13%).

No fatal injury cases were recorded involving a mobile crane during the seven-year period of analysis.

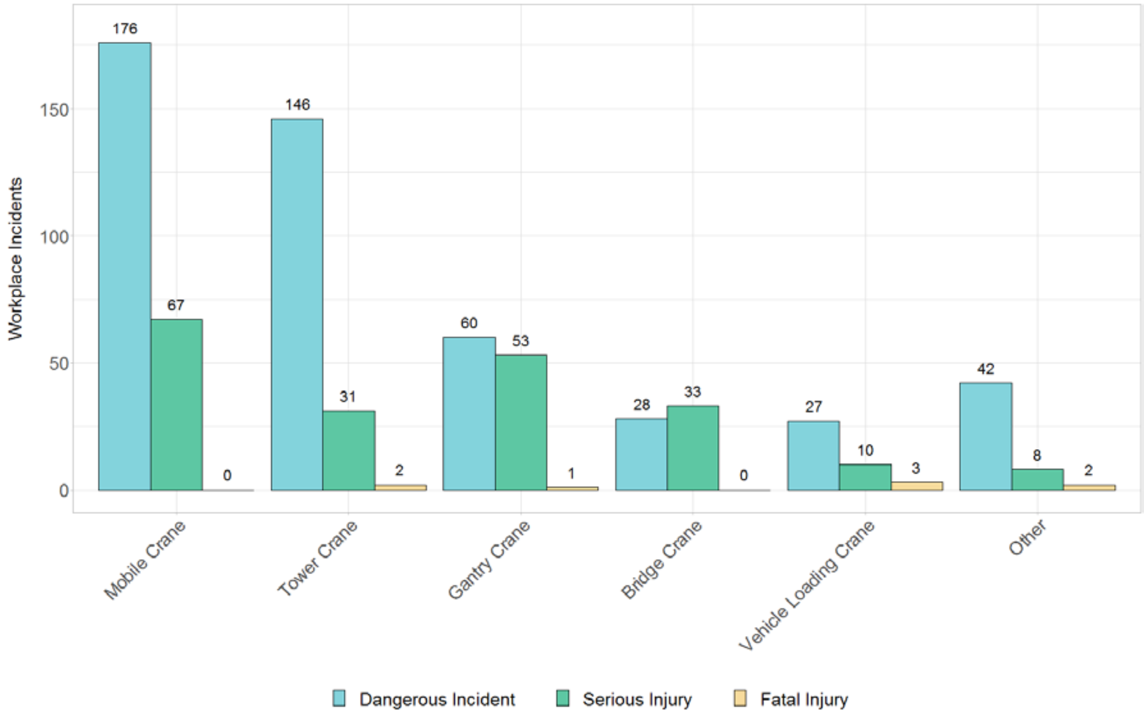

Figure 7. Seriousness of crane safety incidents by type of crane.

Mechanism of incident vs. type of crane

General statistics of the mechanism leading to a crane safety incident are presented in Figure 8. Definitions of each mechanism are provided in Appendix 8.

'Hit by load' and 'Hit by crane's part' were the most frequent types of incidents (42% and 19% respectively) and accounted for a high proportion of incidents for all crane types. However, Figure 8 also illustrates that different crane types (mobile, tower, and other types) have different profiles of incident mechanism. A chi-squared analysis confirmed the mechanism of the incident varies significantly by crane type (χ^2 (14) = 148.2, $p < 0.001$). The most common type of incident for mobile cranes is crane collapse. Tower crane incidents most commonly involve a person being hit by a crane load or being hit by the crane itself.

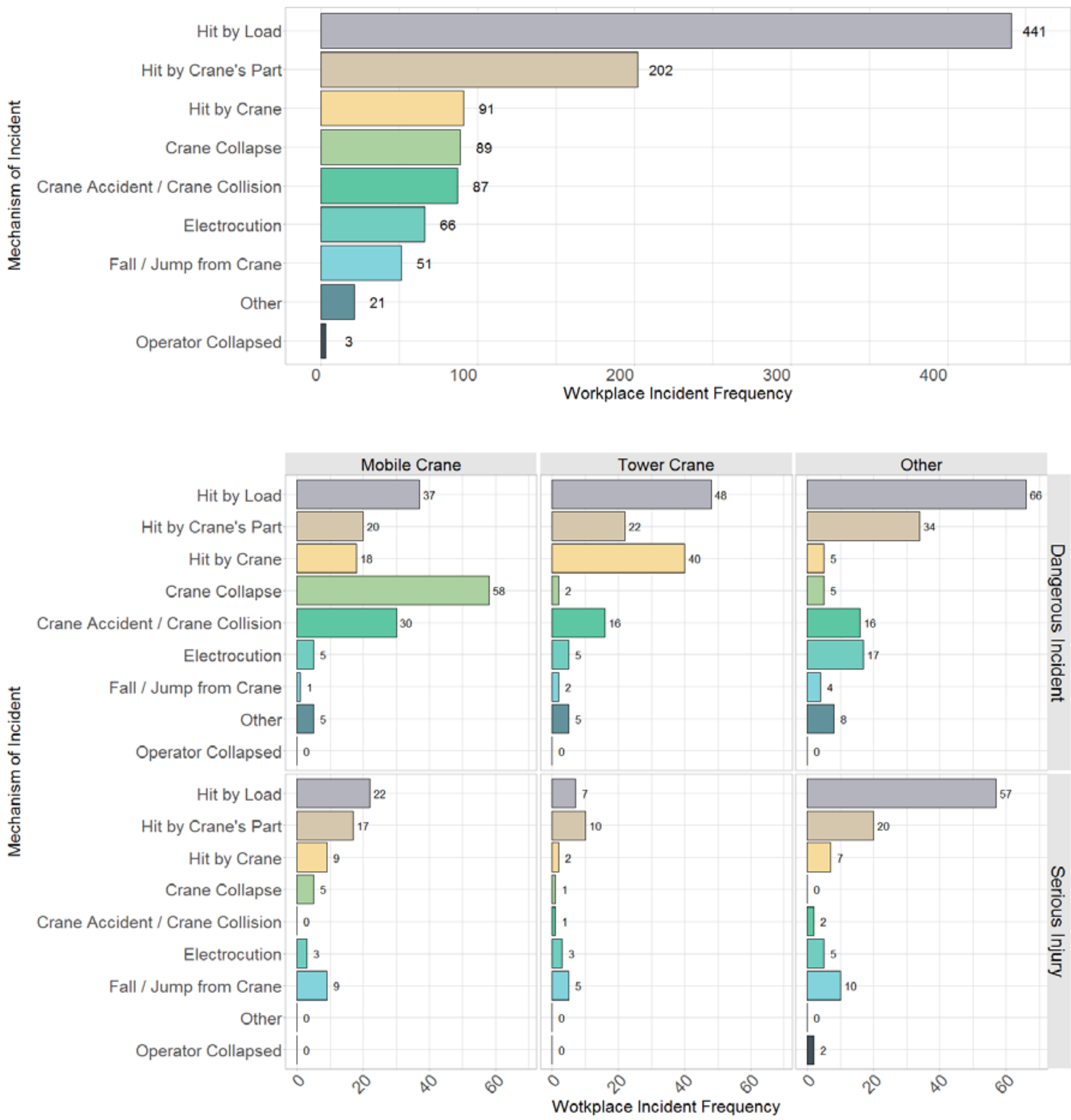

Figure 8. Crane safety incidents by incident mechanism. Top panel – mechanism of incident as a function of workplace incident frequency for all crane types. Bottom panel – mechanism of incident as a function of three crane types in addition to dangerous incidents and serious injuries.

A further analysis of information gleaned from the 'incident details' field in the WSMS workplace incident dataset showed that the top three occupations of persons involved in crane safety incidents resulting in serious injury are general worker (48%), crane operator (25%), and dogman (12%).

Out of the 530 incidents in which the action of the crane (at the time of the incident) was specified, 56% of the incidents related to lifting actions, 17% to slewing actions, and 10% to loading actions.

Time series analysis

Crane safety incident time series analysis

Figure 9 shows the number of serious injuries, dangerous incidents, and total incidents, that occurred from 2012 to 2018. The number of crane safety incidents recorded in NSW increased significantly between 2012 and 2018.

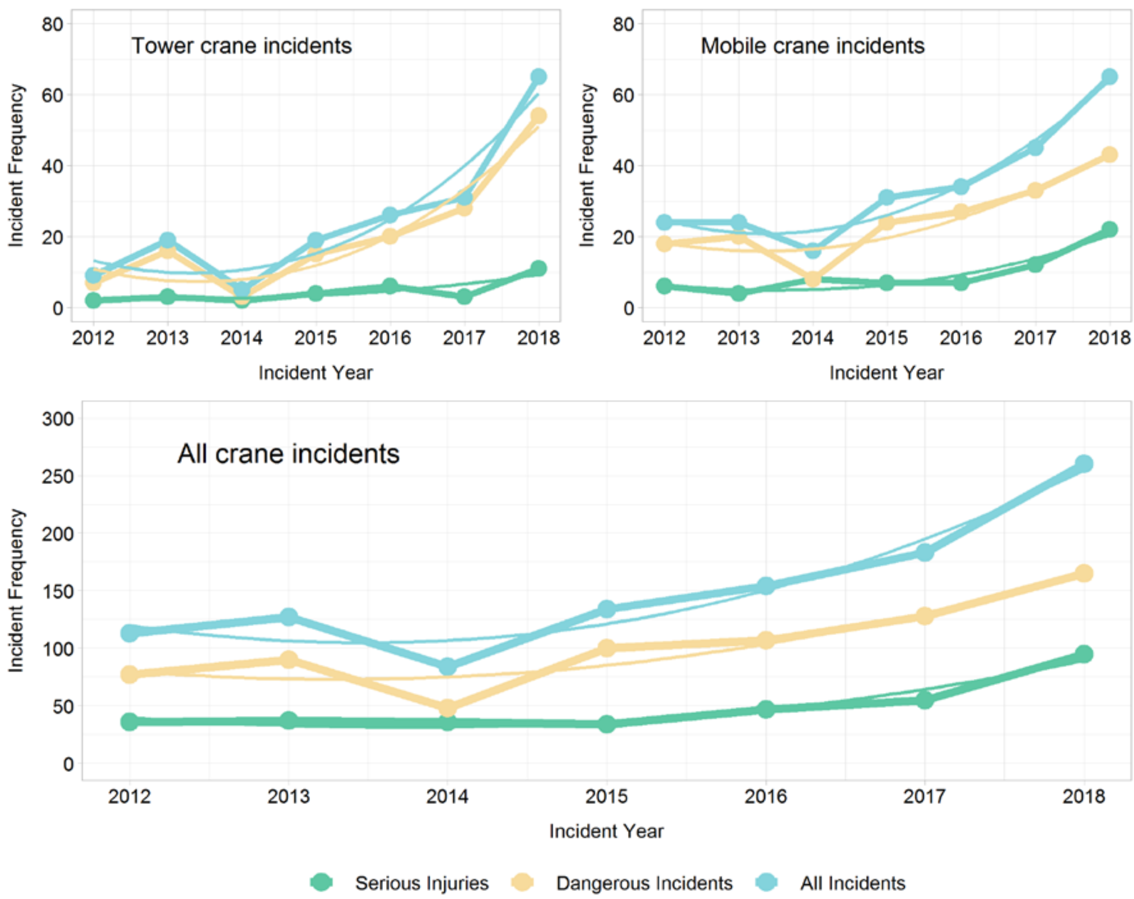

Figure 9. Time series analysis of crane safety incidents, 2012 to 2018.

A Savitzky-Golay filter has been applied to smooth the data and to present the trends as curved lines.

The number of incidents resulting in serious injury per year was stable from 2012 to 2015. From 2015 to 2018 the number of incidents resulting in serious injury more than doubled. It is noteworthy that the number of cranes in operation also increased significantly during this period (see next section for an analysis which normalises for the number of cranes in operation). A similar trend was apparent for dangerous incidents which were relatively stable in number between 2012 and 2015, but which increased markedly in frequency from 2015 to 2018.

Linear models were fitted to the time series data displayed in Figure 9 to determine whether there was a significant increase in incidents resulting in serious injury and/or dangerous incidents involving tower and mobile cranes between 2012 and 2018.

Of the four linear models generated, only one related to incidents producing serious injury and involving tower cranes did not exhibit a significantly positive slope (mobile cranes – serious injuries $F_{1,5}$ = 9.091, p – 0.030; dangerous incidents $F_{1,5}$ = 10.660, p = 0.022; tower cranes – serious injuries $F_{1,5}$ = 6.265, p = 0.054; dangerous incidents $F_{1,5}$ = 11.06, p = 0.021). No differences were found when comparing the trends for mobile or tower cranes incidents leading to serious injuries (z = 0.908, p = 0.182), or dangerous incidents (z = 0.971, p = 0.166). Thus, safety incidents involving cranes have increased significantly in recent years, and this is true for both mobile and tower cranes.

Normalised tower crane time series analysis

As noted in the previous section, to more appropriately understand changes in the incidence of crane-related safety incidents it is important to consider the frequency of incidents relative to the amount of crane activity (or number of cranes in use). To consider the relative frequency of incidents, the incident data was normalised to take into account the total number of standing tower cranes in Sydney[9]. The RLB crane index (RLB, 2019) provided the total number of tower cranes in operation in the Sydney area each quarter from Q2 2015 to Q4 2018.

The number of serious injuries and dangerous incidents was normalised to reflect incidents per 100 tower cranes in operation in Sydney (see Table 8). Note that the data are only complete for incidents where the type of crane could be identified in the database records.

Table 8. Tower crane safety incidents normalised by number of tower cranes standing in Sydney 2015-2019.

Column one shows number of standing tower cranes in Sydney every quarter from Q2 2015 to Q1 2019 (Ncranes). Number of serious injuries (NSI) and number of dangerous incidents (NDI) are shown per quarter, as are normalised frequencies of serious injuries and dangerous incidents per 100 cranes (SInorm and DInorm). Data reconstructed from the RLB crane index® 14th edition.

Quarter	Ncranes	NSI	SInorm	NDI	DInorm
Q2 2015	162	1	0.62	0	0
Q3 2015	187	0	0	0	0

9 Although this index relates only to tower cranes it was the best available proxy measure of crane activity during the period of analysis. For the purposes of this analysis only incidents that could be identified as involving tower cranes were included.

Q4 2015	213	1	0.47	4	1.88
Q1 2016	251	0	0	7	2.79
Q2 2016	289	0	0	2	0.64
Q3 2016	305	3	0.98	5	1.64
Q2 2016	315	1	0.32	3	0.95
Q1 2017	325	0	0	12	3.69
Q2 2017	334	2	0.60	4	1.20
Q3 2017	342	1	0.29	4	1.17
Q4 2017	351	0	0	5	1.42
Q1 2018	347	2	0.58	8	2.31
Q2 2018	342	3	0.88	10	2.92
Q3 2018	321	2	0.62	13	4.05
Q4 2018	316	1	0.32	13	4.11

Figure 10 presents a time series analysis of normalised serious injuries, dangerous incidents, and total incidents, related to tower cranes in Sydney between Q2 2015 and Q4 2018. The number of dangerous incidents per tower crane in operation increased steadily since 2012.

Linear models were fitted to the normalised tower crane safety incident data to test whether the increase in incidents over time was statistically significant. Serious injuries did not exhibit a significantly positive slope ($F_{1,13} = 0.745$, $p = 0.404$); however, dangerous incidents involving tower cranes showed a significant upward trend ($F_{1,13} = 11.42$, $p = 0.005$). The datasets analysed do not provide a clear explanation as to why dangerous incidents involving tower cranes increased significantly in this period while incidents involving serious injury did not.

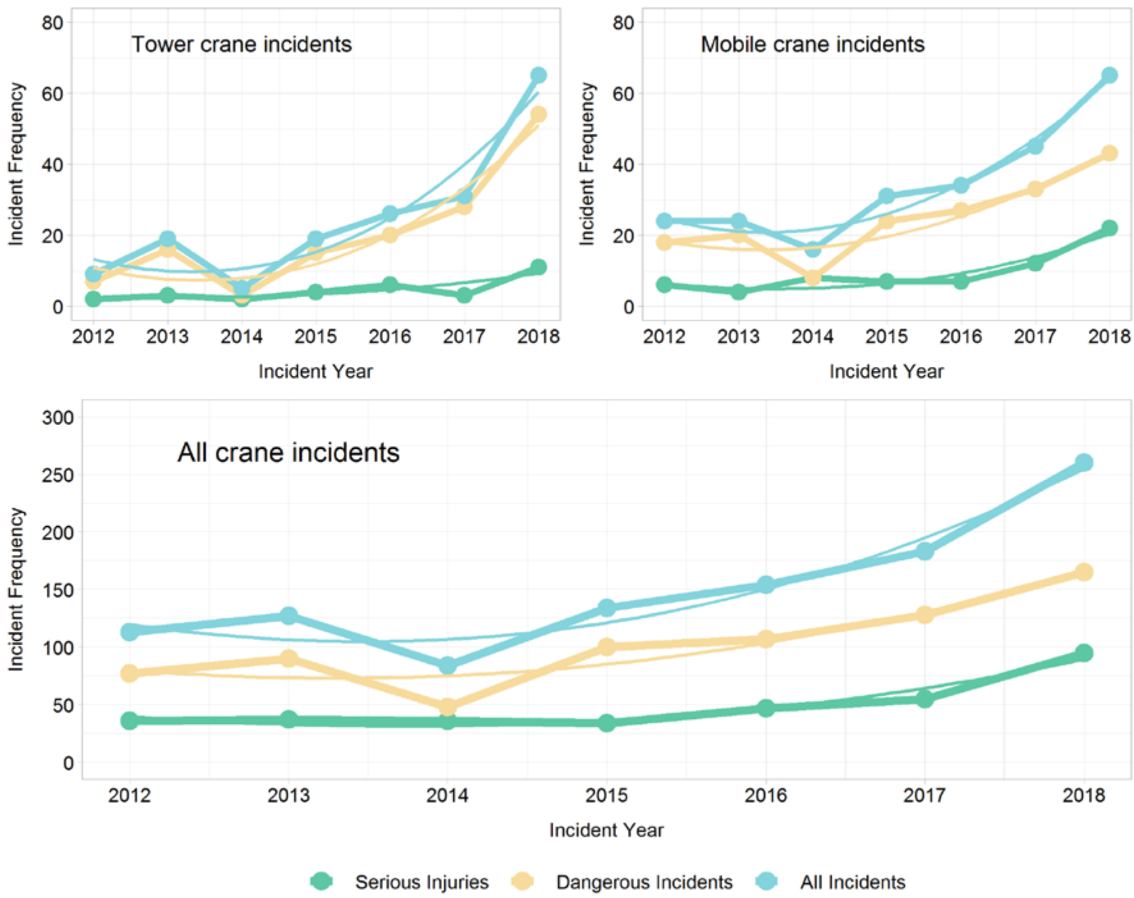

Figure 10. Normalised time series analysis of dangerous incidents and serious injuries involving tower cranes in Sydney.

Note: incident rates have been normalised for the number of tower cranes standing at three-month intervals. A Savitzky-Golay filter has been applied to smooth the data and to present the trends as curved lines.

Causal factors

Causal factors for serious injuries and dangerous incidents

The cause of incident was extracted from the 'Action Taken' and 'Incident Description' fields of the WSMS workplace incident database (see section on data cleansing and Figure 1). Causes of incidents were classified into five major groups:

- human error
- faulty equipment
- weather conditions
- unauthorised access to a crane

- medical condition[10].

Causes were only labelled as such if they were easily identifiable and could be confidently described as the immediate cause of a specific incident. Where an immediate cause was not readily discernible, no main cause was reflected in the analysis.

Figure 11 shows the distribution of causes for serious injuries, dangerous incidents, and all incidents involving cranes. Cases in which the immediate cause was identified as human error made up 82.1% of all incidents. This proportion did not differ significantly for serious injuries or dangerous incidents. Faulty equipment was the second most frequent cause of incidents (12.4%). Together these two causes accounted for 94.5% of all incidents.

10 Causes listed here refer to immediate causes and do not take into consideration shaping factors or originating influences which may have contributed to the cause of an incident.

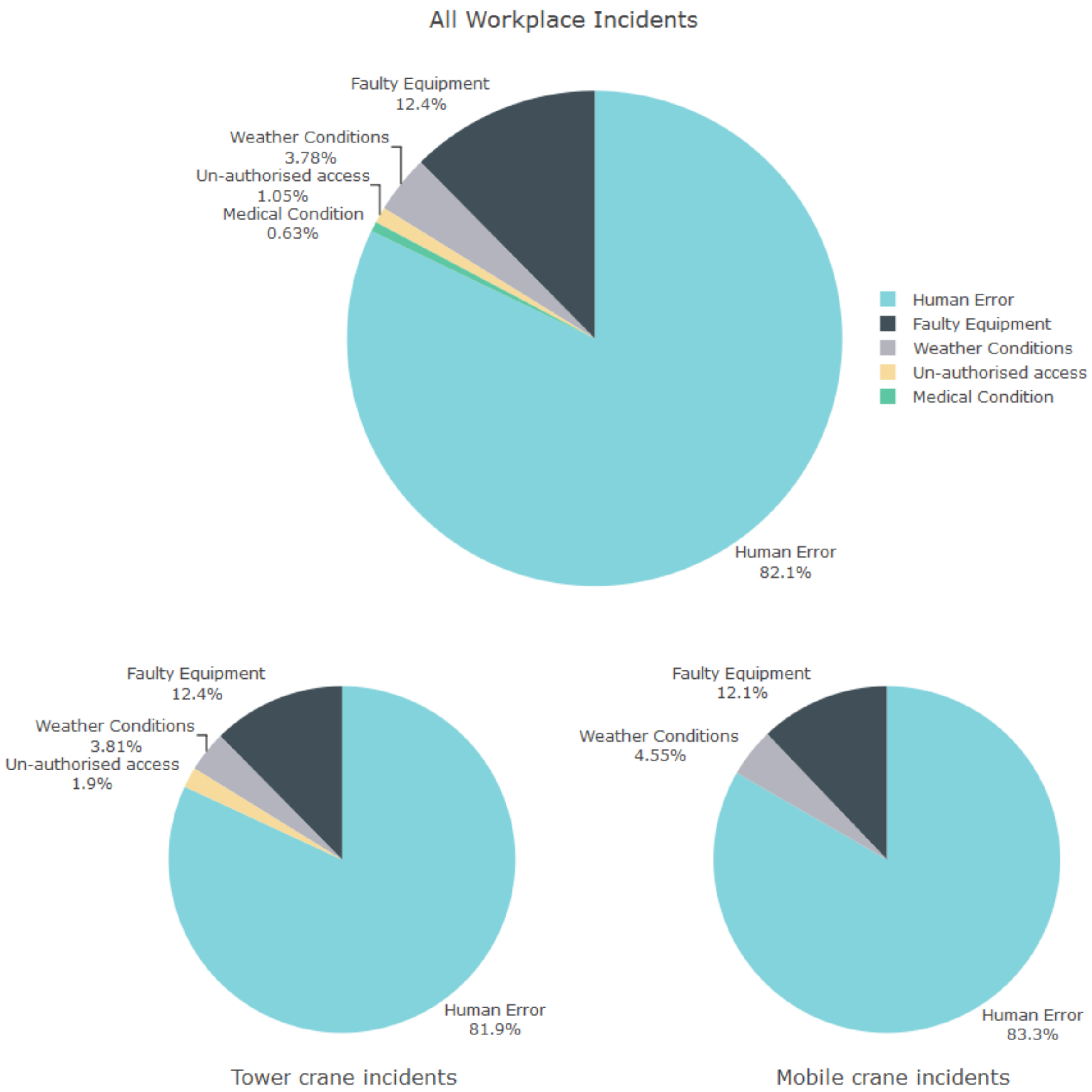

Figure 11. Distribution of the immediate causes of the crane safety incident for all crane safety incidents (top chart), for crane safety incidents involving tower cranes only (bottom left chart), and for crane safety incidents involving mobile cranes only (bottom right chart).

Only incidents occurring after 2012, and where an immediate cause was identified, were included.

Time series analysis of crane safety incident causes

Figure 12 shows a time series analysis of the causes of incidents between 2012 and 2018. Distribution between causes remained relatively stable over the time period; however, the proportion of incidents attributed to human error increased significantly from 72% in 2016 to 89% in 2018. The proportion of incidents attributed to faulty equipment decreased from 21% in 2016 to 11% in 2018.

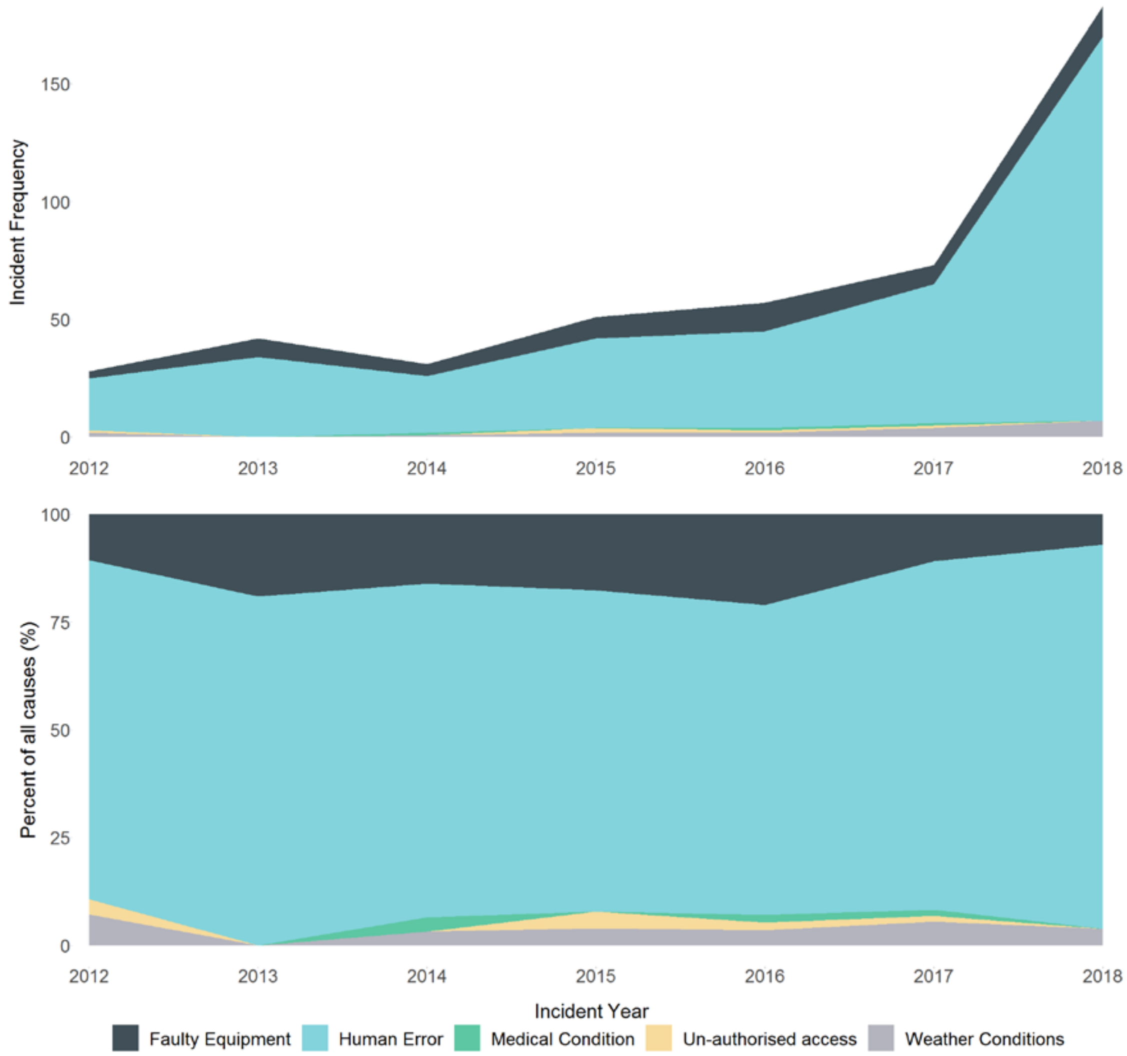

Figure 12. Distribution of the immediate causes of crane safety incidents per year.

This graph compares the proportion of immediate causes of incidents for a specific year. An increase in proportion of one cause of incident from one year to the other (for example, human error from 2017 to 2018) means there is an increased proportion of incidents for which this immediate cause has been identified. It does not mean there is an increase of the number of incidents for which this immediate cause has been identified.

Geographical analysis

Further analysis was undertaken of workplace incidents in NSW by geographical location. For the purposes of this analysis, NSW was split into regions based on the Australian Statistical Geography Standard (ABSGS) SA4 statistical areas (ABS, 2016).

Serious injuries and Dangerous incidents

The geographical distribution of both serious injuries (SI) and dangerous incidents (DI) were found to be similar (see Table 9).

Most incidents occurred in Sydney (61% and 63% of all SI and DI respectively), followed by Newcastle and Lake Macquarie, and Illawarra/South East NSW, with 15.7% and 12.4% of all SI and DI respectively.

Table 9. Frequencies per region of incidents resulting in serious injuries (SI) and dangerous incidents (DI).

N represents the number of incidents, and %SI and %DI represent the proportion of serious injuries and dangerous incidents in NSW.

Regions	NSI	%SI	NDI	%DI
Sydney	205	61.7	444	63.3
Newcastle and Lake Macquarie	37	11.1	77	11.0
Illawarra	26	7.8	32	4.6
Hunter Valley excl. Newcastle	24	7.2	59	8.4
Capital Region	8	2.4	8	1.1
Southern Highlands and Shoalhaven	6	1.8	10	1.4
Riverina	6	1.8	8	1.1
Coffs Harbour – Grafton	5	1.5	17	2.4
Central Coast	5	1.5	21	3.0
Mid North Coast	4	1.2	8	1.1
Central West	3	0.9	6	0.9
Richmond – Tweed	2	0.6	5	0.7
Murray	1	0.3	3	0.4
New England and North West	0	0.0	3	0.4
Total	332	100.0	701	100.0

Fatal injuries

Fatal injuries were also analysed with respect to location and main cause. Of the 15 fatalities that occurred between 2012 to 2019, immediate causes for eight fatalities could be confidently determined from the WSMS workplace incident database. Unauthorised public access (that is, where trespassers climbed onto a crane and fell or were electrocuted) and human error were reported to be the most frequent causes of fatality (40%, or six of 15 incidents). Figure 13 shows the main causes and locations of crane-related fatal injuries.

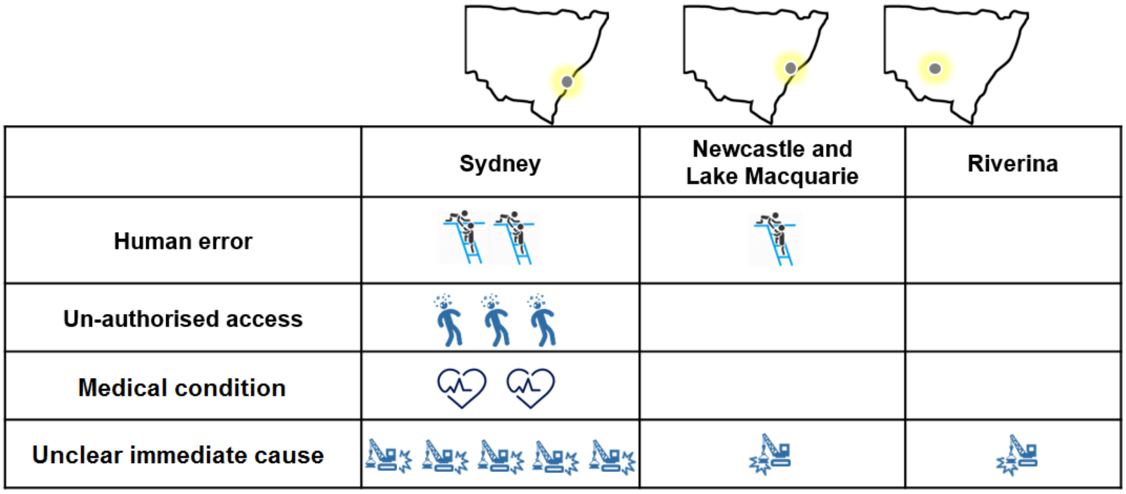

Figure 13. Geographical distribution of fatal injuries due to crane safety incidents as a function of the immediate cause of the incident.

Each symbol represents one fatality. The graph includes fatalities that have occurred since 2012 and for which an immediate cause was identified.

High Risk Work (HRW) licensing

HRW licences relevant to crane-related activities

In total, 67,275 workers are currently licensed either for rigging, dogging, or operating a crane. A large proportion (77.6%) of these workers hold a licence for dogging. About half (48.9%) hold a licence to operate a crane, and 25.4% hold a licence for rigging.

Figure 14 provides details of workers' licensing in relation to crane-related activities.

More than half of the workers (57.6%) are licensed to work in only one role: that is, they are licensed just to undertake rigging, dogging, or operating a crane. The most specialised role is dogman, with 35.7% of licensed dogmen holding only one licence. Among workers licensed to operate a crane, 20.5% hold only an operators' licence. Riggers are relatively less specialised with only 1.3% of licensed riggers holding a single licence. The majority of riggers (88%) also hold a licence for dogging.

About one in ten workers (9.4%) holding a HRW Licence relevant to crane activities are licensed to perform all three roles. Of 33.1% of workers who hold two types of licence, most hold a licence for dogging (98.1%) in combination with a licence for operating a crane or for rigging.

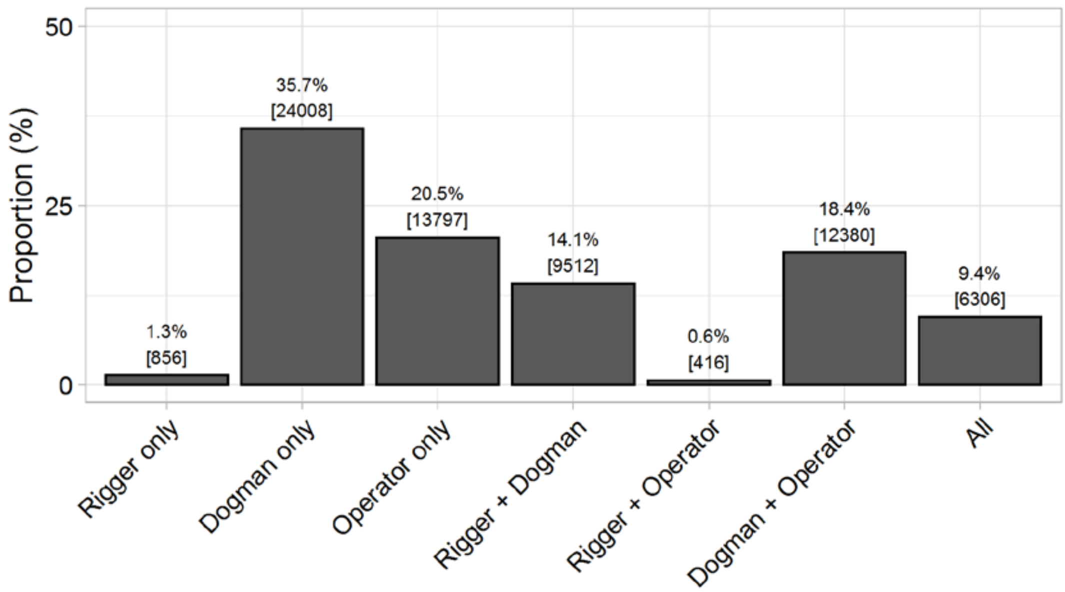

Figure 14. Proportions of HRW licences held by individuals for crane-related activities.

'Rigger + Dogman' means the individuals have both a rigging and a dogging HRW Licence.

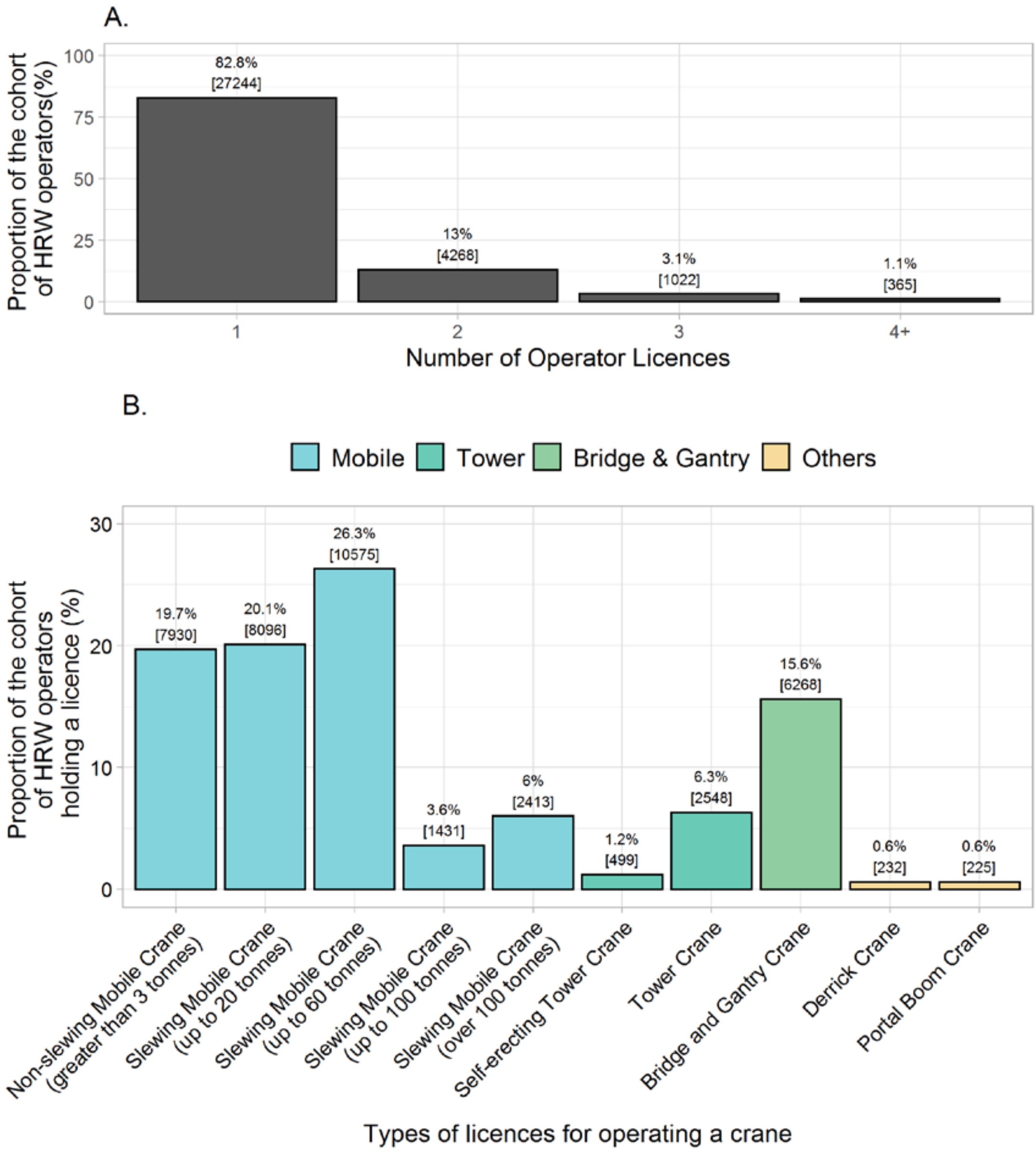

Figure 15. Proportion of licenced crane operators as a function of the number of crane operation licences held (top panel), and as a function of the type of crane operation licence held (bottom panel).

The top panel of Figure 15 shows the proportions of crane operators as a function of the number of different cranes they are licensed to operate. The results indicate that operators are highly specialised with most holding a licence to operate one type of crane only (82.8%). Fewer have licences to operate two types of cranes (13%), and very few are licenced to operate three or more types of crane (4.2%).

The bottom panel of Figure 15 presents the proportions of crane operators as a function of the type of crane they are licensed to operate. The three most frequent licences held relate to mobile cranes. In decreasing order, slewing mobile crane (up to 60 tonnes) is the most commonly held licence with 26.3% of the crane operators holding this type of licence, followed by slewing mobile crane (up to 20 tonnes) and non-slewing mobile crane (greater than 3 tonnes) which are held by 20.1% and 19.7% of crane operators respectively. Note that these three licences allow the operation of the lightest types of mobile cranes (all less than 60 tonnes). The most common types of cranes which operators are licensed for, after mobile cranes, are bridge and gantry cranes (15.6%), followed by tower cranes (6.3%).

Age and experience of currently licensed riggers, dogmen and crane operators

The age and the experience of workers who hold High Risk Work licences related to crane activities (that is, rigging, dogging or crane operation) was examined. The results are presented in Figure 16.

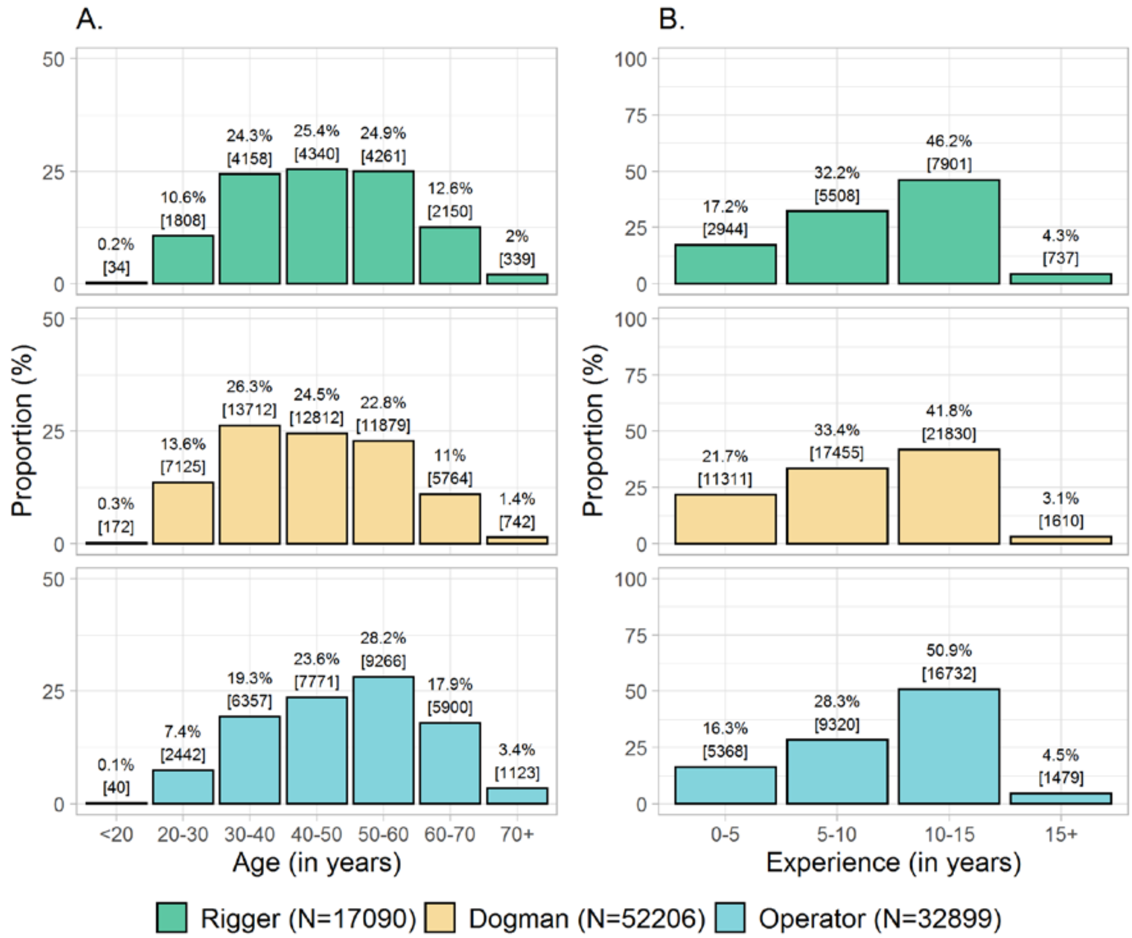

Figure 16. Licensed riggers, dogmen, and operators, by age and experience.

Experience in a role is calculated as the time period for which a licence in this role has been held. If more than one licence was held in a role, experience was calculated as the time the oldest licence had been held. The analysis was performed separately for different types of licences (that is, if an individual held two licences, such as dogging and operating a crane, this person would be counted twice in the analysis – once for their age and experience in holding the dogging licence, and once for their age and experience in holding the operating licence).

Independently of the role, the results show that between approximately 60% and 70% of the cohort are over the age of 40. Most workers licensed to engage in HRW related to crane activities have between 10 and 15 years' experience in their roles.

Operators are, on average, the most experienced and oldest of the cohort of licensed workers engaged in crane-related activities, with an average of 49.1 years of age and 9.4 years' experience. Riggers are, on average, slightly younger (46 years of age) and less experienced (9.1 years). Dogmen represent the youngest and least experienced population of licensed workers, at 44.5 years of age and 8.5 years' experience.

High Risk Work licensing and crane safety incidents

Using the HRW Licence database, individuals involved in crane-related safety incidents were identified to determine their licencing details at the time of the incident (see Table 10).

Of 280 individuals with a HRW Licence and identified to be involved in crane safety incidents, 68 were not included in this analysis since more than one individual could be identified under the same name, and therefore a reliable matching of data was not possible.

Eighty-one names could not be found in the licensing database at the time of the recorded incident. It must be noted that a 'text string' search was performed for the HRW Licence-holders' names, as they appeared in the 'Incident Description' field of the WSMS workplace incident dataset. One possible explanation for these individuals not appearing in the HRW Licence database might be that their names were incorrectly scribed by inspectors in their reports.

Of the 131 individuals who could be identified in the HRW Licence database, 29 (or 22.1%) were found to be licensed for another role than the one they were reported performing at the time of the incident. For example, a worker holding a licence only for rigging at the time of the incident was reported as being the dogman in one workplace incident. Finally, 102 (77.9%) of HRW Licence holders involved in crane safety incidents (who could also be identified in the HRW Licence database) were found to be licensed correctly for the role (dogging, rigging, or operating) they performed at the time of the incident.

Note that this analysis does not account for the different variations of licence existing under the same role. For example, 'operating' includes all licences related to operating a crane. The present analysis does not distinguish between the range of licences existing to operate different types or classifications of crane.

Table 10. Licensing status of persons involved in crane safety incidents.

Column one describes the role of the individual. Column two describes the number of individuals identified in crane safety incidents by name. Column three describes whether the individual could be uniquely identified by their name in the HRW Licence database. Some names were not unique and therefore could not be matched to a single individual. Column four lists the number of individuals who could not be found in the HRW Licence database. Column five lists the number of individuals licensed for the wrong role at the time of the incident. The last column lists the number of individuals licensed for the correct role at the time they were involved in a crane safety incident.

Role	Number of persons identified	Non-identifiable	No licence recorded	Licensed for another role (at time of incident)	Correctly licensed (at the time of incident)
Rigger	32	8	12	2	10
Dogman	81	18	19	17	27
Operator	167	42	50	10	65
Total	280	68	81	29	102

A chi-squared test of independence was performed to compare whether the age and experience of the 102 HRW workers involved in crane safety incidents (and found to hold a valid licence for their role at the time of the incident) differed significantly from the age and the experience of the HRWs currently licensed for the same role according to the HRW Licence database.

Age was only found to be a significant risk factor for the occurrence of crane safety incidents for operators ($\chi2$ (6) = 22.30, p = 0.001). Experience was found to be a significant risk factor for crane operators ($\chi2$ (3) = 43.27, p < 0.001) and dogmen ($\chi2$ (3) = 34.84, df = 3, p < 0.001). The analysis revealed that, more than expected, dogmen and operators with less than five years' experience in their role were involved in crane safety incidents. In other words, dogmen and operators with fewer than five years' experience in their role are more at risk of involvement in crane safety incidents.

Figure 17 presents a graphic representation of the difference in experience between the general population of crane riggers, dogmen, and operators, currently licensed compared to those individuals identified as having been involved in crane safety incidents who were correctly licensed at the time of the incident. The average experience of the entire population of operators, dogmen, and riggers, was 9.4 years, 8.5 years and 9.1 years respectively. For operators, dogmen, and riggers, who were involved in crane safety incidents, the experience was significantly lower at 6.5 years, 5.4 years, and 6.7 years respectively.

The results show that workers with less than seven years' experience (approximately 30% of the overall group) are, on average, involved in the majority of workplace crane safety incidents. It is important to note that these workers are not necessarily young workers, as age was only found to be a significant risk factor for crane operators.

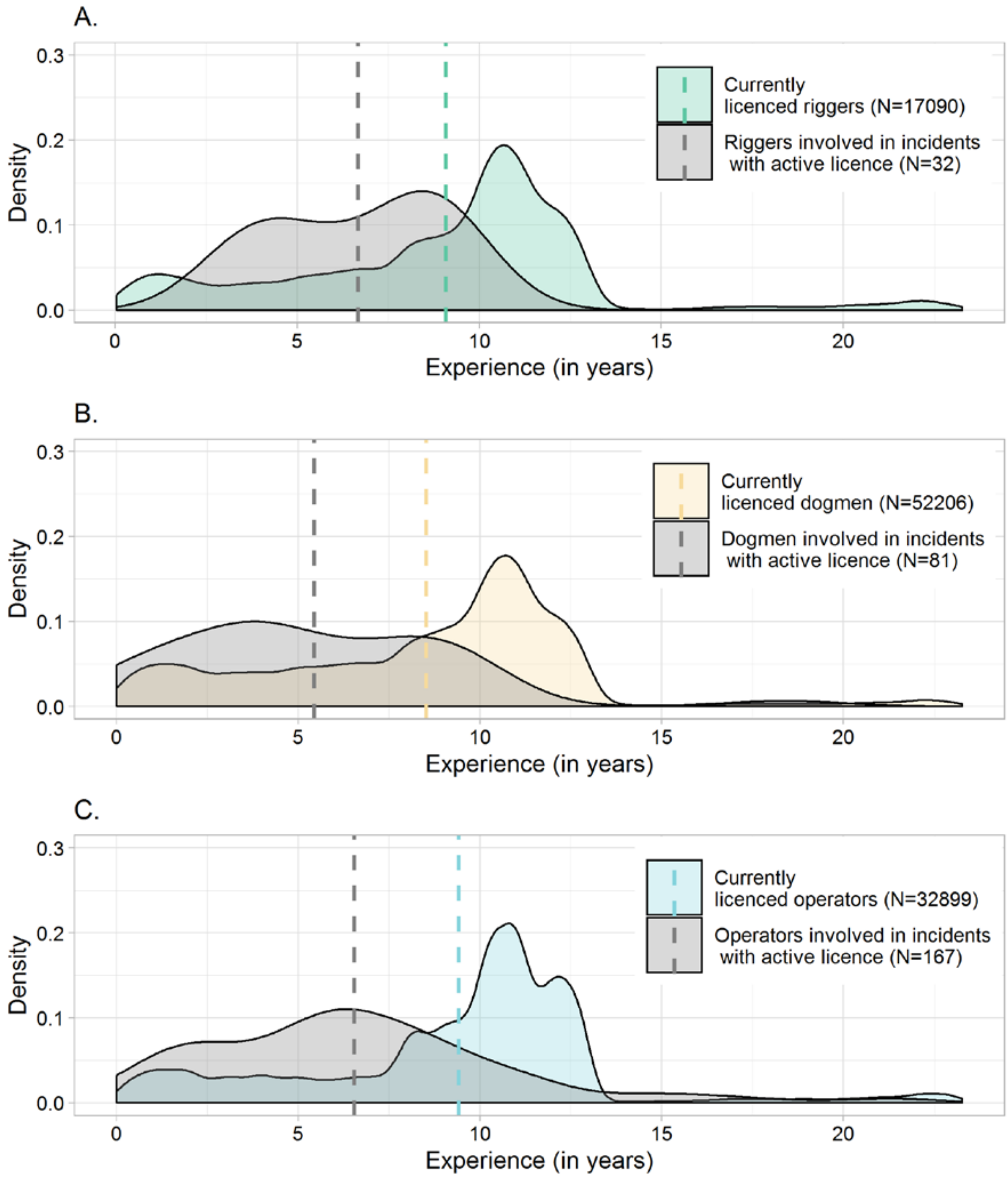

Figure 17. Comparison of age and experience profiles of licensed workers involved in crane safety incidents compared to all licensed workers.

Density curves show experience (in years) of HRW Licence holders involved in incidents at the time of the incident (grey filled), and the experience of all HRW Licence holders currently licensed (colour filled). The top panel shows the density curves for riggers, the middle panel shows density curves for dogmen, and the bottom panel shows density curves for operators. The dashed lines represent the averages of the underlying distributions.

HRW training

The RTO database was examined to check whether workers involved in crane safety incidents were correctly trained to perform their roles. The results are presented in Table 11.

Of 280 workers identified in crane safety incidents, 212 were omitted from further analysis since more than one individual could be identified by the same name and therefore a reliable dentification was not possible.

A total of 13 names could not be found in the training database at the time of the incident. Of 55 individuals who could be identified in the HRW training database, 12 (or 21.8%) were found to have been trained for a role other than the one they were reported to be engaged in at the time of the crane safety incident.

A high proportion of HRW Licence holders (43 individuals, or 77.9% of individuals identified in the HRW Licence database) were found to have been trained correctly for the activity they were performing at the time of the incident (for example, dogging, rigging, or operating).

It must be noted that this analysis does not account for different variations of training existing under the same role. That is, a worker with an operators' licence would be considered (in the analysis) to be correctly trained for operating a crane, no matter the type of crane involved in the training.

The top panel of Figure 18 shows the number of RTOs and their size. The middle panel shows the distribution of trainees by RTO. This shows that a small number of RTOs (n=10, 8.5%) is responsible for training more than half the workers trained to perform high risk work (n=14,175, 50.2%). In other words, a quarter of the total number of RTOs involved in training of crane-related HRW is responsible for training 84% of the currently licensed workers engaged in crane-related HRW.

A chi-squared analysis revealed the RTO's number of trainees as not a significant risk factor for a licensed worker to be involved in a crane safety incident ($\chi 2$ (2) = 0.05, p = 0.976); that is, a trainee has the same chance of being involved in a crane safety incident whether they were trained by a large RTO or a small RTO.

Table 11. Training experience of workers with HRW licences involved in crane safety incidents.

Results of a search within the training database for the 280 workers with HRW licences found to be involved in crane safety incidents. Column one describes the role of the individual. Column two describes the number of individuals identified in crane safety incidents by name. Column three describes whether the individual could be uniquely identified by their name in the training database. Some names were not unique and therefore could not be matched to a single individual. Column four lists the number of individuals who could not be found in the training database. Column five lists the number of individuals trained for the wrong role at the time of the incident. The last column lists the number of individuals trained for the correct role at the time they were involved in a crane safety incident.

Role	Number of persons identified	Non-identifiable	Not found in training database	Trained for another role	Correctly trained
Rigger	32	23	1	3	5
Dogman	81	56	4	3	18
Operator	167	133	8	6	20
	Total	212	13	12	43

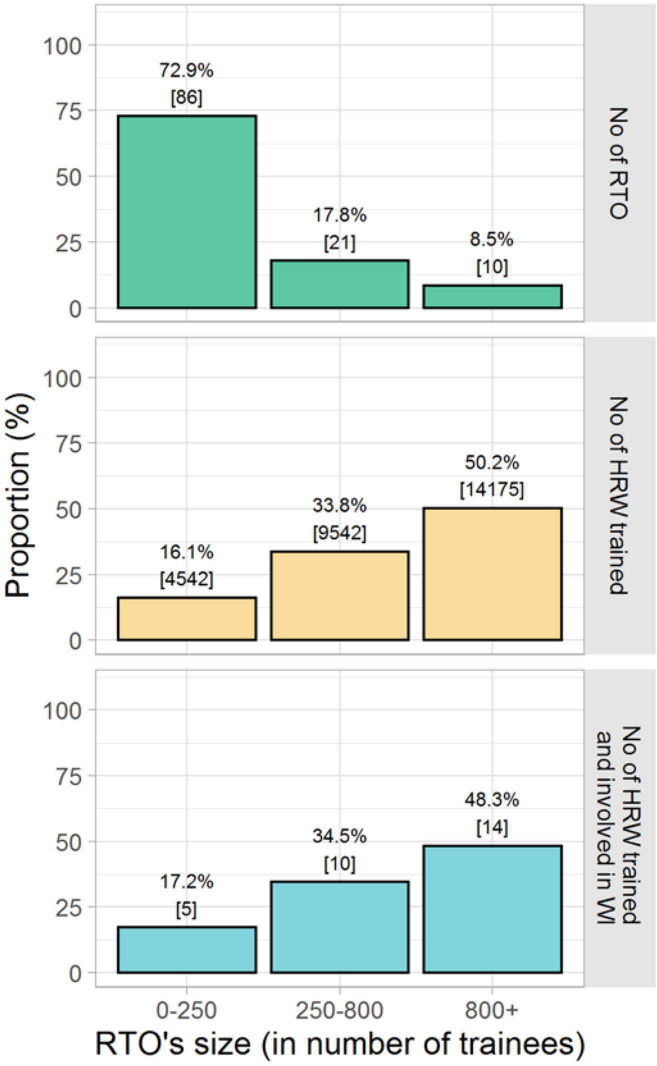

Figure 18. Training and incident experience of licensed workers involved in crane-related activities, by RTO size. Proportions and numbers of RTOs (top panel), HRW trained (middle panel), and HRW trained who were involved in a crane safety incident (bottom panel).

PCBU crane ownership and history of compliance notices

A total of 390 PCBUs was found to own the 2,313 cranes registered in NSW, with an average time for owning a registered crane of approximately 7.8 years.

Figure 19 presents the number of cranes owned per type of crane. Most PCBUs registered as crane owners were found to be specialised regarding the type of cranes they owned, rarely holding registration for both mobile and tower cranes: only 17 PCBUs, or 3.2%, owned both crane types. Slightly more than half the PCBUs hold registration for one crane only (n=273, 51.3%).

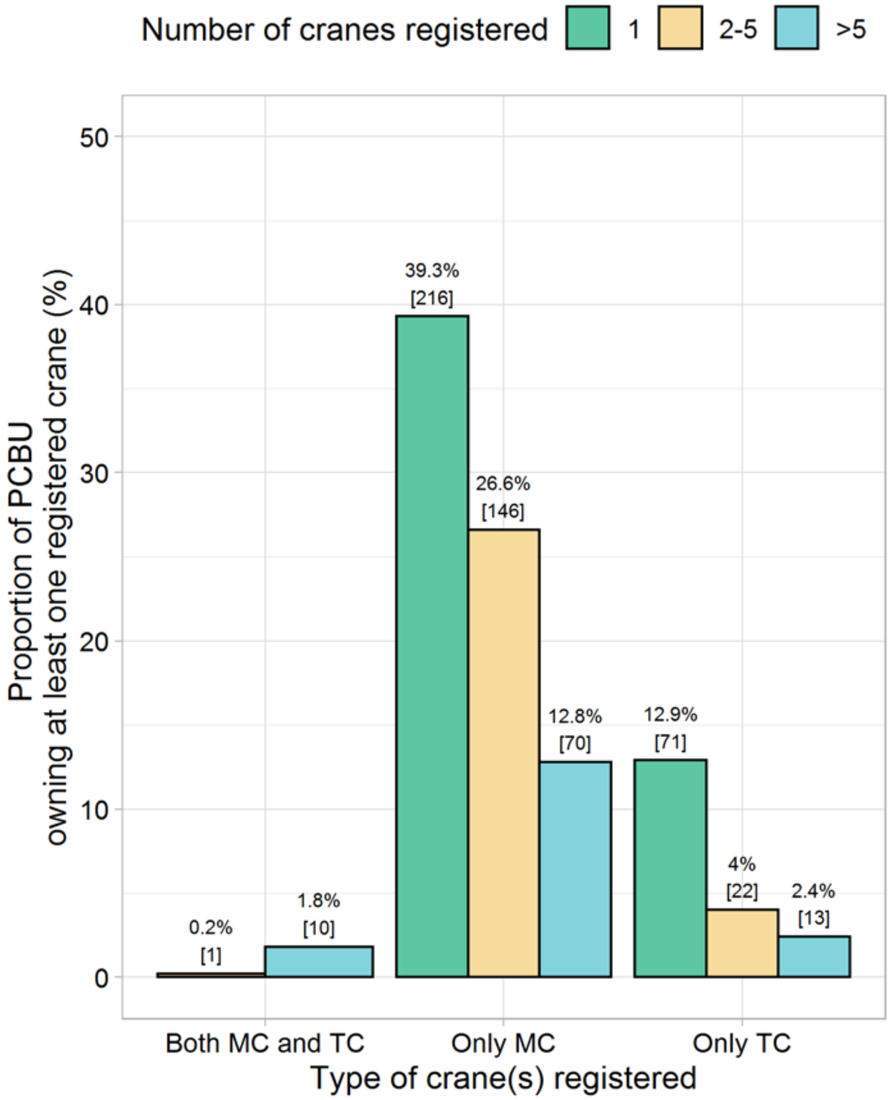

Figure 19. Proportion of PCBUs owning at least one registered mobile crane (MC) or one registered tower crane (TC) as a function of the type of cranes owned (mobile crane, tower crane, or both), and the total number of cranes owned.

The number of notices issued against a PCBU by SafeWork NSW between 1 January 2007 and 1 February 2019 was used as an indicator of the capacity of a PCBU to work in line with WHS requirements. Note that notices issued for all WHS infringements, not only those that were crane-related, were included in this analysis.

The top panel of Figure 20 presents the number and distribution of previous compliance notices issued to PCBUs owning at least one registered crane in NSW as at 1 February 2019. The majority of crane owning PCBUs have no history of notices (n=388, 63.5%). For the remaining PCBUs, 100 (18.8%) received between 2 and 10 previous notices, and 46 (8.6%) received more than 10 notices in the period under consideration.

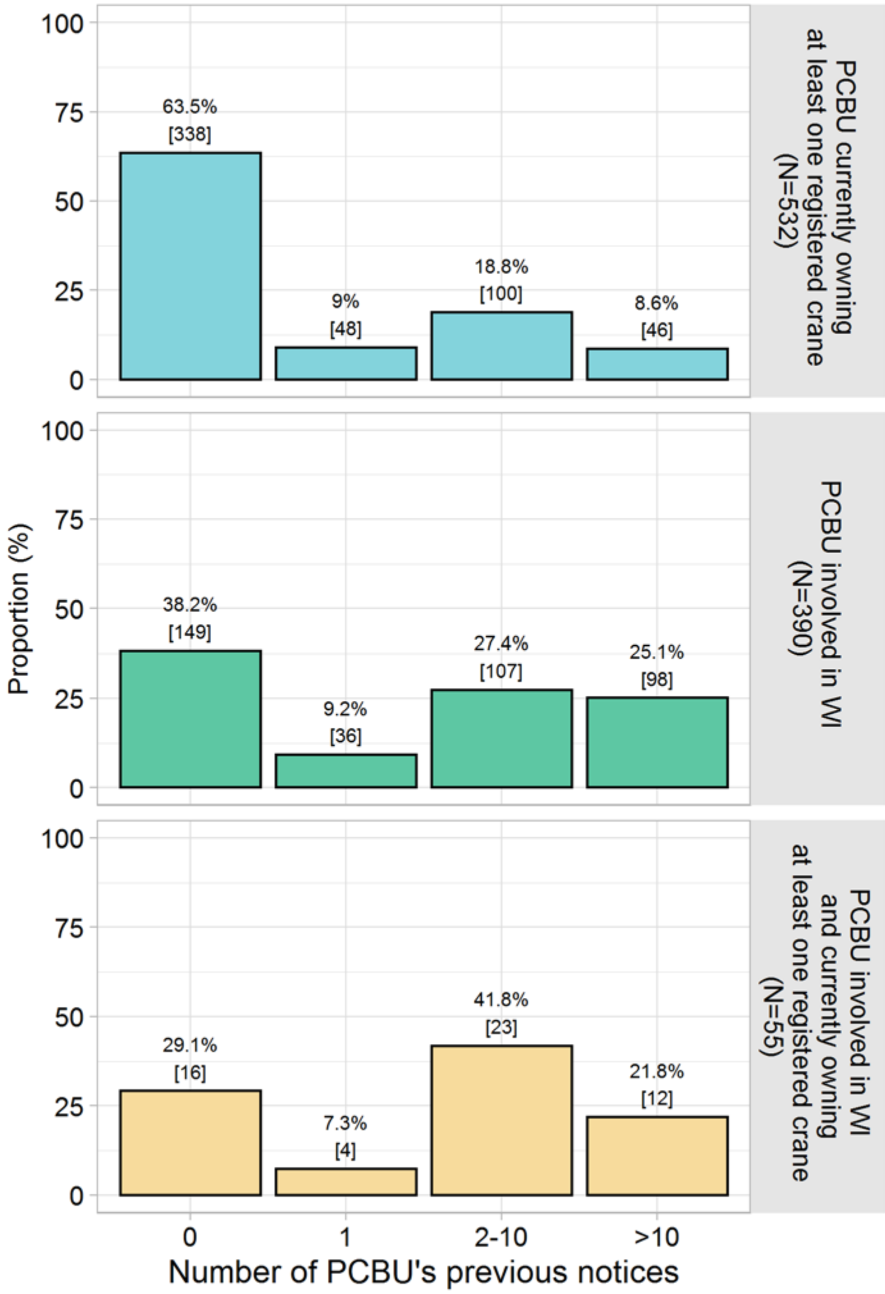

Figure 20. Proportion of PCBUs as a function of the PCBU's previous number of notices.

Top panel shows the proportion for PCBUs owning at least one registered tower or mobile crane. The middle panel shows the proportions for PCBUs that have notified or have been identified in crane safety incidents. The bottom panel shows the proportions for PCBUs owning at least one registered tower or mobile crane and that has also been identified in a crane safety incident.

Characteristics of PCBUs involved in crane safety incidents

Finally, the population of PCBUs currently owning at least one crane (Figure 20, top panel) was compared to those involved in a crane safety incident (although not necessarily owning a crane) (Figure 20 middle panel).

The Australian Business Number (ABN) of the PCBU could be identified in 390 (36.2%) of crane safety incidents reported (36.2%). A chi-squared analysis revealed the history of notices as a significant risk factor for crane safety incidents (χ^2 (7) = 580.94, $p < 0.001$).

As Figure 20 illustrates, when comparing the distributions in the top and middle panels, PCBUs with no history of compliance notices are less likely to be involved in subsequent crane safety incidents (38.2% against 63.5%). In contrast, PCBUs with more than 10 compliance notices are more likely to be involved in subsequent crane safety incidents (25.1% against 8.6%).

The bottom panel of Figure 20 compares owners of registered cranes only. The 390 PCBUs found to be involved in crane safety incidents were extracted from the list of 532 PCBUs that own at least one registered crane. The search resulted in 55 PCBUs that are registered as owning at least one crane and that were found to have been involved in a crane safety incident between 2012 and 2017. A chi-square analysis revealed a history of notices as a significant risk factor for workplace incidents (χ^2 (7) = 372.89, $p < 0.001$). An examination of the results showed that PCBUs with no history of notices are less likely to be involved in crane safety incidents, whereas PCBUs with two or more notices are more likely to be involved in crane safety incidents.

Discussion

The research was undertaken in response to the persistent frequency of safety incidents involving cranes in the Australian construction industry. In Australia, 47 workers were killed in incidents involving cranes between 2003 and 2015 (Safe Work Australia, 2016a). Safe Work Australia (2019) also reports that there are, on average, around 240 serious injury claims arising from crane safety incidents every year.

The aims of this research project were twofold:

1. To identify causes and contributing factors associated with safety incidents involving cranes in the construction industry.
2. To explore strategies to reduce the risk of crane safety incidents in the construction industry.

The research utilised three different methods. First a review of the extant literature was conducted to produce a synthesis of previous research analysing the causes of crane safety incidents in the construction industry and measures identified for the prevention of such incidents. Second, an analysis of quantitative data collected by SafeWork NSW, pertaining to the occurrence of crane safety incidents and the licensing of workers in relation to the use of cranes was undertaken. Third, in-depth qualitative analysis relating to crane safety incident causation and strategies for prevention was collected from industry stakeholders and subject-matter experts. This qualitative data was analysed to develop cause-effect trees and a crane safety incident causation model, as well as to develop themed suggestions as to how crane safety incidents could be prevented in the Australian construction context.

This following discussion describes key findings from the three component parts of the research. The discussion identifies four main areas of crane safety incident causation and provides suggested solutions to address key areas of:

- workforce competence
- supply arrangements, communication and planning
- equipment design, maintenance and use
- The industry and regulatory environment.

Workforce competence

The analysis of Safework NSW data showed that human error is the most frequently identified causal factor in crane safety incidents in NSW. This result is consistent with findings published in other parts of the world. This finding may be partially explained by the propensity of most traditional investigation methods to focus on the immediate causes of an incident, which has led, especially in tasks where a human operates a machine, to an increased focus on operator performance as the primary cause. However, modern safety incident causation models enable the explanation of wider range of causal factors for safety incidents in the construction industry, including those involving cranes (for example, work planning, time pressure), rather than allocating blame solely on the machine operator.

Notwithstanding this, the proportion of crane safety incidents attributed to human error in NSW found in SafeWork NSW data suggests workforce competence may be a key issue for crane safety incidents in the NSW construction industry. Industry experts consulted in the research also identify workforce competence to be a critical factor in the prevention of crane safety incidents. Industry participants in the interviews and focus groups were critical of the current licensing system for crane operators (and others who work with cranes), arguing the possession of a HRW Licence may not reflect that a worker is sufficiently knowledgeable to operate a particular make or model of crane. The industry participants also perceived a lack of consistency in the training provided by RTOs, which impacts workforce competence and safety. Interestingly, the analysis of the SafeWork NSW data revealed that the size of the RTO at which a worker is trained does not impact their likelihood of being involved in a crane safety incident. Participants also commented that experience in relation to the use of a particular make or model of crane is an important factor in safe operation and that, in the absence of a 'log book' system, employers and principal contractors are not easily or universally able to determine or verify an operator's competence in using a particular crane.

Focus group/interview participants frequently raised workforce inexperience as having an impact on safety. The importance of experience was supported by the quantitative analysis of data from SafeWork NSW which revealed a significantly higher proportion of crane safety incidents than expected involve operators with fewer than five years' experience. For the purpose of that analysis, experience was deemed to be the length of time they had held the relevant High Risk Work Licence. It did not relate to experience related to a specific make or model of crane. Focus group and interview participants also perceived it is 'too easy' to obtain a licence for crane operation, dogging, or rigging, which negatively impacts workforce competence and safety when combined with an overheated construction industry environment and high level of demand. Inexperience was also reported to be a risk factor for dogmen in the NSW quantitative data analysis. This is noteworthy because the literature review revealed that improper lifting practices (such as lifting over people) contributes to crane safety incidents.

Analysis of SafeWork NSW data also revealed that 22.1% of workers licensed to perform High Risk Work, and who were involved in crane safety incidents, were undertaking work for which they were not licensed correctly at the time of the incident. This suggests the licensing system is not operating in an effective way. The literature reveals that time pressures inherent in work at construction sites can sometimes create pressures that encourage unqualified workers to perform certain tasks.

The literature also identifies the competence of persons who plan and coordinate the use of cranes and lifting operations at a worksite as being critical for the safe use of cranes. Participants in the focus groups and interviews similarly commented on the fact that site-based decisions with the potential to impact the safe operation of cranes are often made by people with little knowledge of crane use or safety, such as site engineers. Participants identified a need for crane safety to be better incorporated into the education or training of engineers who enter the construction industry and who are likely to take on project management or supervisory roles.

Suggestions for addressing issues associated with workforce competence

In relation to identified causal/contributing factors relating to workforce competence, a number of suggestions were made by industry participants in the focus group consultations and interviews. These are summarised below. First, participants advocated a more stringent licensing system that would consider the experience of workers, as well as their training records. The formal recording of experience (in a log book, for example) was deemed important for ensuring workers have sufficient relevant experience to perform particular tasks. This would also assist employers and principal contractors to verify the competence of workers to operate a particular make or model of crane and/or perform a particular task in relation to the use of cranes at a construction site.

Some participants suggested implementing a tiered licensing system which would reflect a worker's level of experience. Thus, workers could potentially have a probationary period (equivalent to drivers of motor vehicles) during which managers and supervisors would be aware of their limited experience and be better able to manage this, for example, by managing workload expectations, allocating appropriate tasks, providing ongoing skills development and mentoring.

The literature review revealed ongoing debate about the relevance of generic training for crane operators, and the potential need to verify competence specific to the make and model of a crane to be operated. Such verification methods were considered important, and the CICA CrewSafe system was identified as a mechanism that supports effective machine-specific VOC processes.

Participants in focus groups/interviews identified the need for specific training for site engineers and personnel with responsibility for planning for, coordinating, and managing, crane use at a construction site. This would require engagement with higher and tertiary education providers to ensure that crane safety is incorporated into programs for people entering engineering and site managerial roles in the construction industry.

Supply arrangements, communication and planning

Most contemporary models of safety incident causation recognise the importance of organisational issues and management actions in contributing to workplace safety incidents. Analysis of construction accidents reveal that many construction accidents can be attributed to professional or managerial failures arising well before work commences on site, most notably in the planning and design stages (Bomel, 2001; HSE, 2003). The project-based and dynamic nature of construction work present challenges for the improvement of work health and safety, which needs to be considered in the project planning and design stages, when the potential to positively influence WHS has been demonstrated to be at its highest (Lingard et al. 2015). Further an emphasis on 'lowest price wins' tendering processes are reported to negatively impact WHS innovation and improvement (Langdon, 2011).

International studies report that construction contractors sometimes use specialist equipment providers in an attempt to 'transfer' their responsibilities for workplace safety risk, believing (incorrectly) that their responsibility can be reduced through contract lift hiring practices. However, principal contractors maintain a responsibility for the management, coordination, planning and safety of site-based activities. The literature review identified management factors in the procurement, planning, on site coordination, and directing of crane activities, are important in maintaining safe crane operations. The industry stakeholders and subject matter experts who participated in the interviews and focus groups attributed poor or insufficient planning to time pressures associated with delivering construction projects. These were often traced back to pressures put on the principal contractor by the client of a project, that are then transferred to crane operators. This could result in pressures to continue working in adverse weather conditions, poor light, and/or working long hours resulting in fatigue. Such pressures were identified by participants in the focus groups and interviews.

Focus group/interview participants also suggested that a 'fixed price' payment mechanism for crane service providers can have negative safety impacts because delays or disruptions impact upon the 'bottom line' for crane companies. Under fixed price payment arrangements, crane operators may be under greater pressure to work in unsuitable conditions or to work excessive hours to 'get a job done,' enabling the contractor to move to the next job. Participants in focus groups/interviews suggested engaging crane service suppliers/operators on an hourly rate is preferable as this mitigates some of the pressures inherent in fixed-price contracts. Focus group/interview participants also observed crane operators are more likely to experience pressure to keep working and feel unable to stop work in unsafe operating conditions under conditions of 'dry' compared to 'wet' crane hire, as operators tend to be employed under more flexible (and potentially precarious) terms in such arrangements.

Site planning and design factors were identified as having the potential to contribute to crane safety. In particular, effective and early communication between the principal contractor and the crane services provider is beneficial in terms of safety. The literature highlighted examples of poor communication between principal contractors and crane companies, particularly related to design and site management considerations, resulting in serious safety incidents. Participants in the interviews and focus groups observed that, in the Australian construction context, communication between principal contractors and crane contractors is often very good. However, participants also observed that, in other cases, communication can be poor. Given the experience and expertise of specialist crane contractors, there are important safety benefits to be gained from involving them early in discussions and decision-making about the type of crane to be used, site access, site conditions, crane location and lifting methods. In some cases crane contractors indicated that they are called to work at a particular construction site with little notice and no opportunity to visit the site beforehand to gauge the requirements and pre-plan for safe lifting operations.

Finally, participants in focus groups/interviews raised concerns about the operation of WHS management systems in the construction industry and the impact of these systems on crane-related safety. In particular, participants commented that Safe Work Method Statements (SWMSs) are sometimes overly long and contain generic information not specifically relevant to crane operations at a particular worksite; for example, documenting the requirement for basic personal protective equipment. Further, participants argued the volume and complexity of safety-related documentation can discourage workers from reading it. Participants described a 'tick and flick' approach to WHS management in the construction industry as providing a false sense of security that effective safety arrangements are in place. Importantly, participants in focus groups/interviews also observed that task-specific SWMSs can be developed in isolation, relating to activities of one subcontractor or work crew, while crane operations typically affect the whole worksite. Participants observed that safety issues arising from the interfaces between subcontractors, work crews or site-based activities are sometimes not identified or effectively addressed by existing work health and safety management processes, which has the potential to negatively impact the safety of crane operations.

Suggestions for addressing issues associated with supply arrangements, communication and planning

The importance of pre-planning lifting operations (with the involvement of the crane operator, principal contractor, and subcontractors) was identified by focus group/interview participants. This was also recognised in the literature which identified the need to involve subcontractors in decisions relating to the best type of crane to use for specific lifting tasks, and the regular (and frequent) review of the adequacy of lifting arrangements at construction sites (Sertyesilisik et al. 2010).

Participants in focus groups/interviews recommended that industry-accepted standard agreements be developed and instigated for the procurement of crane services. These could include:

- standard clauses identifying responsibilities for safe operation of cranes at a worksite
- clearly articulating in tender documents agreed maintenance requirements and safe operating parameters for using cranes.

Participants believed that such standard clauses would establish clear responsibilities in relation to the safe use of cranes, remove ambiguity about the circumstances in which crane operations should cease in unsafe conditions and ensure that maintenance requirements are understood, planned for and adhered to.

Participants also suggested developing standard templates so that crane operators could document situations in which work should be ceased (for example, poor weather).

The literature review also highlighted the opportunity to use technologies, such as 'back-to-base' data loggers, to:

- capture important data about crane use
- provide operators with objective data to support decisions made about safe operating conditions
- potentially reduce operators' unwillingness to raise concerns or stop work if necessary.

It is important to ensure good communication about design issues, construction processes, scheduling, and sequencing of operations. International crane safety incidents documented in the literature review highlight the importance of communicating important information (particularly when circumstances change) to crane supply companies (see, for example, the incident described in Appendix 1).

Improvements may also be made to site-specific planning documents regarding safety of crane operations to ensure the documents:

- contain safety-critical information about hazards and risk control strategies relevant to crane-related activities
- are easy to read and understand
- address and communicate issues relevant to specific crane use and lifting tasks to be undertaken at a construction site.

The literature also emphasises the importance of conducting a pre-lift meeting, including all relevant parties at a construction site. At these meetings, safe working arrangements for lifting would be agreed on and each party's role and responsibility for safety in the lifting operations would be documented. This idea was supported by comments made by focus group/interview participants who noted the benefits associated with visiting a construction site before deploying a crane. Making such a site visit enables site-specific hazards to be identified and planned for; however, in some instances crane operators indicated contractors' timelines preclude them from making a pre-deployment site visit.

Equipment design, maintenance and use

Many parties have responsibilities for crane safety. These include:

- crane designers, manufacturers, importers and/or suppliers
- crane owners and other persons with management or control of the crane or the workplace where a crane will operate
- competent persons who inspect cranes
- crane operators (SafeWork Australia, 2015).

Thus, crane designers, manufacturers, importers and suppliers have responsibilities to ensure that the cranes they design, manufacture, import or supply are safe to use. They also have a duty to ensure that safety-relevant information is communicated from designers, to manufacturers, importers and suppliers right down to the end user of a crane. Crane owners and persons with control of a workplace where a crane is being used also have responsibilities for making sure that the crane is fit for purpose, is used in accordance with manufacturer's specifications and that maintenance work and examination/testing requirements are met to avoid technical equipment failures.

The literature review revealed that technical equipment failure is a causal factor associated with crane safety incidents with (or with the potential for) the most serious consequences. The analysis of SafeWork NSW crane safety incident data revealed that, after human error, faulty equipment is the most common cause of crane safety incidents, although the number of crane safety incidents caused by faulty equipment fell by almost one half between 2016 and 2018.

Participants in focus groups/interviews identified the standard, reliability and condition of equipment as a causal/contributing factor for some crane safety incidents. Immediate circumstances identified by participants (relevant to the quality or condition of equipment) included the operation of substandard cranes, and structural or electrical failures. The operation of substandard cranes was traced to design and importation factors, generic or poorly written or translated manufacturers' information about crane use requirements, and inadequate maintenance of cranes and related equipment. Inadequate maintenance was linked to industry demand and pressures applied by clients and principal contractors to continue working, which can make maintaining a maintenance regime challenging for crane contractors/companies. The quality of maintenance management is also identified in the international literature as a key factor impacting risk associated with crane use in the construction industry.

Structural or electrical failures of cranes or their components were traced to modifications of crane installations, as well as perceived deficiencies in the enforcement of WHS regulations, compliance with Australian Standards and/or registration, inspection regimes for cranes.

Analysis of the international literature revealed that design-related factors are identified – albeit rarely – as contributing safety incidents involving tower cranes. Equipment design can, therefore, be considered a latent condition in crane safety incident causation in some circumstances.

Suggestions for addressing issues associated with equipment design, maintenance, and use

Industry participants in focus groups/interviews raised concerns about the quality of information (for example, maintenance records) provided about cranes supplied or imported from overseas. The importance was emphasised of checking that imported cranes comply with the relevant Australian Standards.

The literature review also revealed that modifications to crane installations, including replacing component parts with parts not supplied by the OEM, is a risk factor in crane safety incidents. In some jurisdictions, the development of a registering and tracking system for crane components throughout their life has been recommended. Thus, any modifications, repairs or replacements would be recorded, enabling them to be carefully checked by a competent person.

Participants in focus groups/interviews suggested more rigorous application and enforcement of crane safety inspection regimes be implemented. In particular, the literature identified third party crane assessment programs as important. CICA CraneSafe is an example of such a program in which crane inspectors are not employed by entities owning or operating the crane being inspected, so are not subject to commercial pressures to maintain operation. CraneSafe also publishes data on the most frequently found equipment faults for each type of crane covered by its inspection/assessment program, which is useful information when purchasing and managing crane equipment.

Industry stakeholders who participated in interviews raised concerns about the aging fleet of cranes in use in the Australian construction industry. Consideration of the usage of cranes in relation to their design life is recommended. Key stakeholders involved in the research pointed out that the age of equipment (in years) does not provide a sufficiently granular indicator of their usage, which would be related to the wear and reliability of components. In the US, for example, recommendations have been made to collect operational data (potentially via a data logging system) that could be used to more reliably measure the functional age of a crane relative to its design life (Smith and Corley, 2009).

Crane components can also be subject to structural or mechanical failure if the crane is used outside specified safe operating parameters, such as lifting loads too heavy for the crane, and/or working outside load chart limitations. The literature review revealed technologies that can help to ensure safe lifting practices are maintained. In particular, the use of 'back to base' data logging technology was advocated by focus group/interview participants.

Industry and regulatory environment

The construction industry is characterised by the use of long (and often complicated) supply chains, with the majority of site-based construction work performed by subcontractors. Subcontracting is widely reported to create challenges for the management of WHS (Arditi and Chotibhongs, 2005). Loosemore and Andonakis (2007) argue that, although trade subcontractors make up the bulk of the Australian construction industry's workforce and often account for over 90 per cent of a project's value they can "lack the resources, culture and skills" to manage WHS risks effectively (p.580). Wadick (2010) argues poor communication between trades and ineffective consultation between workers and managers in relation to work health and safety increase the dangers associated with subcontracting in construction projects. Further, 'payment-by-results' arrangements under which subcontractors are typically engaged can encourage corner-cutting (Mayhew et al. 1997). The role of the regulator overseeing and promoting health and safety in this challenging industry environment is critical. The research revealed a number of areas in which regulators' actions have the potential to positively impact the safety of crane operations in the construction industry.

The literature review tended to focus on causal/contributing factors in the immediate environment, or circumstances of crane safety incidents. However, some studies did consider industry-level systemic factors as contributing to crane safety incidents. These included competitive pressures within the industry, the internationalisation of construction markets and features of the regulatory environment, including inspection/enforcement regimes and certification requirements for crane use.

Analysis of SafeWork NSW historical incident data also focused on more immediate circumstances of crane safety incidents. However, the analysis did suggest some systemic issues at play. For example, PCBUs that own at least one registered crane are significantly more likely to be involved in a crane safety incident if they have a history of receiving two or more notices in SafeWork inspections prior to the incident. Thus, a track record of WHS compliance issues with WHS legislation is a predictor of future crane safety incidents. This suggests providing additional support to construction organisations or worksites at which WHS compliance issues are found may be an effective 'early intervention' strategy for preventing crane safety incidents.

Focus group/interview participants made comments about regulatory behaviour, suggesting the announcement of inspections before the event reduced their effectiveness in ensuring the safety of crane activities. Participants commented that worksite inspections are sometimes announced prior to their occurrence and the operations of smaller crane operators (particularly in the case of mobile cranes) may not be subject to inspection. Potentially this creates an inspection/enforcement gap in which cases of non-compliance may not be identified.

Participants also commented on the current 'overheated' construction industry market as contributing to long working hours and fatigue: crane companies are put under considerable pressure by principal contractors who, in turn, are under pressure to meet clients' construction project programs. Combined with a shortage of skilled and experienced personnel, this was perceived to be a 'perfect storm' among focus group/interview participants who observed that less experienced workers are operating under increasing work intensity, in a context in which equipment maintenance is sometimes deferred and irregularities are overlooked in the interests of maintaining project progress.

Suggestions for addressing systemic industry factors

Focus group/interview participants suggested the level of enforcement of crane-related safety requirements should be increased. Using crane registration and location data to inform proactive (and unannounced) inspections of worksites was suggested. However, in relation to the use of mobile cranes, a mechanism for capturing the start and finish dates at which cranes would operate at particular locations would be required.

Participants also suggested the regulator could play a stronger mentoring/advisory role in providing advice and guidance about how to prevent safety-related incidents involving cranes. The model of crane incident causation developed in this report is one mechanism the regulator can potentially use to leverage the advice provided about factors to consider when managing risks associated with crane use at construction sites. However, given the identified impact of competitive pressures and the multi-layered system of contracting and subcontracting, targeted advice should be provided to construction industry participants whose actions (or omissions) could impact on the safety of crane activities, from clients and principal contractors through to designers, large subcontractors who use crane services, and crane companies. Improved communication and coordination between stakeholders have the potential to improve safety in crane activities. For example, integrating specialist knowledge about lifting operations into decisions made during the design stage of a construction project has the potential to reduce WHS risks at the source, through designing for safe construction.

It is important that all relevant industry stakeholders understand the role they can play in ensuring safety in crane use and lifting operations at construction sites.

Crane safety incident causation and prevention

Workplace safety improvements are shaped by knowledge and assumptions about how accidents happen (Gibb et al. 2014). Understanding how accidents occur is important in order to distinguish between factors that are relevant and require some action, and factors that are unimportant and can be ignored (Swuste, 2008). However, compensation-based surveillance systems may not capture sufficient information to be used effectively for prevention purposes. Safety incident causation models 'represent, classify and efficiently organize' safety-related knowledge and provide a theoretical framework for the investigation of incidents and the identification of hazards present in a workplace' (Arboleda and Abraham, pp. 274–5). Hollnagel (2002) argues that incident causation models can make safety communication and understanding more efficient.

The crane safety incident causation model developed in the qualitative component of the research provides an evidence-informed taxonomic framework that can support the analysis and understanding of factors causing or contributing to crane safety incidents in the construction industry.

The model extends the consideration of causal factors beyond an incident's immediate circumstances. It identifies site management issues as shaping factors in crane safety incident causation, and factors in the broader construction industry and regulatory environments as originating influences with the potential to contribute to crane safety incidents.

Proposed uses for the crane safety incident causation model

It is proposed that the crane safety incident causation model be used in two ways.

First, the model can be used to guide crane-safety incident investigation and analysis. In providing a series of prompts and guidewords, the model can be used to identify the immediate circumstances surrounding a crane safety incident, and trace these immediate circumstances to the shaping factors and originating influences that lie at their 'root cause.' The guidewords and prompts provided by the model are likely to produce a greater degree of consistency, and reduce the chance that important factors may be missed in such analysis. They also provide a basis for the quantification (and potential ranking or weighting) of factors in the future. This could be based on a retrospective analysis of incident data or further expert analysis. The use of the crane safety incident causation model as an investigation tool has the potential to prompt participants to consider factors operating at deeper levels within the system of work than the immediate circumstances of an incident (that is, shaping factors and originating influences). It is also likely to produce greater consistency in the classification of causal/contributing factors[11].

Second, the model could be used to inform an analysis of risk factors inherent in construction activities in which cranes are to be used. In this way, the model could be used to identify relevant factors that should be considered when planning for crane use in a particular context. Understanding these factors, and the ways they can 'play out' to impact the safety of crane use, has the potential to improve the quality and consistency of risk identification and management, and to ensure appropriate controls are identified for crane-related activities.

11 Over time, and as the model is used, it is likely that new causal/contributing factors will be identified. Thus, the crane safety incident causation model should be regarded as a 'living' document.

Conclusion and key findings

The research revealed that factors that cause or contribute to crane safety incidents operate at different levels within the prevailing work system in the construction industry. The literature review identified the following as causal or contributory factors to crane safety incidents:

- the regulatory environment
- prevailing levels of worker skill and competency
- industry supply issues
- site planning and management issues
- physical worksite conditions
- human errors and equipment failures.

These factors were also identified by Australian construction industry stakeholders and representatives in the qualitative component of the research.

Data collected from these stakeholders and representatives was subjected to a systematic analysis process to create cause-effect trees. These trees formed the basis of the development of a bespoke crane safety incident causation model. It is suggested that this model be used as a guide to incident investigation, as well as a tool to communicate crane safety issues and inform risk assessments related to crane operations in the Australian construction industry.

Participants in the focus groups and interviews also identified opportunities to improve crane-related safety in the Australian construction industry. Industry experts consulted in focus groups/interviews also identified strategies that could assist in preventing safety incidents involving cranes. Suggested strategies fell into seven topic areas, as follows:

- training and competence
- development of a code of practice for crane operations
- communications and awareness raising
- the role of the regulator
- design and import issues
- technology use
- procurement and the management of commercial relationships.

It is recommended that these suggestions be explored further, in consultation with a broader range of stakeholders, to develop short, medium and long-term actionable measures that will improve the safety of crane use in the Australian construction industry.

Appendices

Appendix 1. The Bellevue crane incident

In November 2006, a 210ft overhead tower crane overturned at a building construction site in Bellevue, WA. The incident led to the death of a bystander, injury to one worker, and damage to three nearby buildings. The crane operator was trapped in the cabin and was eventually rescued by firefighters. The crane had been in use on site for about 2 months when the incident happened. At the time of the incident, wind speed was negligible and there was no load on the hook.

Due to site restrictions, a steel frame had been designed for the crane base. The frame comprised two girders and two beams attached to existing concrete columns which supported the crane above existing post-tensioned slabs.

Incident investigations concluded the crane base was under-designed. Based on the early information received from the crane supplier, the designer had used structural ties between the building core and the crane tower to bear the crane overturning moments. Therefore, these moments were not considered in the crane base design. The ties were subsequently eliminated by the contractor due to a delay in the core construction. However, the base design had not been modified to accommodate this change. This issue was attributed to a major miscommunication between the contractor and the designer, as well as severe time pressure which led to simultaneous design and fabrication of the base.

The structural collapse was initiated by fatigue cracking at the connection between one of the beams and the girder. The designer had used a standard design for the connection. However, due to space restrictions the beams were coped at both ends, but the web stiffeners on the beams were truncated and mislocated causing stress concentration at the connection points. This design issue was combined with the large moments which, with the elimination of the ties between the crane and the building core, were exerted to the base frame during the crane operation. Consequently, fatigue cracks developed at connection points. This further compromised the structural adequacy of the base to resist forces due to crane overturning moments, and eventually led to structural collapse and crane overturn.

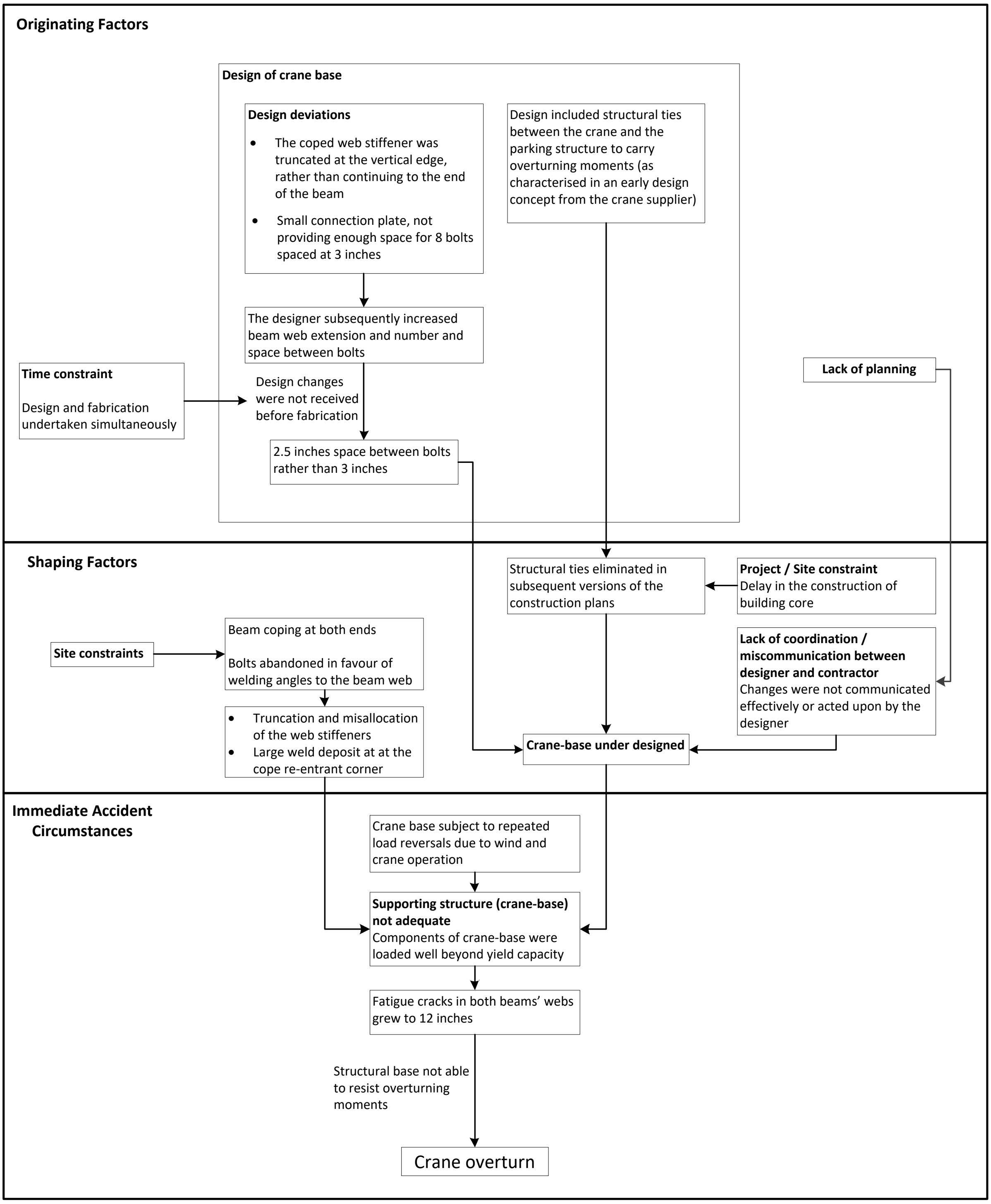

Figure 21. The Bellevue crane incident. Based on McDonald et al. 2011.

Appendix 2. A fatal mobile crane incident

A rough terrain hydraulic mobile crane, with a lifting capacity of 20 tonnes, was lifting a section of a new high-voltage electricity transmission tower. The project had been underway for almost a year. The tower was made of five sections. The crane had already lifted two sections and had started lifting the third section. The tower section was made from steel, with a 3m by 3m section and 10m long. The crane was attempting to stand up the section by lifting one end of the section while the other end remained on the ground. During the lifting process, when the end of the section was approximately 5m off the ground, the section unexpectedly fell. One of the crane crew, who was holding a guide rope and standing directly underneath the load, sustained severe injuries and died when he was struck by the tower section.

The crane was bought secondhand and imported to Australia. As part of the importation process, approvals were obtained from various government departments and the crane was inspected to ensure its compliance with Australian standards. The crane had two winch drums, one to hoist the main (larger) hook block and the other to hoist an auxiliary (smaller) hook block. At the time of the incident, the auxiliary winch was in operation.

The crane had been fitted out with a 'free fall' system. The free fall mechanism could be engaged using two toggle switches, one engaging the free fall function on the main winch (denoted by a 'M' sign) and the other engaging the free fall function on the auxiliary winch (denoted by a 'S' sign). Beside the switches on the controls panel, the signs indicated two positions, 'Free' and 'ON'. According to the crane manual, the free fall function would be engaged on each of the two winches when the relevant switch was put into 'Free' mode. The 'ON' position, on the other hand, denoted that the free fall mode was disengaged (that is, the winch clutch was engaged). When the switches were in an 'ON' position, a green light indicator would turn on. The winches would not go into free fall by only putting the switch into 'Free' position. Multiple steps were involved including: lightly pushing down the auxiliary winch brake pedal, putting the switch into 'Free' mode, pushing the brake pedal further down until a shudder is felt, and slowly releasing the pedal until the auxiliary hook goes into free fall.

The Queensland Mobile Crane Code of Practice (2006) requires that free fall function on mobile cranes be locked out with a 'keyed lock out'. For this particular crane, a 'lock out bar' had been attached to the control panel, horizontally across the switches, to prevent the free fall toggle switches moving into the free fall mode. The lock out bar had been screwed to the panel at both ends. Investigators considered this a simplistic solution in comparison to using a lock out bar which is more tamper proof than a screw type bar.

During the incident investigation, it was found that the lock out bar had been attached to the incorrect side of the toggle switches, actually preventing the free fall function from being disengaged. The crane operator was unaware the crane was in free fall mode. He had never been shown how to engage the free fall function, and he had thought it was not operational.

Although the crane had undergone several major and minor repairs, services and inspections since the lock out bar was installed, the bar's incorrect position had not been identified.

As post-incident tests revealed, since the switches were already locked into the 'Free' position, an inadvertent push on the brake pedal, which was adjacent to the winch pedal, could get the auxiliary winch into free fall. In addition, a warning buzzer, which was supposed to go off just before the free fall, was not heard during the test. Once the crane got into free fall, the operator would have had inadequate time to brake and stop the free fall.

The incident investigation concluded the incorrect installation of the lock out bar was a contributor to the incident, although no direct causal relationship was proven. It was acknowledged that the features on the control panel with the use of words 'Free' and 'ON' were confusing. Although, the crane manual explains these words and the process of engaging the free fall function, the evidence suggested the lock out bar had been installed without any regard for the manual. Similarly, the crane inspections were undertaken regardless of the crane manual and it was assumed the free fall function was not operational. The non-functional auxiliary winch light and warning alarm had perhaps contributed to engagement of the free fall function being undetected. Furthermore, post-incident inspections concluded there was no mechanical fault to the winch. Thus, most likely, the winch had gone into free fall due to an inadvertent brush against the pedal by the operator, while the free fall system had already been engaged and was in a standby mode due to the incorrect position of the control switches.

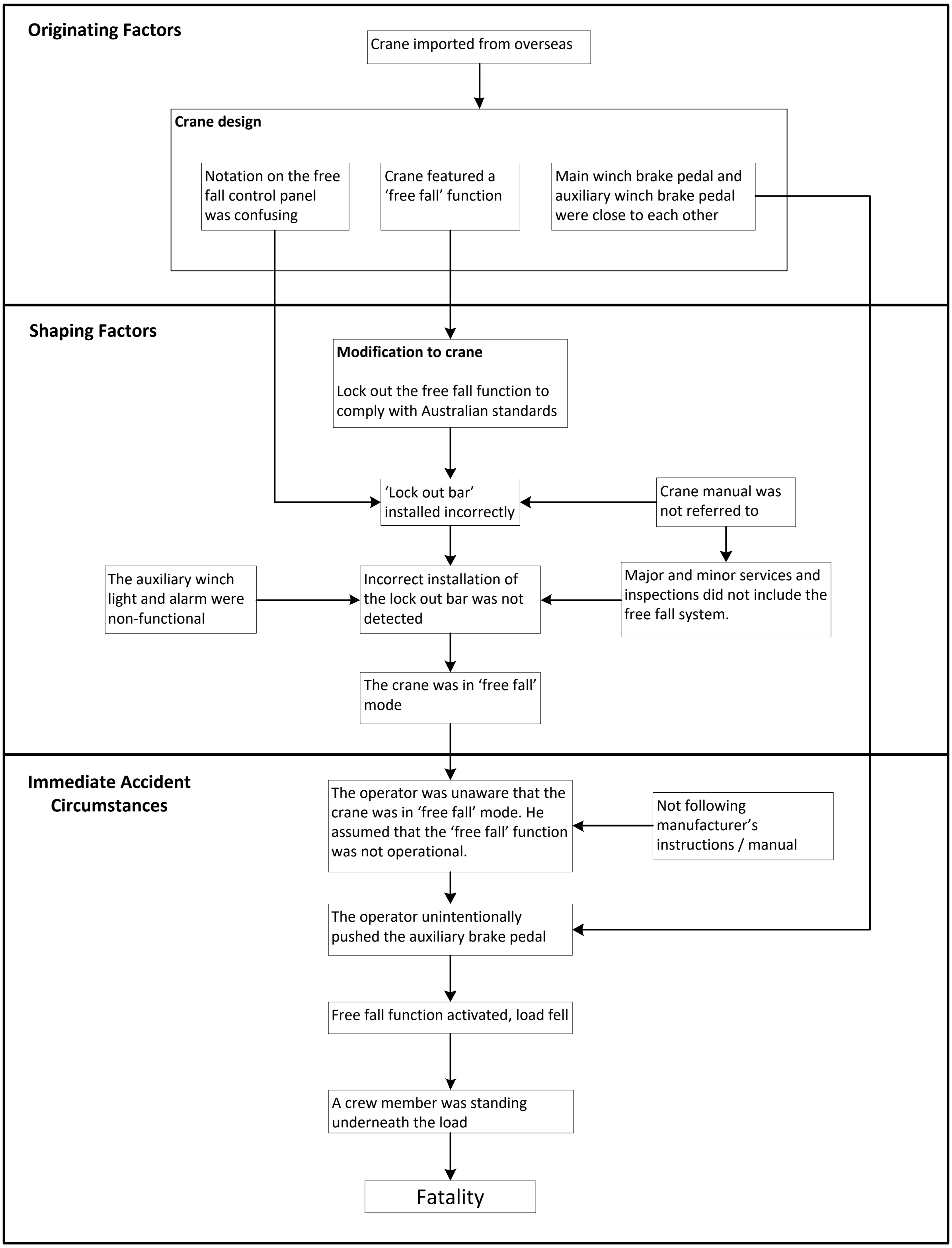

Figure 22. A fatal mobile crane incident.

Based on a report produced by the Queensland Office of the State Coroner.

Appendix 3. A tower crane incident

In March 2008, a luffing tower crane collapsed in New York City, killing seven people. The crane mast was laterally supported by steel beam ties connected to the building's structural slabs at the 3rd and the 9th floors. The ties at each floor consisted of three wide flange beams fastened at one end to the building floors, and at the other end pinned to a square steel collar surrounding the mast of the crane. The tie beams on the 3rd and the 9th floors were installed using a mobile crane at the time of the crane's initial installation. The employees were installing the tie beams on the 18th floor without using any mobile crane. This was the first time the employees were installing the tie beams in this manner by using the crane itself.

Workers had increased the height of the crane by inserting four additional tower sections about an hour before the incident. This had occurred with no problems. The crane was then placed back in operation. At the time of the incident they were adding another lateral 'tie-in' collar to support the crane tower at the 18th floor level. Connecting the crane mast to the 18th floor slab through the tie beams to provide lateral support involved the following process:

- Erect a steel collar around the crane mast by suspending it from the mast steel members above the collar. During this operation, the collar would not be physically connected to the mast but could have an approximate gap of 2 inches between the collar and the mast.
- Connect the collar to the 18th floor by three tie beams. One end of the tie beams would be fastened to the structural floor slab, and the other end placed in the collar pocket and pinned.
- Finally, re-plumb the crane to eliminate the gap between the collar and the mast by tightening the blocks to provide a tight fit. There would be no positive connection between the collar and the mast. The tie beams were to transfer lateral loads only, and not gravity loads.

The construction company had approval to raise the crane. The crane had been inspected the day before the incident with no violations found.

The collar weighed approximately 11,200lbs and came in two halves. The collar was fabricated by the crane manufacturer two years prior to the incident.

Approximately one hour before the incident, the crane hoisted the first half of the collar, weighing approximately 5,600lbs, and brought it near the 18th floor. Each half of the collar was equipped with six lifting lugs from which it could be supported. The crane hoisted the first half of the collar on the east side of the crane mast. As the hoist approached the crane mast, the employees using the tag line positioned the collar by hanging it at northeast and southeast corners by two 2-inch wide polyester slings choked around the column flanges and the steel angles of the K-braces.

Each sling was attached to a come along which, in turn, was connected to chain fall fastened to the collar lifting lugs.

In a similar manner, the other half of the collar was then brought by the crane on the west side of the crane mast, again lifting at lugs. This half of the collar was also hung by two 2-inch wide polyester slings on the northwest and southwest corners using the same arrangement described above. When both halves of the collar were levelled and plumbed, the two halves were bolted together with four bolts on the north side and four bolts on the south side.

There were no reported problems to this point. The employees then began to place tie beams into the collar. At the northwest end, there were two tie beams to be placed, and on the northeast side one tie beam was to be placed. At the time of the incident, only the east tie beam, still supported by the crane, was placed in the pocket of the collar, but the pin was not yet placed when suddenly the employees heard a popping sound. Then the employees heard another popping sound followed by a third sound.

The Occupational Safety and Health Administration (OSHA) investigation revealed a sling failed under load, allowing the unattached collar to slide down the tower and crash into a building 'tie-in' collar at the 9th floor level of the building. The two loose tie-in collars then crashed into the supporting collar at the 3rd floor level. This was not ripped out but supporting braces were broken. The lack of lateral ties transformed the crane mast into a free-standing structure with no lateral support above the 3rd floor. The counterweights of the crane were facing away from the building and so were effectively pulling the crane away from the building. The loss of the tie-in supports permitted the mast section to rotate and fall away from the building. The upper tower sections fell onto a lower neighbouring building. The top of the crane separated from the mast during this and fell to the ground.

The OSHA report revealed that four synthetic slings were used to support the collar and, if choked properly and in a good condition, these slings would provide an ultimate failure capacity of approximately 20,000 pounds. Given the weight of the collar at 11,200 pounds, the four slings, if all are supporting the collar weight equally, would provide a factor of safety of approximately 7 or more. However, if the slings were not choked properly, and if one of the four slings failed, the capacity of the remaining slings would be greatly reduced. All four slings failed in the incident, with each sling shearing in two pieces.

It was also acknowledged that none of the slings were protected against sharp edges of the column legs and the steel angle legs. OSHA proceeded to determine whether the slings placed in the V-shaped crotch could have a significantly reduced capacity to support the load.

OSHA engaged a sling expert to examine the sling remnants and provide an opinion on the failure of the slings. After microscopic examination of the fractured surfaces of the slings, the tests indicated that the slings failed at loads significantly lower than their ultimate capacities due to contact with edges of the wide flanges. OSHA was most interested to determine the load carrying capacity of the slings when trapped in a V-shaped notch with sharp edges of the crane mast legs and the steel angles of the braces.

Further tests were undertaken to replicate the actual manner in which the slings were used at the time of the incident. Twelve slings (made by the same manufacturer as those involved in the incident) were tested. They were choked around the column flange and trapped in the V shape. It was concluded that under sustained load, the slings failed at approximately 7,100 pounds, significantly lower than 20,000 pounds (5,000 pounds x factor of safety of 4.0 = 20,000 pounds). The failure was also preceded by popping sounds similar to what the employees had described hearing before the incident. The testing also showed that elongations of the slings was not consistent suggesting the collar must be levelled by using come alongs as it is being lifted. If the levelling is not undertaken at all four corners, and if the collar is permitted to dip at one corner greater than at other corners, then the load of the collar might be taken by only two slings instead of four. This would double the load on the supporting slings.

Post-incident examination of one of the slings used in the lifting revealed the sling was already frayed and deteriorated, even before it was used to support the collar. The situation worsened when the sling was choked around the column, forcing it into a V-shaped groove. Degradation and damage to the sling was so great the expert suggested it should have been discarded and not used.

Further, the installation process deviated from the manufacturer's guidelines. The lifting points used did not correspond with manufacturer's instructions. When the collar was positioned around the crane mast, the employees had no alternative but to suspend the collar in a way that meant the slings were choked around the column (into a V-shaped groove). This reduced their load carrying capacity. If the collar had been supported in the manner recommended by the manufacturer, the slings would have had adequate capacity because they would have been supported from steel members directly above the collar. Furthermore, according to the manufacturer, each half of the collar should be supported at four points instead of two. If the instructions contained in the drawing were followed, the collar would have been supported at eight locations (rather than four), until the two halves were bolted together.

The City of New York's Department of Buildings also conducted an investigation and issued a report one year after the incident. The main findings were as follows:

The collar section being lifted was suspended from the tower at only four points, contrary to the manufacturer's recommendations, which require the use of eight points.

The points on the collar from which it was suspended from the tower were not intended for that purpose by the manufacturer.

The synthetic slings used to suspend the collar were choked around the tower in a manner that is not in accordance with industry practice, and which reduces the strength of the slings. Specifically, the slings were not protected from the sharp edges of the vertical tower members, and the slings were bunched and edge loaded in a V-shaped area.

One of the four slings was in a deteriorated condition and should not have been used.[12]

OSHA's conclusions in relation to this incident were similar:

The choice of using polyester slings to suspend the collar at four points was questionable as they are subject to large elongations under tensile loads, creating a need to constantly monitor and level the collar.

The collar was rigged improperly in that the slings used to suspend the collar were choked around the vertical legs of the crane mast and was seated in the V-shaped groove between the angle bracing and the flange of the crane mast leg. This significantly reduced the load carrying capacity of the slings.

The slings were not protected against sharp edges for cuts and abrasions.

A deteriorated sling, which should have been discarded if proper inspection of the sling was done prior to its use, was used to suspend the collar.

The crane raised the collar from the ground, hoisting it at locations different from the crane manufacturer's recommendations. This led the employees to suspend the collar from locations above which there were no horizontal members. This resulted in choking the slings around the legs of the crane mast.

Each collar half was suspended at two points instead of at four points as recommended by the crane manufacturer.[13]

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12 https://www.ishn.com/articles/87959-report-improper-rigging-operations-caused-fatal-new-york-crane-collapse-3-17
13 https://www.osha.gov/doc/engineering/2008_r_02.html

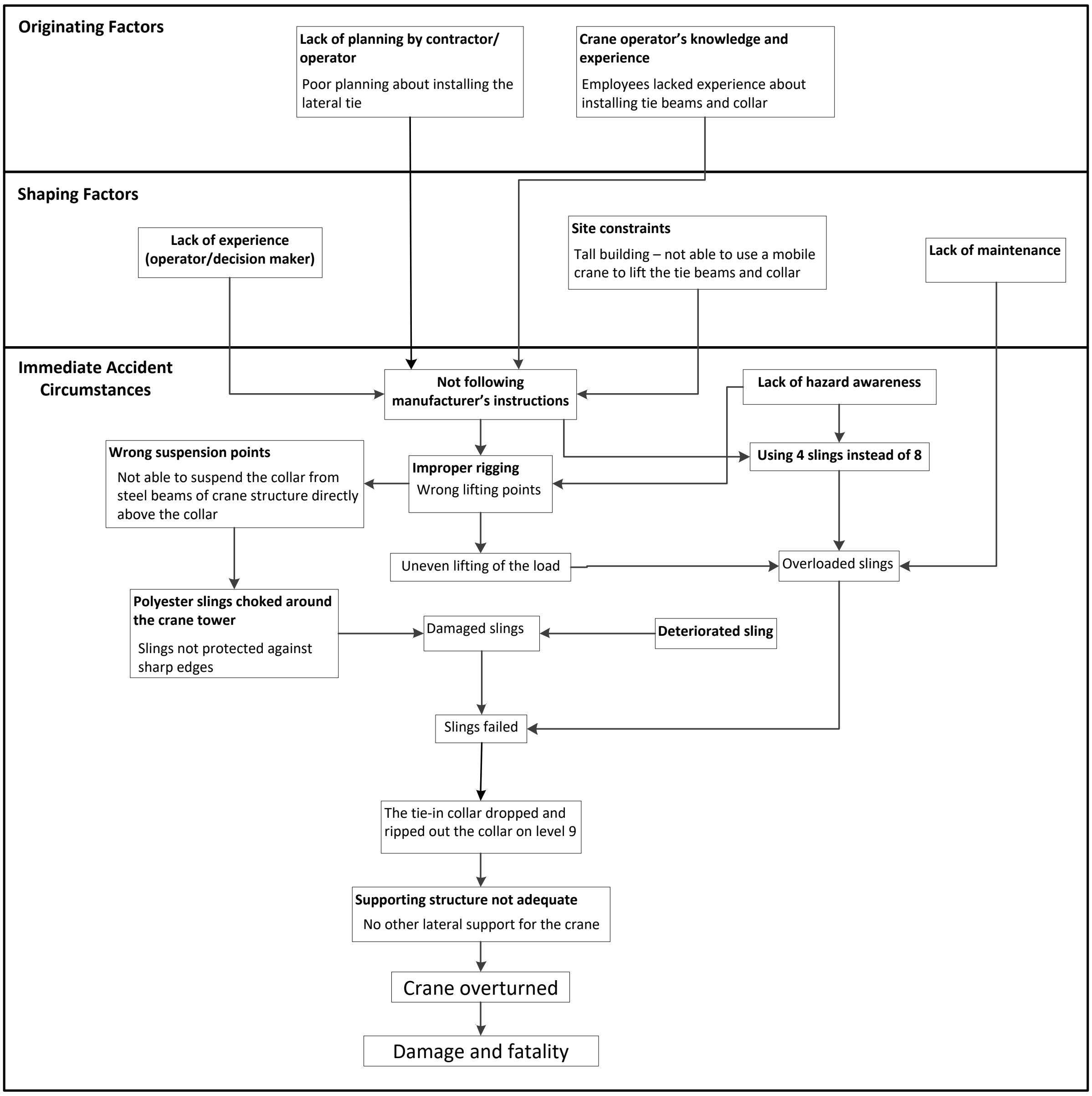

Figure 23. A tower crane incident

Appendix 4. A mobile crane incident

A 500-ton mobile crane collapsed while repairs were being made to a cathedral building that had sustained damage in a recent earthquake. The contractor appointed to undertake the repair work decided to erect a scaffold system on the roof of the cathedral's centre tower to access damaged ornamental/decorative components. The centre tower's roof height was approximately 320ft, so to build the scaffold system the contractor needed to use a crane to transport scaffold pieces and structural beams to roof level. A crane company was engaged to assemble the crane and undertake the lifting operation.

While lifting the scaffold components amid thunderstorms and heavy rain, the mobile crane collapsed. The crane's telescopic boom was 152ft and the attached lattice jib's length was 276ft.

The crane tipped, overturned and fell its full length along a road adjacent to the building. It damaged three parked vehicles and a historic building. The crane operator sustained non-life-threatening injuries. The incident had the potential to cause significant loss of life and damage.

The telescopic mobile crane was relatively new at the time. It was a seven-axle mobile crane equipped with a telescopic boom and a lattice jib. Three months before the incident the crane had been load tested and certified by a competent person.

Four days before the incident the crane was positioned adjacent to the cathedral. The four outriggers were extended and the pads were lowered onto the pavement. The rear right outrigger pad was positioned near a catch basin, 15ft away. This was a masonry structure constructed more than 100 years ago.

The crane commenced work the day after it was assembled. After a few lifts (of approximately 3,200 pounds) the operator and others observed cracking in the asphalt pavement at the rear right outrigger pad. Cracking continued the following day, causing a settlement of a quarter of an inch at the right rear outrigger pad.

The crane company placed two 12-inch thick timber mats, 32ft long and 4ft wide, side by side on the asphalt, and added an 8ft by 9ft steel pad between the mats and the rear right outrigger pad. The purpose of the mats and the steel pad was to uniformly spread the load over a larger area and minimise any additional settlement.

The following day, after performing the daily inspection, the crane operator set the 152ft long telescopic boom to 82 degrees. The attached lattice jib length was 276ft. A lift was made carrying 3,200 pounds of scaffold components without any problem. The next load was steel I-beams that weighed 8,600 pounds. The load was rigged and delivered to the roof of the tower (approx. 320ft high). As the load was being released on the roof, intense lightning and rain began. The weather obscured the view of the jib from the operator's cab.

The load was released and the operator raised up the hook to clear the cathedral tower. The operator then swung the boom and jib counter-clockwise to the west and began luffing the jib down to a lower angle to let the storm pass by. The operator argued that, because it takes approximately 20 minutes to telescope the boom inward due to the crane's 12-part pulley system, he decided not to telescope the boom inward. Instead, he lowered the jib to near zero degrees and lowered the boom to approximately 68 degrees to minimise risks from possible lightning and thunderstorm activity.

The operator reported feeling a sudden vibration of the crane after which the boom began to fall and the counterweight rose until it almost stood vertical. The counterweight then rotated, hit the pavement and the timber mats supporting the outrigger, and pierced through the pavement. The north counterweights became separated from the crane and fell off. The counterweights on the south side remained connected.

An OSHA investigation determined that, when the telescopic boom reached an angle of 63 degrees to the horizontal, and when the jib was nearly horizontal, the overturning moment of the crane was 8,000,000 ft-pounds. The stabilising moment at this position of the crane was computed to be 7,980,000 ft-pounds, and hence the failure.

The load chart provides the maximum permissible load that can be hoisted at various working radii. Working radius is defined as the horizontal distance from the centre of the turntable to the vertical axis of the load being hoisted. Furthermore, the telescopic boom angles at which permissible loads are provided at different radii are also given. At the time of the collapse the crane had a working radius of 344 feet. This was beyond the allowable radius provided in the load chart which did not go beyond 260 feet, with the boom at an angle of 75 degrees. Moreover, in the load chart applicable to this crane, only two angles for the telescopic boom were provided (that is, 82 and 75 degrees). So, the boom could only be operated between angles of 82 and 75 degrees. If the boom was at an angle greater than 82 degrees or at an angle lower than 75 degrees, then the crane would be in violation of the load chart, and a failure could be imminent.

At the time of the collapse, the overturning moment was greater than the balancing moment due to the larger radius and lower angles of the boom and the jib. Even though the crane was not hoisting any load at the time of the incident, the weight of the headache ball and the riggings were enough to create instability at a radius of 344ft, resulting in the crane overturning.

This was verified by data retrieved from the crane's data logger that provided insight into the actual configuration: that is, the angle of the boom, the angle of the jib, the crane platform's orientation, the load at the time of the collapse, the utilisation ratio, and the outrigger reactions. The crane collapsed at approximately 11.00am, which coincided with measurements of the vertical angle of the boom falling from 70 to 68 degrees, and the vertical angle of the jib falling from 4 to 0 degrees. Shortly prior to the collapse, at 10.44 am, the jib was at an angle of approximately 51 degrees and was then well within the load chart. At 10.52am the crane jib was suddenly lowered, at which time it was operating outside the load chart. At this stage it appears the crane was automatically shut off. However, at 10.56am the crane began to operate once more. It is not clear why this happened but one explanation (denied by the operator) is that the operator by-passed the crane's automatic shutdown mechanism. At 11.00am the crane's data logger shows that the front-left outrigger pad had lifted. The collapse followed immediately.

The crane operator denied hearing any warning in the cabin, but the data logger suggests he was able to continue operating the crane for some 8 minutes after it was outside the load chart.

The OSHA analysis revealed that if the operator had maintained the boom at 81 degrees and the jib at 22 degrees, the incident would not have happened, despite the raging storm.

OSHA concluded that the right rear support of the pad settled approximately 6 inches before the incident but did not cause the collapse. Its contribution to the collapse was minimal. If the crane had been operated within the load chart, the collapse would not have occurred despite the settlement.

Further, OSHA reported the wind speed at the time of the collapse was approximately 15 miles per hour with no appreciable gusts. Therefore, wind did not cause the collapse.

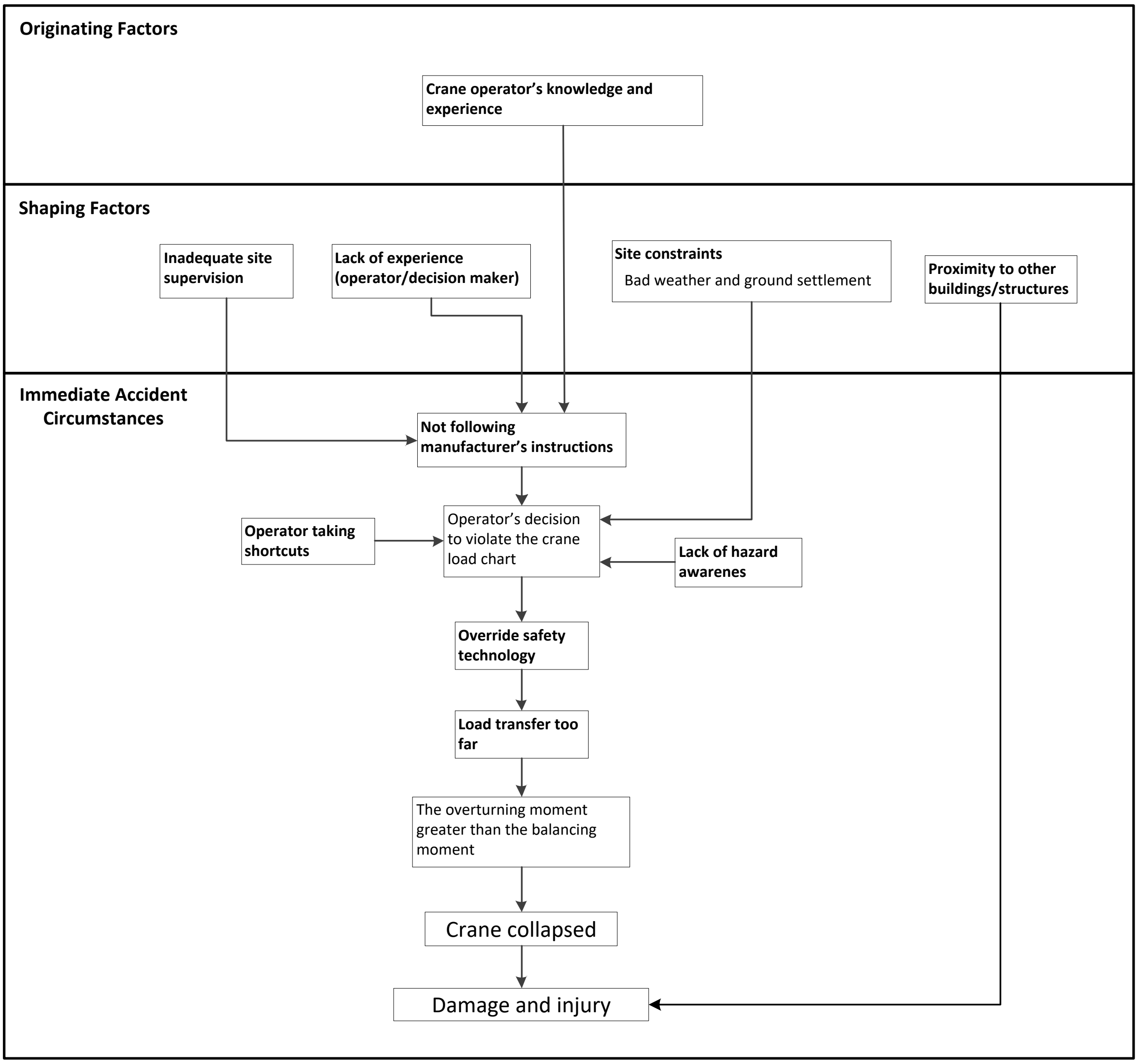

Figure 24. A mobile crane incident.

Source: https://www.osha.gov/doc/engineering/2012_r_02.html

Appendix 5. Crane incident causation analysis table

Level	Issue	Definition	Quote(s)
IMMEDIATE CAUSES	Working in unsuitable weather conditions	Working outside in conditions that are not suitable. Conditions may include, but are not limited to, storms, wind, rain and excessive heat.	I think more people being aware of what damage the wind can do, especially customers. Understanding how much we can go with the wind. And the danger… cranes are designed to lift straight up and down, not drag sideways and that sort of thing. So, weather and wind and rain can be horrendous for the guys that are working outside in it. Especially they get you on site and they say they want you to wear safety glasses, and the doggies are trying to look after them, and they've got rain come on their safety glasses, and they can't see because the portable lights are blinding their eyes, and they're trying to plumb the load up… so weather and wind and rain can be horrendous for the guys that are working outside in it.
	Lighting/visibility	Adequate lighting and visibility are important to the safety of crane operations. This issue particularly relates to night work or work in poor lighting.	The lights can be a pain because if they're facing the wrong way, if they're blinding you, sometimes you can't see. Tower cranes, we don't like them doing them at night, but you end up running into darkness a lot of the time especially in winter.
	Not following manufacturer's instructions	Crane manufacturer's instructions contain specific information about product specifications, erection and dismantling instructions, and maintenance requirements. Without this information, workers may not understand how to safely assemble/disassemble or operate a crane.	Then go to [project name] where the process is that a crane basically is getting dismantled and the processes of following the actual manufacturer's guide how to pull it apart wasn't followed. Not all of them are computerised and have all the gizmos on them to stop you lifting or whatever. So the technology is not the same on them all, so you can have operators that over lift and do things with them that they shouldn't do.

Level	Issue	Definition	Quote(s)
	Hazards not identified	Crane activities in a construction site context present a range of safety hazards. Being able to identify these hazards and respond appropriately to them is important for safe working.	… you always have a visual. If it's on some sort of concrete slab beside a building and you can see cars going around underneath, close, you will go down and have a quick little look to see what's under there, you know? But it's like driving across a football field. If you go into a job where you've got to drive across the Sydney cricket ground, we know, we've been in there before, we can do it. But, if it's wet, that's a hard judgement, you've got to take that call. Yeah, it's hard. I guess from a risk management point of view, the risks are constantly changing, because no day is ever the same. The environmental risks on site are always changing and always need to be reassessed.
	Lapse of concentration	A lapse in concentration can affect the way in which work is undertaken. Being distracted can lead to errors and safety incidents when performing high risk work such as crane operation.	
	Existing soil conditions not considered	Ground conditions vary from one workplace to another and even within a single workplace. Failure to address poor ground conditions to ensure a crane is stable can cause the crane to overturn.	Because it's all a below ground hazard that… unless you get a geotech sign off on it, it's a – you might still have those incidents, but at least we've done – People think that just because they did it at the start of the job, that they don't have to continually do it. You have to.

Level	Issue	Definition	Quote(s)
	Changes to ground conditions when it rains	Weather conditions can also impact ground conditions. The stability can also be reduced by the soil drying out due to hot and sunny weather. Undertake a suitable and sufficient site investigation after weather events to determine the nature of the ground conditions. Monitor groundwater and soil saturation levels.	…the changing ground conditions because we put in project conditions, but what was there yesterday might be different to what is there today.
	Crane position where services are located below/above	Contact with overhead powerlines can pose a risk of electric shock or electrocution when operating the crane. It can be difficult for crane operators to see powerlines and to judge distances from them. Equally important is to identify underground services and nearby excavations.	So the other thing that occurs on those sorts of sites is that they quite often set up over underground services. Because it's only short duration work they don't do 'dial before you dig.' They strike power lines regularly because they work in close proximity to power lines. They're all aware that power lines are a major issue but of course, as I said before, they get a phone call the day before, they turn up next morning, they have a quick look, they decide where the set-ups going to be which is usually somewhere between the footpath and the base frame of the building.
	Supporting structure not adequate	Prior to setting up a crane on site, the structure supporting the crane should be reviewed in a risk assessment process to determine whether the structure is suitable.	If it's on some sort of concrete slab beside a building and you can see cars going around underneath, close, you will go down and have a quick little look to see what's under there, you know?

Level	Issue	Definition	Quote(s)
	Loads being carried too heavy for the crane	If a crane is overloaded, a structural or mechanical component may fail or the crane may overturn. The lifting capacities of cranes are specified on a load chart. They should not be exceeded, except during load testing of the crane by a competent person under controlled conditions.	What about the lack of availability, so it might not be the right crane for the right job. So, you can't get the one you want and you're going to wait three months but the project's got the green light so they just whack up a remote control one, without naming brands. … rather than, say, having a 130-tonne crane put here, they need – because of their lack of real estate – they need to try and do it for a 60 tonne in the corner. It's not the right crane for the job.
	Load transfer too far away	The counterweight, the support structure, and the stability of the boom are affected by the distance from the load's origin point to the base of the crane. The rated load weight also varies based upon the distance from the crane's base to the load at the end of the boom or jib.	… if you have to pick up 10 tonnes at 10 metres radius, that may only be 80 percent of the capacity of the crane. So, you've got an extra 20 percent to deal with the other swiss cheese variables. But if you order in a 60-tonne crane, the 60-tonne crane might be cheaper to get there, cheaper to operate, so on and so forth, but that's 10 tonnes at 10 metres. So, the load or the position of the crane don't change, but your capacity, you might be lifting at 90 percent or 95 percent of capacity. So, you're still within the capacity of the chart, we'd advocate every day that you are allowed to lift to the chart, but that reserve that's left is only five percent not 20 percent.
	Crane too small for tasks being performed	Different crane types suit different project needs. Choosing carefully will ensure the right crane for the job is selected.	… rather than, say, having a 130-tonne crane put here, they need – because of their lack of real estate – they need to try and do it for a 60 tonne in the corner. It's not the right crane for the job.

Level	Issue	Definition	Quote(s)
	Unfamiliar with plant being operated	Workers in control of cranes need to be competent to use it safely. This includes having the correct skills, knowledge, experience, and risk awareness. This should be specific to the crane type, make and model.	Going further, too, with that experience is different cranes, different operation modes, different procedures.
	Negative interaction between adjoining tasks/activities on site	It is common for a number of trades to be performing activities concurrently at a worksite. If consideration is not given to interdependencies and interrelated safety issues, unanticipated hazards can arise.	I was just going to say, it's particularly the layout and this is why you're talking about is it causing you accidents. It's restricting slew, which direction, where you can slew, what you can slew over. It’s more being landlocked. So if you haven’t got the planning for the radius to either weathervane or where you can’t weathervane because you’ve got another building. Or, if you’ve got another crane in a proximity or vicinity of the crane you’re in.

Level	Issue	Definition	Quote(s)
	Not following procedures	Safety-related procedures are intended to reduce the risks of incidents by informing workers of the correct way to perform a task. Failure to follow procedures increases the risk of safety incidents.	We have to break the rules or else you can't get the job done. Breaking the rules then adds risk. Then go to [project name] where the process is that a crane basically is getting dismantled and the processes of following the actual manufacturer's guide how to pull it apart wasn't followed. ...now that was a crane that had the latest dynamic LMI in. The guy hit the override seven times. It timed out seven times......Like, it was the latest, latest, latest crane. Had every failsafe in it. EN13000 compliant LMI, and they still had an accident. One is, if you have a plan, then you don't implement it, you can't assume the success of the plan is going to be delivered. Likewise, you can't just say, "I have a plan therefore, I'm going to go do it" because the plan may not have been well thought out.
	Operators taking short cuts	Taking shortcuts to increase efficiency or improve productivity can have serious safety consequences.	Last week I got away with lifting 10% more than the cranes as I can lift, today is 12% more. There's not much more than 10%, so I'm probably okay. We've got to do it in a way that's wrong equipment and wrong lifting gear. Consequences by the operator, safety margins, money and family and 'I think I'll get away with it'. Is there a four-hour time or whatever and they don't want to go back to the yard and pick up the stuff, so they just do it.

Level	Issue	Definition	Quote(s)
	No lift plan/plan is not reflective of the situation	Good practice and correct lifting methods enable large objects to be lifted efficiently and safely. However, incorrect lifting methods can result in safety incidents. Lifting activities should be carefully planned to ensure the correct procedure is followed for a particular situation.	Poor understanding of what you're actually lifting and where you've got to lift it to. Where you're able to set it up.
	Override of safety technology	Safety technology includes engineered devices or controls (safeguards) installed to ensure an activity or equipment is operated within designed safe operating limits. A safety override refers to such mechanisms being ignored or circumvented (for example, by being switched off).	… now that was a crane that had the latest dynamic LMI in. The guy hit the override seven times. It timed out seven times… Like, it was the latest, latest, latest crane. Had every failsafe in it. EN13000 compliant LMI, and they still had an accident.

Level	Issue	Definition	Quote(s)
	Structural/electrical failure of crane	Structural failure may include the failure of any crane component, such as the boom, jib, hydraulic rams, or wire rope. Electrical failure can be inherent or related to failure to verify electrical supply and wiring connections in accordance with relevant standards.	It was bolted down to a mangalloy bar, which are a very high strength steel bar. They don’t like being welded too. They were welding a concrete, and they tack welded the reo onto the mangalloy bar to hold it in place. And the mangalloy bar’s snapped and we nearly had a tower crane down in [inner city street name]. It snapped at one corner, and they managed to tie it down before it snapped the other three. … failure a number of years ago of a luffing wire There are holes in some of the manufacturing of the locking system, and principally in some of the older stuff where there was a push to reduce mass of the crane and increase performance. My hotspot is luffing wires and the evidence shows that it’s problematic out there at the moment. It was down at [Sydney suburb] where basically the design of a structure required a crane to be hand levered, yep, and with that process it failed. I don’t know any of the elements that were basically contributing factors, but they were looking at the actual section of the actual support for the tower crane failed. There was talk at that time that might’ve been in our substandard metals or pins and things like that, so design is now playing a role.

Level	Issue	Definition	Quote(s)
	Lack of hazard awareness	Cranes should be sited where there is clear space available for erection, operating and dismantling. Consideration should be given to proximity hazards such as overhead electric lines and conductors, power cables, radio frequency wave transmitting towers, nearby structures and building, hoists, stacked materials, other construction works, the flight paths of airfields, the route of aerial ropeway and other cranes, public access areas including highways and railways, etc. Omission of hazard identification can lead to safety incidents.	Some have built in tech to stop… or gets to assist the operator but at the same token, those who don't have it and they're relying only on the operator. … if people aren't aware of what restrictions are in place, then they make wrong judgements of error and can create an issue.
	Operating substandard crane	Operating reliable equipment is critical in delivering a safe working environment. Substandard plant or equipment is a safety hazard.	… the operator was reporting the wires broke. Wires broke, site manager was signing it off, was going down to the plant yard. Plant manager was receiving it off the fax, put them in a folder, no-one was picking it up. Ultimately that crane driver should have been able to go in, throw those keys on the table and say, 'that's it, I'm not operating'.

Level	Issue	Definition	Quote(s)
SHAPING FACTORS	Working outside standard working hours	Fair Work Australia states that a standard working week is 38 hrs, spread between 7am and 7pm. In some instances, it may be a requirement or permit condition to work outside of the standard spread of hours to limit disruption and impact on the public.	… if we do 7.00 until 5.00 every single day, we're used to day shift. Then all of a sudden, it poses a risk when we're asked to do something at night. How do you manage fatigue?… and that's where that comes into play.
	Long working hours	Fair Work Australia states that a standard working week is 38 hrs, spread between 7am and 7pm. Research has begun to identify evidence of a relationship between long working hours and an increased risk of occupational injuries.	… first to arrive, last to leave, with mobile cranes, there's also the setup time, pack-up time that's often not accountable by some persons .. with the hours of work by restrictions from [the public road authority] and council and things like that because then we're forced to do night shift and guys have worked all day. And then your body clock doesn't adjust, so you've got fatigue factors coming into play. Then we get, maybe on a six-hour shift, even at night, and we need eight to ten hours of sleep.
	Shift work/rostering schedule	Shift work involves working outside the standard working hours of 7am to 7pm. It typically involves workers working in 'relays'. Shift work (at night) can upset sleep patterns and has been linked to fatigue and human error.	Well, all your authorities with infrastructure and things like that. They're the ones that govern when we can and can't go which then poses risks on hours of work. And so, you have an understanding, going back on [name's] comment, is hours of work; if we do 7.00 until 5.00 every single day, we're used to day shift. Then all of a sudden, it poses a risk when we're asked to do something at night. How do you manage fatigue, doing… and that's where that comes into play.

	Crane company overcommits	In the context of increased demand for services, and pressures to maintain business performance, companies sometimes overcommit by taking on more work than can be easily resourced and managed within a given timeframe.	They're booked out for four jobs, but don't know how they're going to fit it in.
	Inadequate site supervision	Supervision of construction activities is important for maintaining safety. Typical supervisory functions include planning and allocating work, making decisions, monitoring performance and compliance, providing leadership and building teamwork, and ensuring workforce involvement.	Like checking the oil and that… if I'd have started the crane back in the day without flipping the cover up and actually pulling the dipstick out and checking it, I'd have got me arse handed to me.
	Lack of competency and experience of crane operator/dogman/ rigger	Competence is the ability to undertake responsibilities and consistently perform activities to a required standard. It combines practical and thinking skills, knowledge and experience. The competence and experience of individuals working in and around cranes is vital. Competent workers have good situational awareness and are able to identify hazards in changing	The first one is that people who are inexperienced – green, if you like – just get their licences and they're then required to do work that only experienced personnel should have. … they're not allowed to make a decision for themselves. … that guy was a dogman for two years, but never had sufficient driver training. But at the end of the day, they want us as companies, safety people, coordinators, allocators, they want us to sign off on people. We don't give them the ticket. We can familiarise people, and this is the biggest problem the industry has today. Supply and demand, lack of training, has caused the problem.

		circumstances and maintain safe working practices.	I think, that there's areas of improvement for worker competence in just ages of experience or years of experience. Some aspects of it are in place, they just need to be followed. Labour hire's always an issue for us because whenever we look at incidents, both with tower cranes and mobiles, they always you know not always but a lot of the time they come down to operator error. You know, all the basic stuff. But then once they get in there, and start doing real intricate lifts, and that's where the accidents are happening.
	Complacency/ overconfidence	Complacency and overconfidence can arise from repeated experience of a specific activity or task. Too much familiarity can create complacency or overconfidence, such that new or emerging hazards are overlooked or the risks they pose are underestimated. Maintaining a sense of unease and the understanding that things can go wrong is important for safety.	… usually mobile crane operators in the lower end of the industry are older, they're highly experienced, they're used to taking risk. Their perception of risk is low because they've got away with it for a long period of time. We think we know what we're doing. But just that one day the wind come from the other direction, and it made it hard. You know? But my experience said we could get it up there, and the other bloke said yeah, and it wasn't about having to finish that job. But just, we were there and that's just how we work. We try to get the job done like everything. … then you've got the other end of the spectrum where they are over experienced, if you like, because they think they know it all.
	Inadequate/ incorrect information provided to crane contractor	Incorrect or inadequate provision of information can increase the probability of operator error, impacting safety and productivity.	There's a lot of emphasis put on information of weights of loads at Tier 1s. And as crane, most of the time, weights are not correct that you're given. You'll go, just ask any of the crane companies here. You'll go to a Tier 4 builder at 7 o'clock; he's not even on site. Now you ask the labourer, what am I doing? I don't know. Then he'll come driving through the traffic going, 'fuck mate, why isn't the crane lifting?' I said, 'well mate, we don't know

			what we're lifting'. And the workers don't give a shit because they get paid from 7.00 until 3.30. They don't care mate. They'll sit there all day.
	Lack of/poor safety in design	Poorly designed plant and equipment, poorly designed interfaces, and poorly designed activities, can result in inefficiencies and safety hazards. Safe design is about integrating hazard identification and risk assessment methods early in the design process, to eliminate or minimise risks of injury throughout the life of a project. It also relates to considering operational activities, taking into account the health and safety of workers.	The structural stability of them cranes, they don't have ballast weight as a footprint because they've tried to make them as light as they can to go on the slabs, and they go into tight areas. Unfortunately, on one of the lifts, you had a situation where on the soffit of the slab, they had a drainage pit. So, they couldn't put the prop there. So, they had to come back something like 400, and then they had another, it was a pipe – a fire pipe – that also got in the way. So, they had to come back another… so they had to move this thing about 900 times. There were some design issues across all equipment, nothing to do with tower cranes, which was sort of driven by the Australia Standards, that probably needs to be reviewed, and we certainly made changes in how we do things relating to material that's used in cranes…
	Inadequate onboarding and industry induction of foreign workforce	Foreign workers have specific characteristics, such as different cultures, background, and language, which distinguish them from locals. Induction is a starting point for an organisation to introduce a culture norm that supports health and safety. Onboarding and industry inductions should aim to provide workers with knowledge of OHS issues	… because the construction industry here in Australia has got so busy now, a lot of foreign workers now. A lot of foreign workers on working visa. They don't understand our systems. They don't understand procedures.

		and safe work practices within the Australian context.	
	Lack of competency and experience of engineers and decision-makers	Designing for cranes and their associated activities requires specialised knowledge and expertise about crane specifications, limitations and operational requirements. Obtaining qualifications as an engineer may not be enough to understand and be competent to consider all that is needed to safely design crane-related work processes.	… the engineers and some of the project managers who are involved don't even know what they're doing, but they dictate the whole scope of the crane. They might be good engineers in their right. But a lot of them have got zero experience with cranes. They were out and out told not to use their pads. They were told by engineering side that the leg of the crane had to go directly over the dry shores. If they had had their pads on the ground, it (an incident) wouldn't have happened. … the engineers and some of the project managers who are involved don't even know what they're doing, but they dictate the whole scope of the crane. I had a job the other week where I knocked it back… where I was lifting the back of the big gate that opens and closes on the boat, and they put their other boats inside. And I lifted 40 tonne or something, and I said, I got it a little way up but I couldn't get it any more. And I said to the boys, 'that's it, can't go any further'. I stopped on that job. It's just not worth it. … the engineers and some of the project managers who are involved don't even know what they're doing, but they dictate the whole scope of the crane. Now, it would be good if SafeWork could put some pressure on Engineers Australia to raise the issue of how can they tell who's competent, you know, if they're receiving certificates from people, how can they tell

			whether they have the appropriate competencies to be issuing those certificates? … people who are engaging any old person just to do a crane foundation design and they don't realise what a true crane engineer does for you is more than just a little foundation design.
	Wet vs dry hire	Wet hire includes machinery and an operator, while dry hire provides the machinery only. Wet hire operators are said to be familiar with the equipment and more cautious, having a vested interest in the condition of their gear. Dry hire allows for a more flexible workforce.	I know that most reputable companies or reputable crane operators – especially with tower cranes and that – that they keep an eye on the weather and when it gets past a too dangerous level or past the manufacturer's specifications, they do call their staff back in and stop work. I know that. But that's with reputable companies. And I mean that, because if they're just dodgy hire people, or a person on body hire is not going to go to the host employer and say they're not going to do that. The issue that I see quite a lot is the conflict of interest that the wet hire crews have. They will ring and report that to the crane company who employs them and the crane company says, 'Mate, I don't give a fuck; you get back to work because if that crane is down out of service, we'll start to get back-charged for that crane not being in service, you get up there and keep driving that crane.'

	Documentation is too generic/not site specific	Information that is not specific to the site or the particular task which is being carried out.	We've got to also look at it when people who don't have the paperwork straight away, they get hold of it, and they start to come as the same, just with a different header.
	Lack of coordination/ oversight of documentation and planning across multiple contractors	Construction projects are known for high risk activities. Coordination can be seen as a process of managing a number of activities being undertaken concurrently in an organised manner so that a higher degree of operational efficiency can be achieved for a given project. A lack of coordination not only negatively affects the traditional construction project parameters of cost, quality and schedule, but the ability to achieve a safe working environment.	We do our own checks. We do our own paperwork, but they never come and indulge themselves with the rest of the site. Quite often because you've got different entities working on the same site, it means that they aren't coordinating between each other and don't have someone overwriting them doing the coordination. They're left to their own devices. You're working in, the probably interaction with other trades and services around, like you say, you've all of a sudden got somebody {next to you}, because they're trying to meet program and keep the project going, I need to dig a trench here.
	Requirement to submit SWMS prior to the job commencing	Principal contractors typically require subcontractors to submit a SWMS prior to commencing work on site. Preparing a SWMS before visiting a site can prevent a workplace-specific approach from being taken and result in generic SWMSs. This may not produce the best safety planning and preparation outcomes.	Well, to go on a project, you've got to produce that before you actually get the work.

	Modifications to crane installations	Alterations or modifications are sometimes made to cranes so they can be used for a specific purpose/location. These may not be subject to required inspection/testing and certification. Some modifications mean that, even though the crane is certified, it is significantly restricted in its use.	The structural stability of them cranes, they don't have ballast weight as a footprint because they've tried to make them as light as they can to go on the slabs, and they go into tight areas. … it was bolted down to a mangalloy bar, which are a very high strength steel bar. They don't like being welded too. They were welding a concrete, and they tack welded the reo onto the mangalloy bar to hold it in place. And the mangalloy bar's snapped and we nearly had a tower crane down in [name of street]. It snapped at one corner, and they managed to tie it down before it snapped the other three.
	Lack of maintenance of plant and equipment	Regular inspections, maintenance and repairs are to be carried out in accordance with the manufacturer's instructions or those of a competent person. Crane maintenance needs to be factored into any type of crane operation, particularly over extended timeframes and the type of environment it is operating in.	… we constantly have a problem with trying to continue the upkeep of maintenance of cranes based on the fact that the builders want to keep on building. Maintenance is also a major issue on mobile cranes and that's because they tend to be going all the time and you really if the crane company's working flat out they don't have time to take a crane out of service so they'll tend to stretch things further and further and then we end up with some rope failure and a few other odds and ends that go on with that. It's because they're designing for a lifecycle period for them to say that these guys, or are buying mobile or him buying a tower crane, or me to go out and buy a tower crane, they're going to say to me – and everyone's got this 10-year thing. It's not a 10-year thing, it's a duty cycle lifecycle. … the fire that we had, one of the issues that we had there was the client was not giving us access to the crane to service it at the regular servicing rules.

	Fatigue	Fatigue can result in a lack of alertness, slower reactions to signals or situations, and affect a worker's ability to make good decisions. Construction workers are at higher risk for fatigue due to the nature of the type of work involved. Factors that can contribute to fatigue are prolonged working hours, physically and mentally demanding work, and working in the elements.	If that guy doesn't get, on his own making, his eight hours' sleep, we can't control that. So, there's a certain responsibility on the people who operate the equipment that take it serious and adjust their lifestyle accordingly.
	Mental health	Construction workers are susceptible to poor mental health. This is often attributed to long (sometimes irregular) work hours, work-life imbalance and psychosocial risk factors in the workplace.	… but it's the hours we do which is the hard thing, the crazy hours. People falling asleep and tired. Yeah, for sure. But I think fatigue is still out there. I mean, everyone still does some crazy hours as much as you try not to, but you still get the days where you're stuck and I live an hour and a half away from here, and then I'll start at 4 o'clock in the morning.
	Site constraints / congestion / layout	Site layout and planning has significant impacts on productivity, costs, and duration of construction. It also impacts the health and safety of those working within that environment. Constraints are usually associated with restrictive site area where storage, transportation, temporary works, and building activities,	… can we also please put air space in there? It is absolutely ridiculous in the last 12 months it started, air space. Can't do this, can't do that. I was just going to say, it's particularly the layout and this is why you're talking about is it causing you accidents. It's restricting slew, which direction, where you can slew, what you can slew over. We've been condensed, condensed, condensed, condensed. It's a big problem everywhere. Melbourne's actually the same now. So you're just working… your extremely limited square metreage footprint all the time.

		are simultaneously undertaken.	
	Lack of empowerment of crane operators	In spite of legislative requirements for worker representation in relation to work health and safety, workers may feel a lack of empowerment and be reluctant to 'voice' health and safety concerns in certain circumstances. This situation can be particularly problematic when subcontracted workers perceive their continued employment would be jeopardised by raising health or safety concerns.	…that the builders want to keep on building… Look, what happens in tower cranes, they say that the builder. The next day, they're not welcome back on site. We've had so many good operators kicked off site because they stick by their guns. Yeah, there is this perception that you won't be invited back if you make life difficult for someone. Yeah, they try and hold you to ransom.
	'Tick and flick' approach to documentation	'Tick and flick' refers to an outcome created by situations of complex paperwork, bureaucracy, and time spent on a process that fails to pass on relevant information in a concise and succinct manner. It is more about getting the paperwork done.	If you have a 40-page documentation to give out to any of your operators, I guarantee you that if they've been operating off the same document for the same amount of time, they've been inducted into it properly, they know what's in it, you can quiz them on it. Any other guys, they go, 'I don't know what's written in it. I don't care,' because it's not relevant. Don't tick and flick and say, 'Yeah, it's here.' Go and inspect where the equipment is before it comes to the jobsite. I audit management systems every day through all the builders and cos there's so much documentation management systems, sometimes the most important documents are just a 'tick and flick' process.

	Procedure doesn’t address or cover high risk activities	Informing a workforce on the proper ways to limit risks while undertaking a task can be captured in a procedure and can greatly reduce the chances that workers will put themselves and others at risk. If risks are ignored or not recognised, then safety measure cannot be put into place.	Well, the documentation will say, before climbing the tower put your gloves on, make sure you’ve got good shoes, make sure you’ve got sunglasses and a hard hat and a vest, and then it was saying nothing about lifting the loads. It will say nothing about know what weight you’re lifting, check that on your chart that it will leave that load from the point you have to start through the – if it’s a tortured path, it might be halfway through your tortured path which is actually the worst location for the crane. So the pickup point and a delivery point might be fine, but you’ve got to go around something, and it’s going around something where you trip over. So a lot of the systems talk about all the gloves and the boots and the glasses, but forget about the lifting activity, which is the big high-risk issue.
	SWMS done in isolation (doesn’t consider other activities on site)	The primary purpose of a SWMS is to help supervisors, workers and any other persons at the workplace to understand the established requirements for carrying out high risk construction work in a safe and healthy manner. Completing a SWMS in isolation may result in identifying key risk factors for the activity, or new or evolving hazards as a result of the activity.	… some of the issues are crane crew does their stuff for the crane, steelies do stuff for theirs and there's this gap in the middle, the lack of interaction between the systems and processes over here and the systems and processes over there. There's a disconnect. We do our own checks. We do our own paperwork, but they never come and indulge themselves with the rest of the site. We're here for four hours and we won't be here tomorrow, so we don't worry about it.
	Overly onerous documentation/too long and not read	The amount of paperwork or level of detail in safety documentation should meet the requirements of the workplace, but not to the extent that it becomes a burden to read and understand.	… clients say you need to sign onto the job permit and there's a whole, then there's an inch and a half of bloody site procedures. And you say, ‘I haven't read that yet, mate’. I think the current style of safety management on sites is doomed from the start. We're expecting people [to read] through 20, 30-page documents.

		One frustration of documents that are too long and overly onerous is that workers can spend almost as much time familiarising themselves with the content and trying to comply as they do completing the task.	It expresses itself in safe work method statements that are 100 pages long and indirectly they become meaningless because they're so monotonous. It diminishes the meaningfulness of the content because the crane operators that are being ear bashed about the SWMS and about the JSA and about the lift plans, and about the onboarding and inductions, and the white cards so forth, all of a sudden [they] just kind of shut down or turn off. ...if it's too long, no one is going to read them. And they just sign the back of them.
	Transient workforce	Some organisations have what is referred to as multi-teaming—having their people assigned to multiple projects simultaneously. Continuously changing personnel on project can be disruptive and create safety concerns through issues such as lack of familiarity with the site or plant, etc.	The crane company will usually have a fleet of cranes. The operator for this one calls in sick today, the one I'm normally driving is sitting in the yard, there is no job for it. So I get put into that one. And sometimes they'll have one big crane and a few little Frannas. So moving from this one to that one is really significant. Some builders might supply their own labour where we might supply a top-up labour or we might supply the whole crane crew, but then, depending on the availability, if we take someone off a job for two days because the builder wants to put their own guy in there, he might not then be available to go back there.
	No specific requirements for cranes and their design for safe operations	There is an assumption that once a crane is certified then it is safe to operate. However, the level of detail can be ambiguous and not provide clear guidance on the limitation of the plant.	We came up with an 80-point checklist drawing all of that stuff out of the standards and manufacturer's specification. Then came up with a voluminous document to satisfy each of that criteria. Most of our guys were gathering the information to say well that's the crane brake test certificate. Had some wonderful diagram on it. They don't know what that means yet they gathered that piece of information. If you work a crane that works with saltwater every day of the week, your manufacturer guidelines wouldn't be the same as what you should be doing cos you've got another factor. I think there's a lack of clarity around the documentation that is required or needed for a crane through that commissioning process or at the end of

			that commissioning process. Even with the Crane Safe program, as good a program as it is, there's not good transparency as to what that actually represents. I know if they've gone through the Crane Safe program, but what does that encompass?
	Proximity of existing structures on site and adjoining properties	Failure to maintain sufficient clearance between other plant and structures may result in a risk of injury from a collision between the crane or its load with other plant or structures. The risk of injury from collision is higher when the regular working zone of a crane is next to another structure. Mobile plant may present a greater risk of injury from collision with a tower crane than a fixed structure, as its position may change.	… there's certain places you can't slew over because if you drop anything it can cause billions of dollars. … can we also please put air space in there? It is absolutely ridiculous in the last 12 months it started, air space. Can't do this, can't do that. I was just going to say, it's particularly the layout and this is why you're talking about is its causing you accidents. It's restricting slew, which direction, where you can slew, what you can slew over.
	Not recognising continuously changing site conditions and/or layout	The needs of construction sites change considerably from time to time throughout the project. As the project progresses, more areas are occupied by permanent facilities leaving less space to place supporting facilities. The types and quantities of material delivered to the site keep changing throughout the construction. Thus, areas needed for storage and fabrication change accordingly. Approach roads	The site's constantly changing. It changes daily. You came in to assess the site and its wrong information by the time you get back there.

		required during initial phases of construction may not be required during later phases, which generates a necessity for a dynamic layout.	
ORIGINATING INFLUENCES	Resource shortage	The demand for workers is fuelled by the high number of construction and infrastructure projects currently underway or planned.	There's so much work out there for mobile crane companies, that they can pick and choose. If we don't want to be compliant to your site, then fine, we'll go work for a builder down the road who only wants X, Y, Z off us. … the fact that the crane industry, regardless of whether it's fixed or mobile, is very incestuous, so you'll have guys that come from… sorry, to say this, but crane companies that are absolute garbage and then they want to move up and then they end up getting a company that's quite well-known, quite good operators and they might… because of the way the industry is, the guys still have to… we're lacking in any labour at the moment. We're on a squeeze with skilled labour… and it happens across all industries. Supply and demand, lack of training, has caused the problem. Lot of crane accidents in the last four or five years, because there's so much work on, and they're just struggling for guys.
	Overheated procurement environment	An increase in the number of active and planned projects sees the building and civil companies struggling to meet the needs of industry. This is placing pressure on the availability of contractors to carry out projects, with	But what comes with complacency over competency is lack of humanoids, lack of labour. We're in a boom now and it's going to continue for at least another five years, NSW government, they've announced when there's 89.4 billion on the books, so in the contract now, then there's another 50 billion every year after for the next five years.

		impacts that range from not meeting delivery timeframes, to increased costs and overall performance.	
	Client demands and expectations	Clients make key decisions concerning project budgets, timelines, objectives and performance criteria. These types of decisions influence health and safety both positively and negatively, directly or indirectly. Indirectly through project documentation, project schedule, and product selection, etc. Directly through imposition of design, extent of involvement, etc.	… we've done work where as soon as people start working over 60 hours a week, the incident rate just … it just goes exponential, and yet it's been enforced in other projects where they say, 'Well, you have to work at least a 60-hour week, because we're not going to get the job done because of the time factors and the pressures put on by the client.' It's quite a big issue where clients assume the position of the principal contractor. Don't be giving directions on stuff you're [not] experienced with.
	Adjoining properties, community expectations, and demands	Owners of adjoining or nearby properties and the broader community can influence a project's scale and design. In addition, they can also be powerful drivers in how and when on site activities are undertaken.	Look, a lot of people in Sydney do have it [audible alarms], but a lot of people turn it off to keep the neighbours happy. By instruction of the builder. They got constant complaints that there [are] cranes beeping all night. If it's a windy night, of course it's going to beep, but residents [are] unhappy about it.
	Authority/ regulator's permit conditions	It is common for local authorities (local councils) and other government bodies to nominate conditions on permits issued. In some instances, these conditions can directly impact how and when crane-	… we might not work at all during the day because some council says we're not allowed to. Which might involve putting the crane up at the last minute. … it's the councils who give unrealistic timeframes to set up as well. You know, the actual regulators yeah the restrictions, just do it between

		related activities are undertaken or how they are carried out.	midnight and 3.00am. Fucking what? Leave two wheels and a witch's hat there? You know, it's thunderbirds go, it's a bit of a set up. There was a seven-hour – not even a seven-hour window – from start to finish to put the crane up. So you had to set a 300 tonne crane up, put up what you could, pack it up, and be off the road, inside seven hours. So how is that safe? … council permits forcing us to do it in other ways that have caused issues in the past. Well, all your authorities with infrastructure and things like that. They're the ones that govern when we can and can't go which then poses risks on hours of work. And so, you have an understanding, going back on [name's] comment, is hours of work; if we do 7:00 until 5:00 every single day, we're used to day shift. Then all of a sudden, it poses a risk when we're asked to do something at night. I bring that up because probably an equal amount or greater of our time is spent trying to get road access more than performing a lift safely. It's difficult to have those costs recovered, so they become overheads that the business wears and the more burdensome these overheads are, maybe energy is being diverted towards part of the business that could have been spent on WHS activities. So, it has that indirect impact, I think, especially when people are spending so much time just trying to get to the job site. If we're in the city we're going in and we're trying to get a crane together as fast as we can, to work all night, and then pack it up as fast as we can to reopen the street. Yeah, I can't catch public transport, starting that time of day.
	Regulatory training requirements	Operating a crane is high risk work and requires those in control, as well as those assisting with crane operations (dogmen and riggers), to have completed	… one of the things that I find is a major problem is the fact that anyone who has nothing to do with construction or mobile cranes at this point in time, they're making hamburgers for the past 15 years, within one week, if they're diligent enough and study hard enough, they can get their open

		recognised training with an RTO.	crane ticket for fixed or mobile crane ticket, or tower crane ticket licence without any experience.
	Lack of consistency in RTO training	RTO's training and assessment practices, including the amount of training they provide, may vary between providers. As a result, there is a risk that training is not sufficient to enable participants to gain the competencies required to safely fulfil the role of crane operators, dogmen, and riggers.	… unfortunately, there's a lot of unscrupulous, left-column RTOs, trainers, assessors – whatever you want to call them – that people are still buying assessors off.
	Training not meeting the needs of industry	There is an emerging disparity between current vocational training for crane operators, dogmen, and riggers, and the expectations of the crane industry. The curriculum is believed to fall short in providing the knowledge, skills and experience to work safely.	But you can go and get a crane ticket in a week. … there's [a] disconnect between the operator training requirements and what is current best practice. Your RTOs and training organisations that will tell, 'This is what you need to do, but for the test, you need to say this.' My main thing is I just think the guys are rushing through now. It should be a minimum couple of years as a dogman and then a minimum couple of years as a rigger, and then you progress to being a full time crane driver if you've got the skills and the common sense, more or less. I don't think you should be able to go out and get your dogman's and rigger's ticket and crane driver's ticket in one week. The first one is that people who are inexperienced – green, if you like – just get their licences and they're then required to do work that only experienced personnel should have.

			… one of the things that I find is a major problem is the fact that anyone who has nothing to do with construction or mobile cranes at this point in time, they're making hamburgers for the past 15 years, within one week, if they're diligent enough and study hard enough, they can get their open crane ticket for fixed or mobile crane ticket, or tower crane ticket licence without any experience. … unfortunately, there's a lot of unscrupulous, left-column RTOs, trainers, assessors – whatever you want to call them – that people are still buying assessors off. They're still fraudulently selling tickets and VOC – verification of competency – as well.
	Principal contractor's demands and expectations	Principal contractors interpret and apply the requirements of the contract to ensure the successful execution of the project. Maintaining productivity may also require continual adjustments to planned activities to meet the requirements of various stakeholders, such as adjoining neighbours, local council, etc. Meeting and maintaining project demands flows down to contractors and workers.	I think that comes down to it. I work for builders that are just, 'push, push, push', and you're working for [name] and we're not push, push, push with that. The guys are saying, 'No!', it's no. Yeah, there is this perception that you won't be invited back if you make life difficult for someone. Yeah, they try and hold you to ransom. … make us do all of this paperwork, and say you can't do this, you can't do that, you can't do that. Once everything is in signed, they turn up and say, 'just get the job done'. But they are tipping a lot of cranes over on these wind farms and stuff with the wind and their tight schedules and they're pushing. Sometimes they'll send us off to do another little [lift], while you're here reach over and grab that. If it's the project manager or the superintendent, they want to get the project done. That's the end of the story.

			You have to go back to them and say, 'Mate, I can't do that.' 'I don't care. Just do it,' and that's what happens.
	Crane contractor knowledge and experience	Contractors bear the responsibility of leading their organisation to achieve objectives and stated goals. Their experience, knowledge management, and decision-making strategies, are crucial factors in making informed decisions.	Like, we're doing a tower crane in [regional city] on Thursday and I've already been down to have a look at the site and told them what area I need cleared to get the crane in of course, and then the tower crane guys on site I've already told the same thing, what area they need to run the crane, to put the crane together. … we'll normally go in a couple of days before, get inducted, have a quick scope of the jobsite, know where to pull up when I get there, I know where to pull up and we start setting up. I think that's probably one of the biggest concerns is lack of experience in the industry, definitely on the client's side but also in a lot of crane companies too, there's a lot of new crane companies around which don't have a lot of experience.
	Impact of EBA vs non-EBA workforce	Enterprise Bargaining Agreements may have additional conditions not applicable to those not working under such agreements. For example, an EBA will nominate rostered days off enabling workers to have appropriate rest and recovery opportunity.	… we're undercut by a number of non-EBA companies who can continue to operate and do whatever they please, I guess on site.
	Increase in foreign workforce	Maintaining the supply of workers to accommodate demand in the construction and infrastructure industry has seen an increasing reliance on workers from overseas to meet industry demands.	… because the construction industry here in Australia has got so busy now, a lot of foreign workers now. A lot of foreign workers on working visas. They don't understand our systems. They don't understand procedures.

	Crane contractor's expectations on crane operators	When focused on tight timelines and project programs, employers may provide instructions to workers that (explicitly or implicitly) put them under pressure to break safety rules.	What about the lack of availability, so it might not be the right crane for the right job. So you can't get the one you want and you're going to wait three months but the project's got the green light so they just whack up a remote control one, without naming brands. No planning, no management planning has gone in place, no lift planning has gone, you know if they say we're putting it in tomorrow, they do that. So the one thing, the drivers are worried about their boss telling them to complete and finish the job and you know do everything they can in their power to ensure but by all means you know they try to put him under pressure to finish the job. They simply will try to please the clients by doing everything in their power to finish the job. So they put a lot of pressure on the drivers to finish the job. So the drivers then sometimes will override their limits by using the overriding keys and they're just working off charts thinking they can finish the job. The issue that I see quite a lot is the conflict of interest that the wet hire crews have. They will ring and report that to the crane company who employs them and the crane company says, 'Mate, I don't give a fuck; you get back to work because if that crane is down out of service, we'll start to get back-charged for that crane not being in service, you get up there and keep driving that crane.'
	Procurement methodology selected	The contracting strategy defines the roles and responsibilities of, as well as relationships among, the client and other parties who contribute to the project (including design consultants, contractors, and suppliers). The type of contract selected also influences the extent of	It is better to get paid by the hour. I'd love to get paid by the hour sometimes, but we can't. We have a fixed rate. So, the costing becomes the event. The job gets delayed. It's a fixed contract, you're in trouble. … it's just spur of the moment bookings and come in and this is what we need to do

		integration of health and safety in a project.	
	Disconnect between industry standards and regulatory requirements	Industry practices/recommendations, such as those of the IPCC, do not align with the legal obligations set out in relevant acts, regulations and standards.	I don't normally gang up on the regulators and say they're a toothless tiger and all that stuff but we can only regulate ourselves to the standards we'll accept. That's fine, that works for a little while but then we got really, really busy and that gets diluted because the cowboys don't know what the IPCC says. They don't know anything about the protocols and they don't give a stuff and it's not regulated. … but the interpretation of the Australian standard in what we should be doing and what's getting done is two different things. We've got a protocol now for a crane coming into our facility or on our scope that's amplified massively over a land-based requirement. I implemented Marine Order 32 which is the international marine crane and lifting equipment requirements, so they don't have ten-year inspections and annual inspections. They have six monthly inspections. It's because they're designing for a lifecycle period for them to say that these guys, or are buying mobile or him buying a tower crane, or me to go out and buy a tower crane, they're going to say to me – and everyone's got this 10-year thing. It's not a 10-year thing, it's a duty cycle lifecycle. There were some design issues across all equipment, nothing to do with tower cranes, which was sort of driven by the Australia Standards, that probably needs to be reviewed, and we certainly made changes in how we do things relating to material that's used in cranes.
	Time/budget pressures to keep the project moving	Sector competition, low contractor margins, tight budgets and pressure to cut programs and costs can	So, that puts pressure on them, forces people to do irrational decisions.

		encourage corner-cutting and impact safety.	But they are tipping a lot of cranes over on these wind farms and stuff with the wind and their tight schedules and they're pushing.
	Level of management by the principal contractor sets the tone/principal experience	A principal contractor's attitude to safety significantly influences behaviour and performance of subcontractors/suppliers. The principal also determines the way safety is incentivised/rewarded within commercial relationships with subcontractors/suppliers.	You have to go back to them and say, 'Mate, I can't do that.' 'I don't care. Just do it,' and that's what happens. … they're not allowing us anymore to bring the best equipment for the jobsite on because so many other factors suddenly start to determine.
	Lack of early involvement/ consultation with crane contractor	Early involvement of a crane contractor enables specialist crane expertise to inform project planning and decision-making. Site layout and construction processes can be designed for the safe use of cranes.	… most of the time they only get a phone call the day before, come and do some lifts tomorrow morning. Like, we're doing a tower crane in [regional city] on Thursday and I've already been down to have a look at the site and told them what area I need cleared to get the crane in of course, and then the tower crane guys on site I've already told the same thing, what area they need to run the crane, to put the crane together. … we'll normally go in a couple of days before, get inducted, have a quick scope of the jobsite, know where to pull up when I get there, I know where to pull up and we start setting up. But our sites are 90% unknown to the crane crews when they turn up on site, because they haven't been there before.
	Lack of planning by the principal contactor	Lack of planning leads to inadequate preparation for the safe use of cranes at a worksite, and can create unanticipated problems and negative safety impacts as	If I only have six hours to do a job, the thunderstorm comes through, I already have a problem. If I have more than 10 hours, I can say to the boys, 'Take half an hour, the thunderstorm is, we wait.' So, it is very important that we address it, that we get the hours we need to do the work.

		construction work progresses.	… it's just spur-of-the-moment bookings and come in and this is what we need to do. … and then we get to a hold point and say the weather's turned too much or… We might start putting one up, but you almost reach the point of no return if you start putting it up, you've got to get the certain hold points before you can then walk away from it and then it's safe, then you can come back to it the next day. So, operating close to the limit by itself wasn't a problem, operating with a gust of wind individually wouldn't have been a problem, but the combination of the two are a problem collectively. So, I think, there's definitely areas for improvement in planning. It's not necessarily that people want to be more cavalier or cowboy, it's just that they don't take the time because the time's not often afforded to them to think something through. For me, it's pulling up in a crane and there's something in the way that has to be moved and then I've got five semi-trailers behind me, of my gear, that are spaced out every 10 minutes to come in, and then next minute, they're all in the street waiting. The client's going off his head, the traffic controllers going off their head, because they're blocking the road, but there's nowhere for them to pull up. There's nowhere for them to park in the city no more.
	Lack of planning by the crane contractor	Lack of planning leads to inadequate preparation for safe use of cranes at a worksite and can create unanticipated problems and negative safety impacts as construction work progresses.	If I only have six hours to do a job, the thunderstorm comes through, I already have a problem. If I have more than 10 hours, I can say to the boys, 'Take half an hour, the thunderstorm is, we wait.' So, it is very important that we address it, that we get the hours we need to do the work. … it's just spur-of-the-moment bookings and come in and this is what we need to do. … and then we get to a hold point and say the weather's turned too much or… We might start putting one up, but you almost reach the point of no return if you start putting it up, you've got to get the certain hold points

			before you can then walk away from it and then it's safe, then you can come back to it the next day. So, operating close to the limit by itself wasn't a problem, operating with a gust of wind individually wouldn't have been a problem, but the combination of the two are a problem collectively. So, I think, there's definitely areas for improvement in planning. It's not necessarily that people want to be more cavalier or cowboy, it's just that they don't take the time because the time's not often afforded to them to think something through. For me, it's pulling up in a crane and there's something in the way that has to be moved and then I've got five semi-trailers behind me, of my gear, that are spaced out every 10 minutes to come in, and then next minute, they're all in the street waiting. The client's going off his head, the traffic controllers going off their head, because they're blocking the road, but there's nowhere for them to pull up. There's nowhere for them to park in the city no more.
	Lack of communication by the principal	Effective communication is important for project performance, including in safety. Poor communication can create confusion and send mixed messages relating safety expectations to subcontractors and suppliers.	I think that comes down to communication. In the strategy is good communication. To me, that is vital. … so you prepare for that day with all the subbies that you work with. We didn't work with subbies but it would be good to have a meeting in the morning where you get the supervisor from every area to come, sit down, run through your works for the day. So relieved knowing what they're doing, and then you come back in the afternoon and have a second meeting so everyone knows where they're at, ready for the morning. That covers what's changed during the day: we've made it across the eastern face of the building; we're going to be running whatever direction tomorrow; this is where we'll be, what you can expect. … and they need to be fully engaged with the client. We've got a system which we call the DCR which is document control register. Before we actually start on the project, we list out all the activities and all the documentation that we're going to prepare for those activities

			that we're going to provide to the client and all the documentation that we require from the client to perform our work safely. I don't think the size of the crane matters, I think it's again more about how you plan a job out. If you don't plan the job out properly then all of a sudden, the guys who are doing the work don't necessarily know what's going on and the site doesn't know what's going on.
	Crane registration regime not linked to inspection regime	There is limited ability to identify the number of crane activities and their locations across the state. Monitoring, inspections, and enforcement activities, may end up being ad hoc as a result.	Now, one of the things that SafeWork can do – and I think they should be able to do very easily, is that every crane that's in the market has a plant item registration. Now, the plant item registration that belongs to each bit of crane equipment. What that does is that highlights to them that cranes that are over 10 years old automatically should in their system signal that they should be requesting in addition to plan item registration… the renewal of the plant item registration, at 10 years, they should also request the major inspection report that says that 'This piece of equipment has received its major inspection' once it passes 10 years old, otherwise, they won't renew the plant item registration. … and if the plant is over 10 years old, and they go to renew their annual plant item registration, and they don't submit a major inspection certificate with it, then they can't get their plant item reregistered.
	Importation of substandard equipment	Substandard imported equipment can potentially put property and lives at risk. Foreign manufacturers often do not follow the necessary testing regime to prove their products meet Australian safety and reliability standards.	I don't know about structural failure but I know tower cranes you used to order from Spain… they came out, brand new cranes but they'd go for crack testing. And the amount of welds that failed through that test, and these are brand new cranes.

Appendix 6. Cause and effect diagrams

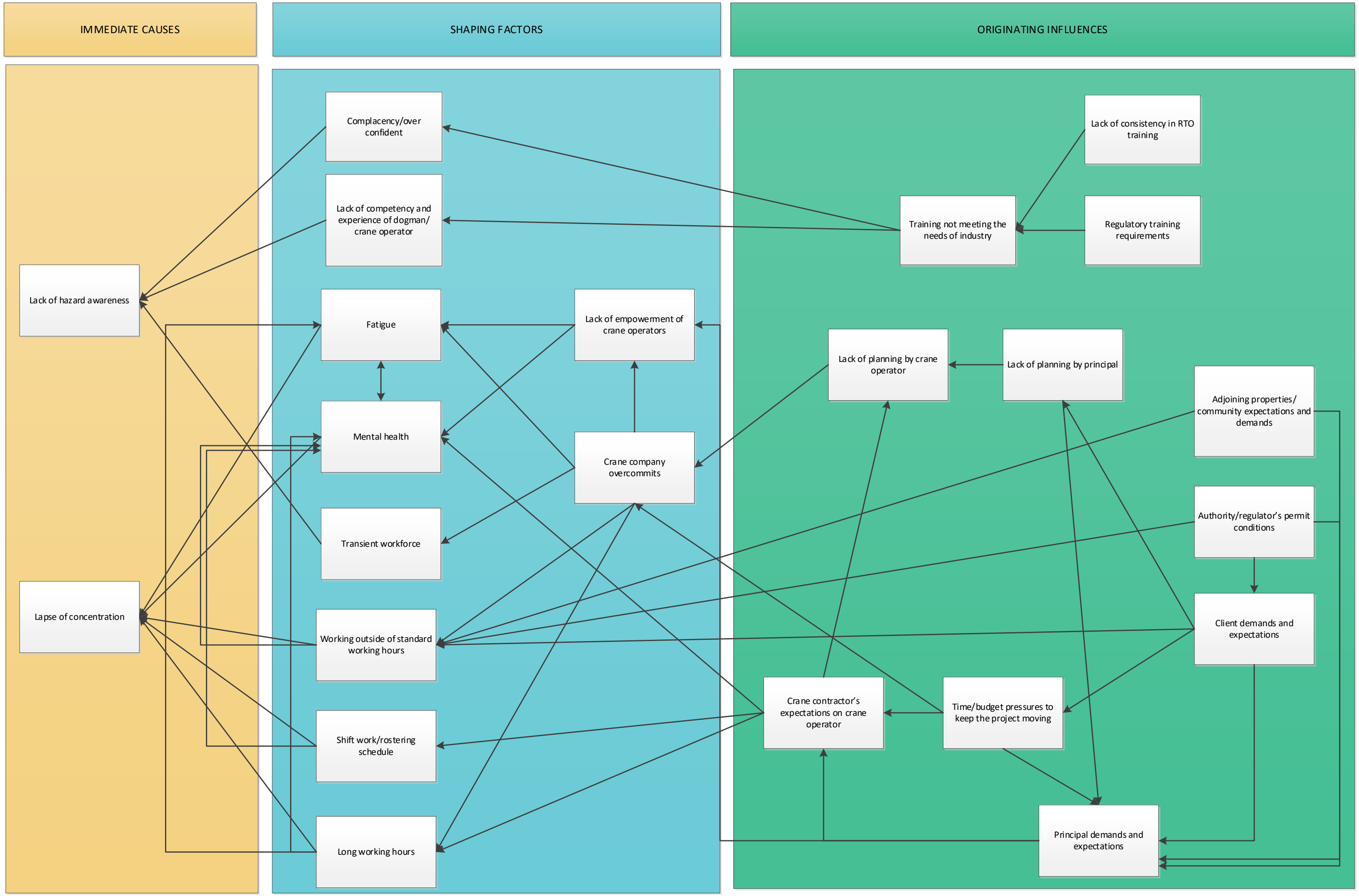

Figure 25. Work environment issues.

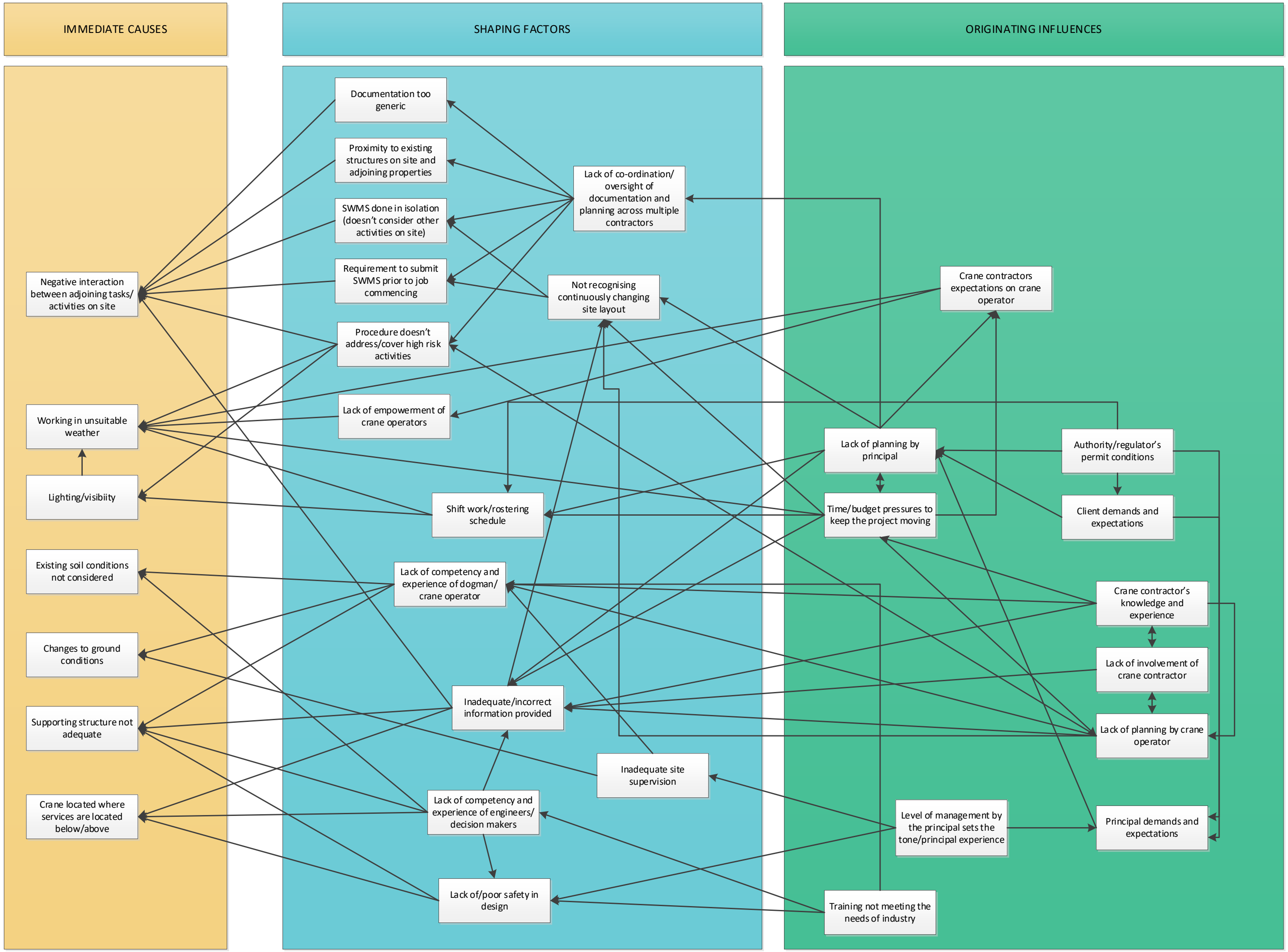

Figure 26. Worksite conditions.

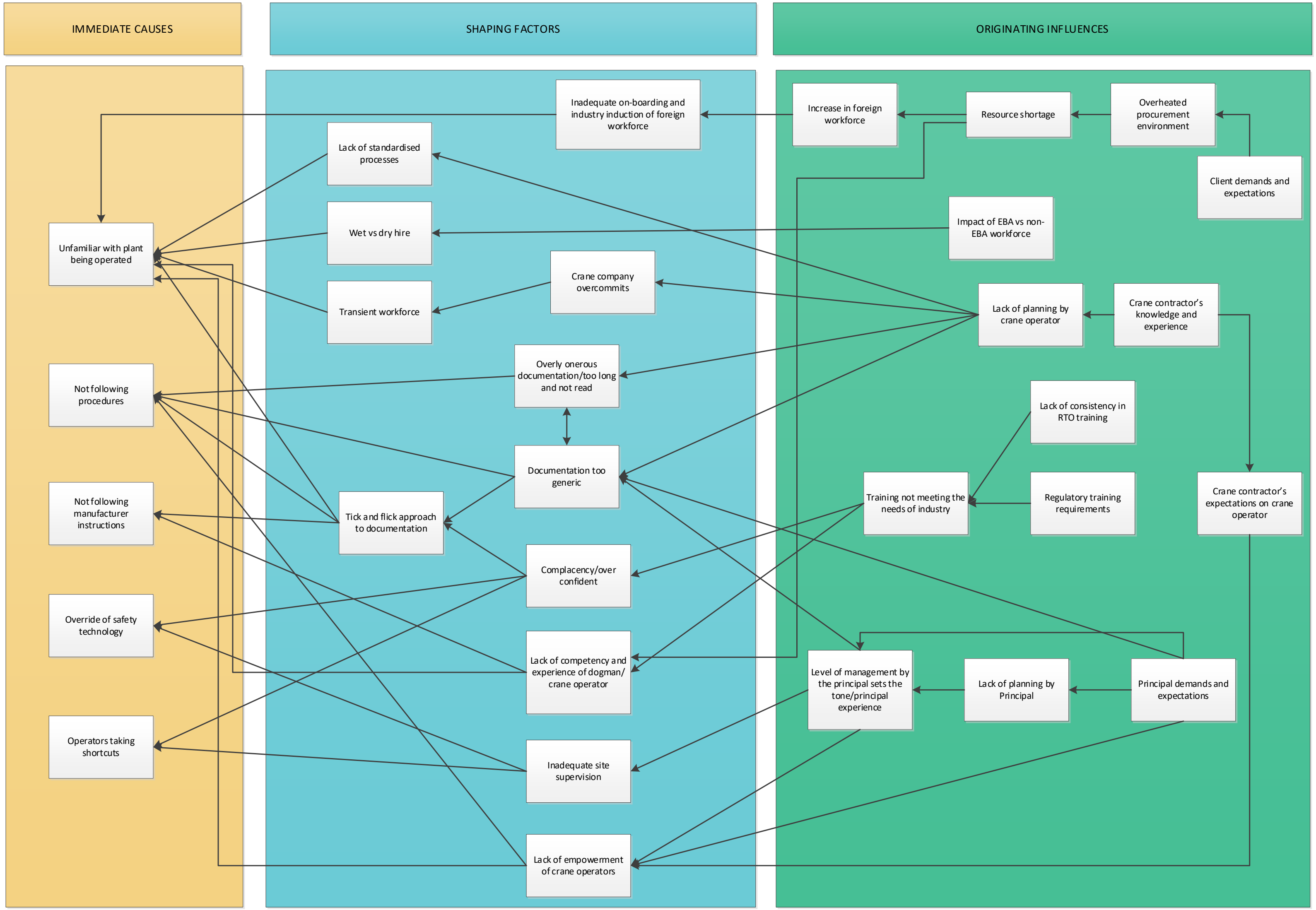

Figure 27. Human factor issues.

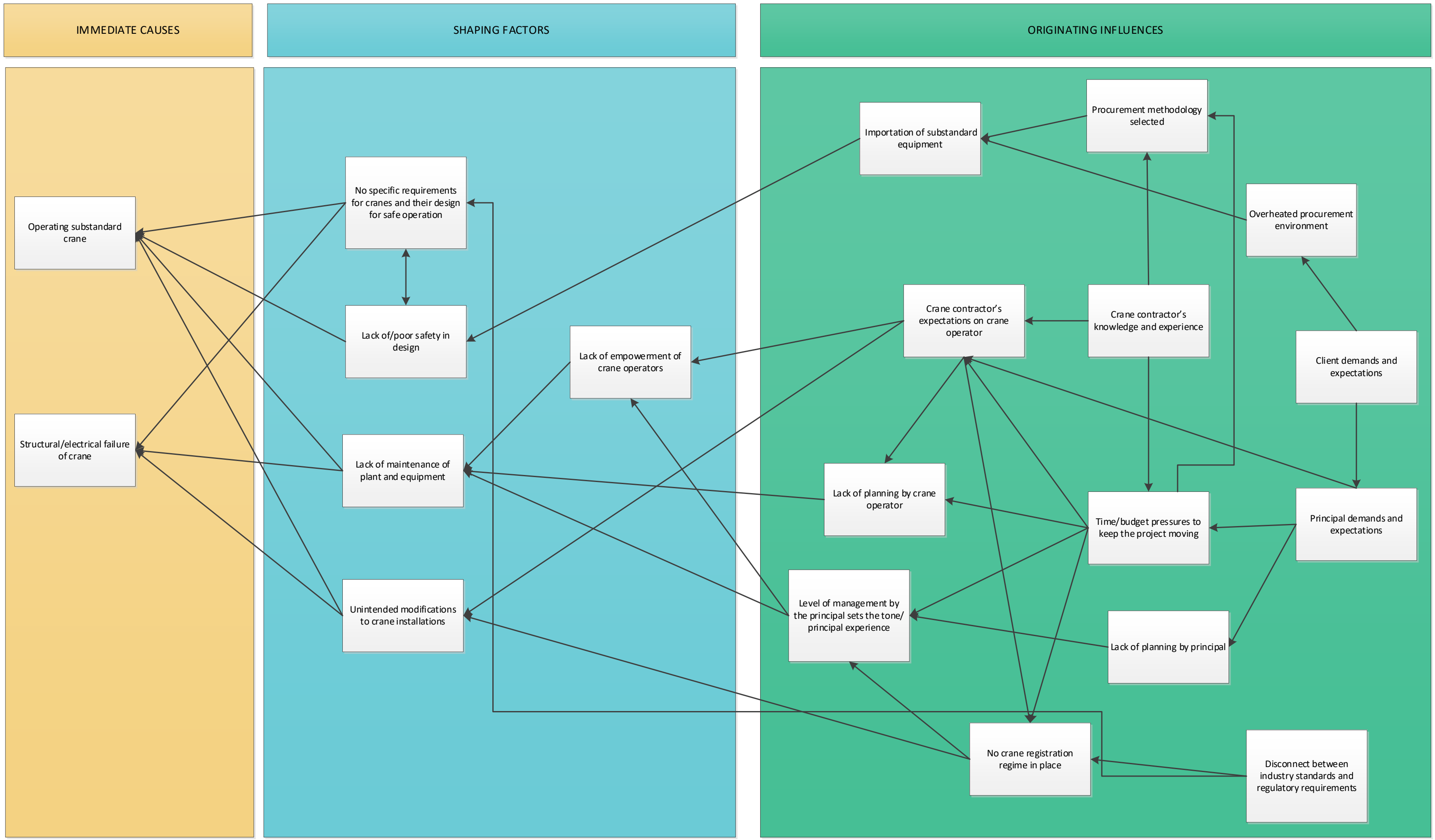

Figure 28. Equipment issues.

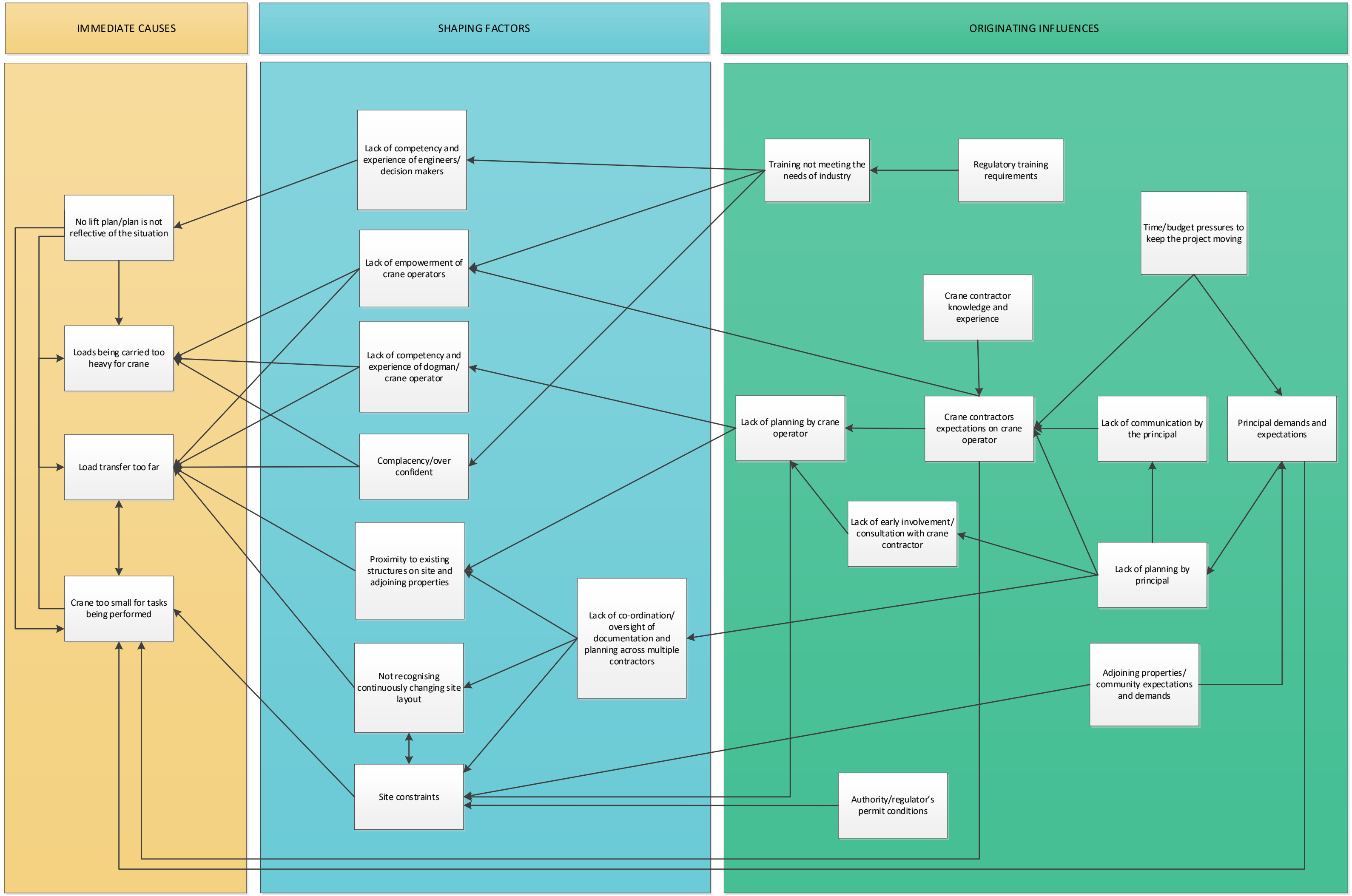

Figure 29. Task/activity issues.

Crane safety incident causation model validation data

Table 12. Frequency with which causal/contributing factors were identified as relevant to crane safety incident scenarios used in the validation.

Model Level	Issue	Tower	Mobile
Immediate	Hazards not identified	3	1
	Existing soil conditions		1
	Changes to ground to conditions		1
	Crane located above/below		1
	Not following manufacturer's instructions	2	2
	Override safety technology		2
	Operator taking shortcuts	2	2
	Load transfer too far	1	2
	Load too heavy	2	2
	No lift plan	2	2
	Lack of hazard awareness	1	1
	Not following procedure/SEMS	1	
	Supporting structure not adequate	2	
	Unfamiliar with plant being operated	1	
	Negative interaction between adjoining tasks/activities on site	1	
	Working in unsuitable weather		1
Shaping	'Tick and flick' approach to documentation	2	1
	Lack of standardised processes		1
	No specific requirements for cranes and their design for safe operations		1
	Inadequate/incorrect information provided to crane	2	2
	Modifications made to the crane		1
	Lack of/poor safety in design	2	
	Documentation too generic	2	1
	Lack of maintenance	1	

Model Level	Issue	Tower	Mobile
	SWMS done in isolation	1	
	SWMS submitted prior to job commencing	1	
	Procedure doesn't address/cover high risk activities	2	2
	Complacency/overconfident	3	2
	Lack of competency/experience	3	
	Inadequate site supervision	3	1
	Overly onerous documentation	3	1
	Site constraints	2	1
	Not recognising /accounting for changing site conditions	1	
	Transient workforce		1
	Fatigue		1
	Wet vs dry hire		1
	Lack of co-ordination/oversight of documentation and planning across multiple contractors	1	1
	Procurement methodology selected	1	
	Crane company overcommits	1	1
	Long working hours	1	
Originating	Lack of RTO consistency in training	1	
	Training not meeting the needs of industry	3	1
	Disconnect between industry standards and regulatory requirement	2	
	Crane contractor's knowledge and experience	2	
	Lack of planning by the crane contractor	3	1
	Lack of planning by the principal	2	1
	Level of management by the principal sets the tone	2	2
	Time/budget pressures to keep the project moving	2	2
	Regulatory training requirements	1	1
	Authority/regulator's permit conditions	2	1
	Client demands and expectations	2	1

Model Level	Issue	Tower	Mobile
	Overseas imports	1	
	Resource shortage	2	
	Overheated procurement environment	1	1
	Lack of early involvement/consultation with crane	2	1
	Crane contractor’s expectations on crane operator	1	1
	Foreign workforce	1	
	Lack of communication by the principal	1	1
	EBA vs non-EBA	1	
	Adjoining properties/community expectations and demands	1	

Appendix 7. Variables included in quantitative analysis

Table 13. List of variables and values included in quantitative analysis.

Variables	List of Values
Incident Type	'Fatal' OR 'Serious Injuries' OR 'Dangerous Incident'
Type of Crane	'Barge Crane' OR 'Bridge Crane' OR 'Derrick Crane' OR 'Gantry Crane' OR 'Mobile Crane' OR 'Portal Boom Crane' OR 'Quay Crane' OR 'Tower Crane' OR 'Two types of Crane involved' OR '[Crane Type Not Specified]'
Action	'Lifting' OR 'Loading' OR 'Slewing' OR 'Unloading' OR 'Dismantling' OR 'Not Operational' OR 'NA'
In Operation	'Yes' OR 'No' OR 'NA'
Loaded	'Yes' OR 'No' OR 'NA'
Load Type	'Yes' OR 'No' OR 'NA'
Work Related	'Yes' OR 'No' OR 'NA'
Mechanism of Incident	'Hit by load': Injured party hit by crane load. 'Hit by crane part': Body part struck by crane part or caught in crane part – for example, body part caught between two sections of crane outrigger. 'Hit by crane': Crane striking injured party or object – for example, crane jib making contact with power lines. 'Crane collapse': Crane collapsing – for example, mobile crane toppling over. 'Crane accident / crane collision': Two cranes colliding. 'Electrocution': Injured party electrocuted by crane. 'Fall / jump from crane': Injured party falling or jumping from crane. 'Other' – for example, crane catching fire, mechanical failure, deformation of crane part.
Incident Consequence-Crane/property/Powerline	'Yes' OR 'No' OR 'NA'
Incident Consequence-Death	'Yes' OR 'No' OR 'NA'
Incident Consequence-Injury	'Yes' OR 'No' OR 'NA'
Is there a human factor involved?	'Yes' OR 'No' OR 'NA'
Faulty Equipment	'Yes' OR 'No' OR 'NA'
Weather	'Wind' OR 'NA'
Offsite Environment Involved	'Yes' OR 'No' OR 'NA'

Variables	List of Values
Main Cause	'Faulty Equipment' OR 'Human Error' OR 'Weather Conditions' OR 'Human Error & Faulty Equipment' OR 'Maybe Human Error' OR 'Faulty Equipment' OR 'NA'
Day of the Week	'Monday' OR 'Tuesday' OR 'Wednesday' OR 'Thursday' OR 'Friday' OR 'Saturday' OR 'Sunday' OR 'NA'
Operator Involved	Yes' OR 'No' OR 'NA'
Operator Name	<Name>
Rigger Involved	Yes' OR 'No' OR 'NA'
Rigger Name	<Name>
Dogman Involved	Yes' OR 'No' OR 'NA'
Dogman Name	<Name>
Notices Issued	Yes' OR 'No' OR 'NA'
State of Investigation	'Completed' OR 'Ongoing' OR 'NA'
Compliance	Yes' OR 'No' OR 'NA'
Victim Type	'Dogman' OR 'Operator / Driver' OR 'Public' OR 'Rigger' OR 'Worker'
Operator HRW Licence Number	<HRWXXXXXX>
Dogman HRW Licence Number	<HRWXXXXXX>
Rigger HRW Licence Number	<HRWXXXXXX>

Appendix 8. Definitions of serious injury and dangerous incident

This appendix describes sections 36 and 37 of the *Work Health and Safety Act 2011*, providing definitions of 'serious injury or illness' and 'dangerous incident'.

Section 36 What is a "serious injury or illness"

In this Part, "serious injury or illness of a person" means an injury or illness requiring the person to have:

a) immediate treatment as an in-patient in a hospital, or

b) immediate treatment for:

  1) the amputation of any part of his or her body, or
  2) a serious head injury, or
  3) a serious eye injury, or
  4) a serious burn, or
  5) the separation of his or her skin from an underlying tissue (such as degloving or scalping), or
  6) a spinal injury, or
  7) the loss of a bodily function, or
  8) serious lacerations, or

(c) medical treatment within 48 hours of exposure to a substance,

and includes any other injury or illness prescribed by the regulations but does not include an illness or injury of a prescribed kind.

Section 37 What is a "dangerous incident"

In this Part, a "dangerous incident" means an incident in relation to a workplace that exposes a worker or any other person to a serious risk to a person's health or safety emanating from an immediate or imminent exposure to:

(a) an uncontrolled escape, spillage or leakage of a substance, or

(b) an uncontrolled implosion, explosion or fire, or

(c) an uncontrolled escape of gas or steam, or

(d) an uncontrolled escape of a pressurised substance, or

(e) electric shock, or

(f) the fall or release from a height of any plant, substance or thing, or

(g) the collapse, overturning, failure or malfunction of, or damage to, any plant that is required to be authorised for use in accordance with the regulations, or

(h) the collapse or partial collapse of a structure, or

(i) the collapse or failure of an excavation or of any shoring supporting an excavation, or

(j) the inrush of water, mud or gas in workings, in an underground excavation or tunnel, or

(k) the interruption of the main system of ventilation in an underground excavation or tunnel, or

(l) any other event prescribed by the regulations,

but does not include an incident of a prescribed kind.

Appendix 9. Focus group and semi-structured interview approach

Focus Group Approach

The approach for focus groups was determined in consultation with the client to encourage the attendees to develop and identify interventions to causal factors, rather than trying to solve a problem they may not recognise or have experience with. There was a maximum of 10 attendees per group with each focus group following the same approach outlined below.

1. Causal Factors
    a. The facilitator led the group to address each of the four elements (below). The group was asked to identify causal factors which were recorded on post-it notes and placed on a flip chart specific to each of the four elements:
        i. Project conditions
        ii. Environment
        iii. Human factors (including power relations)
        iv. Safety Management
    b. Once the attendees had reviewed each element, the group was then asked to review the causal factors and identify the top three for each of the four elements.
2. Strategies and Intervention

The facilitator then led to group to discuss interventions for the prioritised causal factors across each of the four elements.

3. Influence and Implementation

For each intervention proposed, the group was asked the following:

a. Who is the key person this intervention needs to reach? (operator, manager, regulator etc)?
b. What about this key person may help or hinder the interventions success?
c. What is the best way to reach this person?

Interview Approach

Interviews were treated as a way to follow up and triangulate data from the focus groups data. As such, interviews followed the same approach as the focus groups in asking interviewees to identify causal factors across the four elements. This was the case for all interviews, except for the first which took a more open-ended approach to the causal factors. This (first) interview sought responses to the following:

1. What causes crane accidents in NSW against the following contexts:
    a. policy/regulatory?
    b. industry/supply chain?
    c. project/planning levels?
    d. business level?
    e. worker/operator level
2. What strategies / programs could prevent incidents across the five levels?
3. Would these strategies / programs be suitable for the NSW context?
4. What would be the barriers/constraints to their effective implementation in NSW?
5. What would need to change in order to address these issues?
6. What could be reasonably achieved within the short, medium and long term to achieve improved outcomes?

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