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Modelling risk factors in earthmoving equipment operations on Australian construction sites: a fuzzy DEMATEL approach

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Abstract

Purpose – Despite advancements in safety technologies in the construction industry, such as building information modelling (BIM), their impact remains limited due to an insufficient understanding of influential areas of risks and their interconnections. Earthmoving equipment (EE) incidents in Australia underscore ongoing safety challenges. This research develops a model of influential risk factors in earthmoving equipment operations (EEOs) through Rasmussen's (1997) risk management framework (RMF), uncovering interrelationships to enhance risk identification and support the application of appropriate solutions aligned with the specific system level where each risk originates and evolves. Thus, it paves the way for comprehensive vertical, horizontal and end-to-end integration of technological and managerial solutions across all layers of safety management.

Design/methodology/approach – A literature review identified seven main categories and 52 sub-risk factors, which were further refined through expert validation via 32 semi-structured interviews and alignment with relevant codes of practice and regulations. The research also applies fuzzy decision-making trial and evaluation laboratory (FDEMATEL) for the first time in the Australian construction context to

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Ethical approval: Ethical approval for this research was granted by the Queensland University of Technology (QUT) University Human Research Ethics Committee (UHREC) or its delegated review body as meeting the requirements of the National Statement on Ethical Conduct in Human Research (reference number: LR, 2023–5693–16275). The approval affirms the ethical rigour of the research design, including the informed consent process, participant confidentiality, and the responsible handling of data.

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analyse cause-and-effect relationships of EEO risk factors within Rasmussen's (1997) framework. This methodology also integrates statistical validation techniques, including corrected item-total correlation and split-half methods within the FDEMATEL framework and sensitivity analysis to ensure response consistency, robustness and reliability, ultimately identifying critical areas for targeted interventions in EEOs' safety management.

Findings – The most influential risk factors across the risk management framework were categorized into cause-and-effect groups, identifying influential factors of EEO incidents. This led to the impact relations map (IRM), classifying factors by causal and effect-driven roles, making influential factors the primary focus for technological advancements and managerial strategies.

Originality/value – To begin with, from the research focus, this study is the first to uncover cause-and-effect relationships of risk factors in the Australian construction context, not only in EEOs but also in broader construction operations. Furthermore, from the research method perspective, a rigorous expert selection approach is embedded in FDEMATEL to ensure robust findings. Ultimately, this shifts the focus of managers and practitioners towards addressing critical dynamic variables, those acting as the Gordian knot within the system, which must be untangled to enable effective safety interventions and informed decision-making in EEOs. These insights strongly support the application of tailored solutions, whether technological (e.g. sensor-based systems, BIM integration and computer vision) or procedural (e.g. regulatory alignment), by aligning interventions with the origin and trajectory of specific risk factors.

Keywords Earthmoving equipment operations, Safety management, Fuzzy sets,
Multi-criteria decision-making technique (MCDM),
Decision-making trial and evaluation laboratory (FDEMATEL)

Paper type Research paper

1. Introduction

Earthmoving equipment (EE) plays a central role in construction operations but remains one of the most dangerous elements on-site, often leading to serious safety accidents due to its complex operation, heavy weight, and powerful hazards (Zhao *et al.*, 2024). There were 168 deaths related to mobile plant and transport in Australian construction sites between 2008 and 2023, of which 65 deaths were related to trucks, excavators, bulldozers, and road compactors (Safe Work Australia, 2023). In Australia, 15% of construction incidents were attributed to interactions between individuals and moving equipment, particularly heavy machinery such as articulated haul trucks, excavators, front-end loaders, and dozers, which represented the second most common cause of incidents, following manual handling incidents (17%) (Woolley *et al.*, 2018). An analysis of 100 construction incident reports in Australia revealed that plant operators were the most frequently identified actors at the staff level, with 70% of the reports attributing causality to their actions. Of the serious injury incidents, excavator buckets were commonly involved, while high-potential events often included heavy vehicle rollovers, contact with overhead power lines, and interactions between heavy and light vehicles (Woolley, 2020). Lingard *et al.* (2013a) highlighted a notable rise in workers' compensation claims related to EE in the Australian construction industry, driven primarily by an increase in incidents involving excavators, backhoes, and other digging equipment.

Various technological solutions have sought to improve earthmoving equipment operations (EEOs) safety, yet challenges persist due to complex risk interactions and the difficulty in identifying causal areas to enhance the effectiveness of safety technologies (Gutierrez-Bucheli *et al.*, 2024; Soltanmohammadlou *et al.*, 2024b). The finding of Soltanmohammadlou *et al.* (2024b) indicate that development of technological solutions in EEOs are not well aligned with systems thinking particularly at the higher RMF levels. Integration of technological advancement in EEOs should go beyond isolated implementation and be embedded within the broader sociotechnical system (Soltanmohammadlou *et al.*, 2024a). Integration of technological advancements in EEOs should go beyond isolated implementation and be embedded within the broader sociotechnical system. According to Sony and Naik (2020), Technological development in EEOs should align not only with immediate tasks but also with broader system elements, including organizational goals, regulatory expectations, worker capabilities, and site-specific processes. For meaningful impact, technologies must be integrated through vertical coordination across system levels, horizontal alignment across functions and stakeholders, and end-to-end support throughout the project lifecycle. To cite an example, although research in computer vision (CV) has rapidly advanced in EEOs, particularly in monitoring of EE through part and activity recognition (Luo *et al.*, 2020; Wen *et al.*, 2023), without integration of broader system-level risk factors, such as regulatory demands, these technologies risk becoming redundant (Fang *et al.*, 2020). Technological advancement should also extend beyond purely technical observation to address context-specific hazards and the social dimensions of operations, including factors such as the operator's mental state and overall situational awareness (Choi *et al.*, 2020; Mehmood *et al.*, 2023). To cite another example, the combination of BIM with technologies such as CAD, blockchain, VR simulation and training, RFID, smartphones, and IoT has been identified as effective in addressing the underlying causes of all six major mental disorders of workers (Nelumdeniya *et al.*, 2023). While Building Information Modelling (BIM)-based automated safety rule-checking aids hazard recognition and risk management activities (Johansen *et al.*, 2021), its success for EEOs safety at the stage of site planning is hindered by the absence of standardised methods for digitally representing and structuring site elements to align with various regulatory requirements and stakeholder needs (Getuli *et al.*, 2025). Formulating information about the entities of EEOs facilitate the information exchange, increase stakeholders' knowledge, and ensures a safer approach to EEOs (Taher *et al.*, 2022). Getuli *et al.* (2025) have emphasized that for the comprehensive implementation of technological solutions in EEOs safety, such as BIM object libraries, it is essential to go beyond technical specifications by incorporating spatial and safety considerations to prevent operational conflicts and ensure worker safety. Ergo, there is a need to incorporate information about dynamic variables on construction sites and integrate them into an agent-based construction site simulator, where each site object functions as an autonomous agent. The coordination of EEOs can be significantly enhanced through BIM-enabled planning, which allows for real-time visualization and scheduling of equipment movements, detection of time-space conflicts, such as between the workspaces of activities and the bounding boxes of machinery, and the use of path planning modules to manage EE movements (e.g. loaders, and dump trucks) (Dashti *et al.*, 2021), site planning of congested sites (Kumar and Cheng, 2015), and underground utility management (Wang *et al.*, 2019). Compared to visually tangible risk factors, other risks in EEOs, such as those related to supervision, regulation, and knowledge, are more difficult to observe and measure (Guo *et al.*, 2021). In this case, integrating technologies such as BIM and computer vision into safety supervision can effectively address other components of the RMF and enable broader system-wide monitoring and feedback (Kulinan *et al.*, 2024). Identifying focal risk areas and their cause-effect relationships is key to directing technology where it can have the greatest system-wide impact, ensuring that solutions align with both technical needs and broader sociotechnical dynamics in EEOs.

Therefore, as technological functionalities convey information on risk factors in EEOs across different levels of Rasmussen (1997) risk management framework (RMF), including government, regulatory bodies, companies, management, staff, environment, and equipment (Soltanmohammadlou *et al.*, 2024b), incorporating causal variables into this digital framework is essential to ensure that safety solutions are effectively tailored to specific contextual challenges and control the root causes of EEO accidents.

Although studies on plant and machinery risk identification in Australia, such as those focusing on EE risk factors (Lingard *et al.*, 2013a, b) as well as crane safety (Lingard *et al.*, 2021) have provided valuable insights, particularly through models like the Loughborough Construction Accident Causation (ConAC) model, the progression of knowledge has largely remained limited to the identification stage (Kazan and Usmen, 2018; Lingard *et al.*, 2021). Nevertheless, as highlighted by the gaps in existing qualitative research around the safety management of plant and machinery in Australian construction sites (Lingard *et al.*, 2021), there is a notable lack of quantitative research aimed at uncovering the complex interrelationships between proximal and distal risk factors in EEOs to support judicious decisions by the relevant decision-makers.

To bridge these gaps in knowledge and practice, a systems thinking approach is required particularly in the Australian construction sector, which emphasises risk control to improve safety but often overlooks systems factors, prioritising immediate, surface-level causes. This paper develops a causal model of risk factors in EEOs within the Australian construction context by categorizing these risk factors across the levels of Rasmussen (1997) RMF. DEMATEL (Decision-Making Trial and Evaluation Laboratory) (Fontela, 1976) is a prominent Multi-Criteria Decision-Making (MCDM) method with a strong capacity to analyse the cause and effect relationships among risk factors within a complex system. FDEMATEL generates impact relations maps (IRM) which form the basis of the causal model by classifying factors based on their cause-and-effect roles and offering a clear visual structure of influence within the within complex sociotechnical systems system (Mohandes *et al.*, 2022; Sadeghi *et al.*, 2023; Zhang *et al.*, 2020). By applying such methods, it becomes possible to move beyond descriptive risk identification and develop systematic models that clarify the areas and characteristics of risk factors to support proactive safety management strategies.

The fuzzy extension of DEMATEL (FDEMATEL) (Wu *et al.*, 2025) is particularly well-suited for addressing the inherent vagueness and uncertainty in human judgements, which frequently arise in real-world scenarios where precise numerical values may not adequately capture the available knowledge (Bellman and Zadeh, 1970; Rostamnezhad *et al.*, 2020). The integrated techniques of corrected item-total correlation and split-half method is embedded within the FDEMATEL framework to achieve higher precision, maintain consistency and improve accuracy in judgement of decision makers. Furthermore, the model, coupled with sensitivity analysis to verify the reliability and robustness of the derived outcomes.

As such, the research questions are:

RQ1. How can the subjectivity of safety experts' responses, the uncertainty surrounding EEOs, and the consistency rate of their evaluations be effectively addressed?

RQ2. How can the cause-and-effect interrelationships among EEOs risk factors within the Australian construction context be identified?

RQ3. What are the most central and influential risk factors that require particular scrutiny?

Leveraging the findings of this paper provide a unique contribution to the construction practitioners' understanding of the main causal risk factors affecting EEOs across the various levels of Rasmussen (1997) framework in the Australian construction context. This research encourages technology developers in EEOs to ground their innovations in a deep understanding of context-based hazards and the focal needs of risk factors. Technologies should not only be data-driven in controlling primary causal risk factors but also capable of detecting and monitoring the behaviour of other influencing factors while supporting the implementation of corrective actions such as site supervision and coordination of EE (Woolley, 2020). By identifying cause-and-effect relationships specific to Australian EEOs, this insight supports decision-makers in assessing systemic safety conditions and guiding the development of technologies that are both targeted and integrated into the broader sociotechnical framework. Moreover, policymakers can gain valuable insight into the specific areas of challenge within EEOs, enabling them to identify which elements of the sociotechnical system require targeted improvements. Collecting and analysing data on the cause-and-effect relationships of accidents in the construction process enables more rigorous and accurate predictions about the causes and consequences of EEO incidents. This capability enhances proactive risk identification and supports the development of targeted safety interventions.

The upcoming sections present the structure of the paper. First, Section 2 provides a brief background and an overview of related previous studies. Section 3 outlines the proposed research methods. In this section, the main categories of risk factors and sub-risk factors are identified based on a rigorous and structured literature review, with insights, attitudes, and contextual experiences shared through semi-structured interviews with Australian experts and adherence to applicable codes of practice and regulations related to EEOs in Australian construction context. From the literature, this is the first application of FDEMATEL as a quantitative approach to uncover the cause-and-effect relationships of risk factors in the Australian construction context with a specific focus on EEO safety. Finally, Section 4 presents the results, while Section 5 discusses their reliability and validation. Section 6 provides a detailed discussion of the findings. Section 7 discusses the implications, while Section 8 outlines the conclusions, contributions, limitations, and future research directions.

2. Background

Work Health and Safety (WHS) laws implemented in many countries are primarily designed to safeguard workers and others from harm associated with work activities (Bayramova *et al*., 2024; Bluff, 2019). In Australia, based on Model Work Health and Safety Regulations 2011 (Safe Work Australia, 2024b), in safety management of EEOs, Persons Conducting a Business or Undertaking (PCBUs) are legally responsible for managing plant-related risks and ensuring workers receive adequate information, training, instruction and supervision (ITIS), even without formal certification. However, prosecutions often focus only on cases where ITIS was absent, offering little guidance on proper delivery (Bluff, 2019). Moreover, despite the presence of national and international standards such as UN Regulations, Global Technical Regulations, and codes of practice and guidelines regulating for importation, utilisation, and safe operation of construction equipment, the practical hurdles to promptly notifying upper-level management of the need for improvements (Woolley 2020), cause the ongoing rate of workers' injury compensation to remain high, highlighting the shared responsibility across all levels is not consistently implemented or practised as intended (Woolley *et al*., 2018). Challenges include limited safety information flow due to the absence of formal input systems for regulations and performance monitoring, delayed communication channels, feedback mechanisms prioritising financial and compliance metrics over safety outcomes, and the significant yet unenforced influence of unions, suppliers, and communities due to their lack of formal governance integration (Woolley *et al*., 2020).

The necessity for identifying causal factors, which are the primary source of underlying issues, remains critical even with technological advances in integrated safety management for EEOs. This underscores the importance of prioritising the effective capture, management, and dissemination of risk information across all levels of Rasmussen (1997) RMF (Soltanmohammadlou *et al*., 2024b).

Within the construction process, as a complex sociotechnical system (STSs) with diverse human and technological components that have non-linear interactions (Bayramova *et al*., 2023), there will inevitably be instances where the magnitude of variability in a single function or activity is sufficient to increase the probability of adverse outcomes, such as accidents or incidents (Hollnagel and Slater, 2018). Systems thinking-based accident causation models such as Rasmussen (1997) RMF conceptualises a hierarchical and interconnected socio-technical structure extending from the governmental level to the work environment level. Applying this paradigm in the domain of construction research sheds light on various aspects of safety management (e.g. underlying causes of the incident in construction safety of developing countries (Mohandes *et al*., 2022),and tower crane safety (Sadeghi *et al*., 2023).

(Soltanmohammadlou *et al*., 2024a) reviewed a total of 87 published papers and applied a systems thinking approach to categorise the risk factors of EEOs into five groups based on (Rasmussen, 1997): regulatory bodies and associations (R), company management (C), construction site management (S), workforce (W), and environment and equipment (E).

Recently, some scholars have employed a systems thinking approach to analyse risk factors in crane incidents in China using empirical data (Zhou *et al.*, 2018), others have applied decision-making methods for assessing risk factors in the excavation process in construction yards (Ilbahar *et al.*, 2018), and root causes of construction site accidents in developing countries (Mohandes *et al.*, 2022). Evidence shows that the causal and contributing factors of Australian construction plant and machinery such as crane incidents originate from multiple dimensions, including (1) regulatory frameworks and socio-economic contexts, (2) planning, management, and operational practices at organisational and project levels, and (3) site-specific behaviours and conditions at the locations where incidents occur (Lingard *et al.*, 2021). Allowing embedded information from causal risk factors to move effectively through the system can help untangle ongoing systemic challenges and support the development of improved safety management practices aligned with Australia’s OHS ambitions (Lingard *et al.*, 2009).

3. Research method

Figure 1 illustrates the research method summary, detailing the sequential steps involved in identifying, validating, and analysing risk factors through expert interviews, designing the fuzzy DEMATEL survey, and conducting consistency rate and sensitivity analyses.

The identification of risk factors began with a literature review and analysis of codes of practice, followed by expert interviews conducted within the Australian construction industry. These interviews refined the understanding of risk factors, enabling the design of a structured questionnaire for data collection. Following this, the FDEMATEL technique was employed to explore the interrelationships among the main and sub-risk factors of EEOs and generate various impactful cause-and-effect diagrams. The interviews and FDEMATEL questionnaires

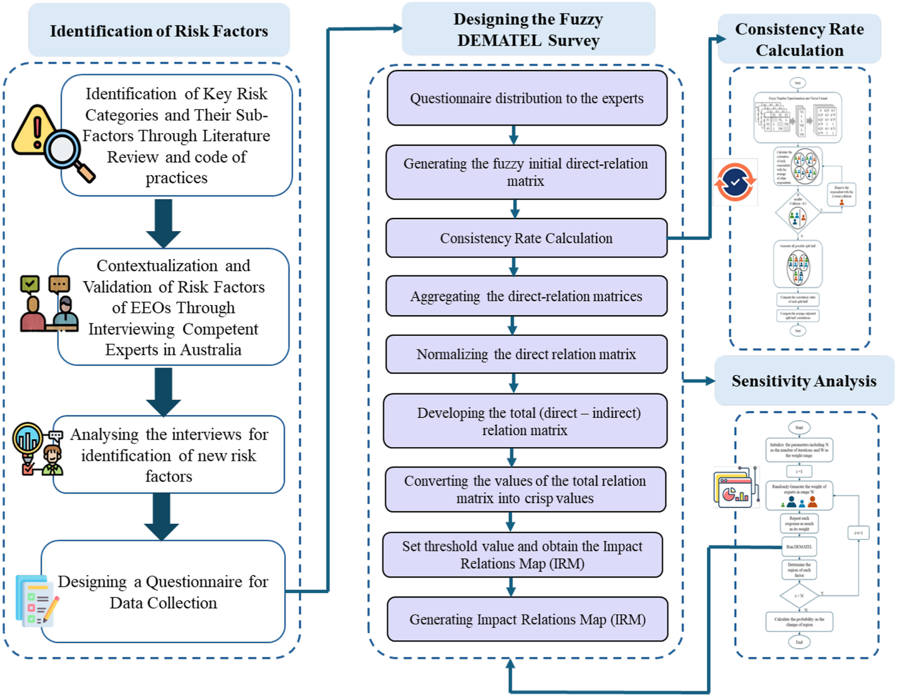


Figure 1. Research method. Source: Authors’ own work

were approved by the University Human Research Ethics Committee (UHREC, approval no. LR, 2023–5693–16275), confirming compliance with ethical standards regarding consent, confidentiality, and data handling. Finally, sensitivity analysis was conducted to assess the robustness of the results and ensure the reliability of identified causal relationships.

3.1 Identification of risk factors associated with EEOs

The extraction of risk factors for EEOs was conducted in two stages: first, identifying risk factors through a comprehensive review of the literature and codes of practice, and second, validating these factors through brainstorming interviews with selected experts. (Soltanmohammadlou *et al.*, 2024a) classified the EEOs safety research into two major types (Type one: Identification of the risk factors of EEOs and Type two: safety solutions of EEOs). This research primarily draws on Type One research to extract and analyse relevant risk factors associated with EEOs. Additionally, Lingard *et al.* (2021) highlighted that some causal and contributing factors identified in the crane safety incident causation model in Australian construction sites might also apply to other plant and work vehicle types. The work of Lingard *et al.* (2013a, b), Lingard *et al.* (2021) served as the cornerstone of risk identification in this study, providing a foundational understanding of safety challenges in Australian heavy equipment operations. As shown in Table 5, the research team subsequently broadened the scope of risk factors through collaborative expert consultation, supplementing the initial framework with insights from peer-reviewed literature on heavy equipment operation risks (Kazan and Usmen, 2018; Sadeghi *et al.*, 2023).

In addition, the refinement of the framework was guided by authoritative resources drawn from Australian jurisdiction-specific Codes of Practice developed under section 274 of the Work Health and Safety Act 2011 (Office of Parliamentary Counsel, 2018), such as Managing the Risks of Plant in the Workplace (Safe Work Australia, 2024a) and Code of Practice for Excavation Work (Safe Work Australia, 2021). In the next stage, a brainstorming interview was conducted with 32 shortlisted experts from various states of Australia to ensure the validity and applicability of these risk factors. To address potential concerns regarding jurisdictional differences in work health and safety regulations across Australian states and territories, this study deliberately selected experts from various regions within Australia. By incorporating a diverse group of professionals, the research captures a broad spectrum of insights and practices reflective of the different regulatory environments. Moreover, this approach reinforces the premise that certain risk factors extend beyond regulatory boundaries and remain relevant to construction work irrespective of specific state or territory contexts (Lingard *et al.*, 2021).

This study employed purposeful sampling to identify and select experts with relevant knowledge and experience (Suri, 2011). The experts were selected based on two criteria to ensure their qualifications and relevance to the study:

(1) A minimum of five years of experience in construction operations or related sectors, such as EE manufacturing or technical training institutions specialising in the operation of these types of equipment.

(2) Involvement in EEOs in the construction process, either in their current role or through prior relevant experience, demonstrating practical expertise in the field.

They were asked to validate the extracted risk factors by sharing their perspectives on those presented for review. Table 1 represents the profile of the experts interviewed to validate these risk factors.

3.2 Fuzzy decision-making trial and evaluation laboratory (FDEMATEL)

The DEMATEL technique (Fontela, 1976) is a robust multi-criteria analysis tool designed to capture collective knowledge and visualise complex causal relationships within systems as

Table 1. Demographics of interviewees

Demographic variable of interviewees		Number
Gender	Male	29
	Female	3
Work experience (years)	≥5 and <10	5
	≥10 and <20	9
	≥20 and <30	13
	≥30	5
Job position	Site management (Safety manager = 15, Construction project manager = 2, Operational manager = 1, Project engineer = 1, Site supervisor = 1, Site engineer = 1, and Project manager = 2)	23
	Earthmoving equipment management (Plant trainer = 3, Earthmoving equipment production manager = 1, and Technical Director Resources = 1)	5
	Managerial board (Managing director = 1 and General manager = 2)	3
	Project compliance manager	1
Highest qualification	Diploma	9
	Graduate certificate	2
	Bachelor’s degree	9
	Master’s degree	12

Source(s): Authors’ own work

well as prioritise central indicators (Cheng *et al*., 2024; Yu and Ma, 2024). Integrating fuzzy logic (Zadeh, 1965, 1975) into DEMATEL overcomes the limitations of traditional crisp values by addressing uncertainty and ambiguity in human judgement. This extension transforms imprecise judgements into precise insights, enhancing the accuracy and reliability of decision-making processes. The process of the FDEMATEL method comprises several essential steps, which are outlined and explained as follows:

Step 1. Design of the questionnaire

A triangular fuzzy number, defined as (a, b, c), represents uncertainty through three key parameters: a, the lower boundary of the value range; b, the most probable value; and c, as the upper boundary. This type of fuzzy number is a specific variant of a trapezoidal fuzzy set, in which the core, or the range of maximum membership, reduces to a single precise point, making it especially useful for scenarios with a distinct peak likelihood (Ren *et al*., 2008). The questionnaires were structured using five linguistic scales and fuzzy numbers, as presented in Table 2. The linguistic terms were used to indicate the strength of the relationships between factors.

Step 2. Questionnaire distribution to the experts

Table 2. Linguistic scales and corresponding fuzzy numbers

Linguistic scale	Abbreviation	Fuzzy number
No influence	N	(0, 0, 0)
Very low influence	VL	(0, 0.25, 0.5)
Low influence	L	(0.25, 0.5, 0.75)
High influence	H	(0.5, 0.75, 1)
Very high influence	VH	(0.75, 1, 1)

Source(s): Authors’ own work

The questionnaires were initially distributed to 42 subject matter experts, including individuals who participated in the interview process. From the interview group, 17 experts provided responses. One additional individual, beyond those initially interviewed, also participated in this stage, bringing the total number of respondents to 18 as shown in Table 3. presents the profile of the respondents who participated in the questionnaire. Each expert was instructed to evaluate the direct influences among the risk factors, ensuring that no cause was assessed as influencing itself. As a result, a total of $n \times (n-1)$ influences needed assessment, where n is the number of causes in each group.

Step 3: Generating the fuzzy initial direct-relation matrix

To create the initial direct relation matrix, for the n factors, k number of experts were asked to assess the impact of the factor i on the factor j. On the other hand, a higher linguistic rating from a respondent reflects the belief that inadequate engagement with the problem of element i has a stronger direct impact on the inability of element j as illustrated in Figure 2. Therefore, the direct-relation matrix is established as $z^K = [z_{ij}^k]$.

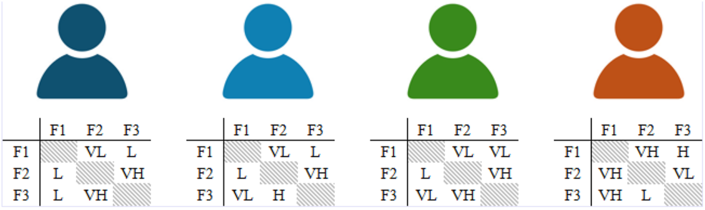
$$Z^K = \begin{bmatrix} 0 & z_{12}^k & \dots & z_{1n}^k \\ z_{21}^k & 0 & \dots & z_{2n}^k \\ \vdots & \vdots & \vdots & \vdots \\ z_{n1}^k & z_{n2}^k & \dots & 0 \end{bmatrix} k = 1, 2, \dots K \tag{1}$$

Where $Z_{ij}^K = (l_{ij}^K, m_{ij}^K\ u_{ij}^K)$, and where z_{ij} indicates the direct effect of factor i on factor j; and when $i = j$, the diagonal elements $z_{ij} = 0$.

Table 3. Profile of experts responding to the FDEMATEL questionnaire without consistency rate

Demographic variable of experts responding to the FDEMATEL questionnaire		Number
Gender	Male	16
	Female	2
Work experience (years)	≥5 and <10	4
	≥10 and <20	4
	≥20 and <30	7
	≥30	3
Job position	Site management (Safety manager = 12, Site supervisor = 1, Site engineer = 1, and Project manager = 1)	15
	Earthmoving equipment management (Earthmoving equipment production manager = 1)	1
	Managerial board (General manager = 1)	1
	Safe work design strategist = 1	1
Highest qualification	Diploma	4
	Graduate Certificate	1
	Bachelor’s degree	4
	Master’s degree	8
	Doctorate degree	1

Source(s): Authors’ own work



	F1	F2	F3
F1	▨	VL	L
F2	L	▨	VH
F3	L	VH	▨

	F1	F2	F3
F1	▨	VL	L
F2	L	▨	VH
F3	VL	H	▨

	F1	F2	F3
F1	▨	VL	VL
F2	L	▨	VH
F3	VL	VH	▨

	F1	F2	F3
F1	▨	VH	H
F2	VH	▨	VL
F3	VH	L	▨

Figure 2. Linguistic ratings reflecting direct impact relationships. Source: Authors’ own work

(1) Consistency Rate Calculation: integrated approach of corrected item-total correlation and split-half methods

Before proceeding to the next main stage of the DEMATEL method, it is essential to evaluate the consistency of the expert responses. This process consolidates individual expert evaluations into a unified matrix, representing the collective perspectives on the relationships among factors. An expert’s responses may significantly differ from others for various reasons, such as a different interpretation of the questions, and can affect the result and reduce the overall consistency. Therefore, it is advisable to assess the consistency of the responses and remove those that lower the consistency of the aggregated matrix (Shieh and Wu, 2016). A key reason for ensuring a consistency rate in the fuzzy DEMATEL method lies in its use of arithmetic means to aggregate expert opinions, unlike the geometric means approach employed in other multi-criteria decision-making methods (MCDM) methods such as AHP (Wu and Tsai, 2012). This distinction underscores the importance of verifying logical coherence and alignment among individual judgements to minimise subjective biases and validate the logical alignment of judgements (Wu and Tsai, 2011). To ensure consistency and refine the collected data from experts, the model outlined in Shieh and Wu (2016) was employed, adhering to the procedural steps detailed in Figure 3.

The steps of this model are as follows:

(1) The collected responses are transformed into a vector format by arranging all values from the matrix, excluding those on the main diagonal, sequentially beneath one another to form a single vector.

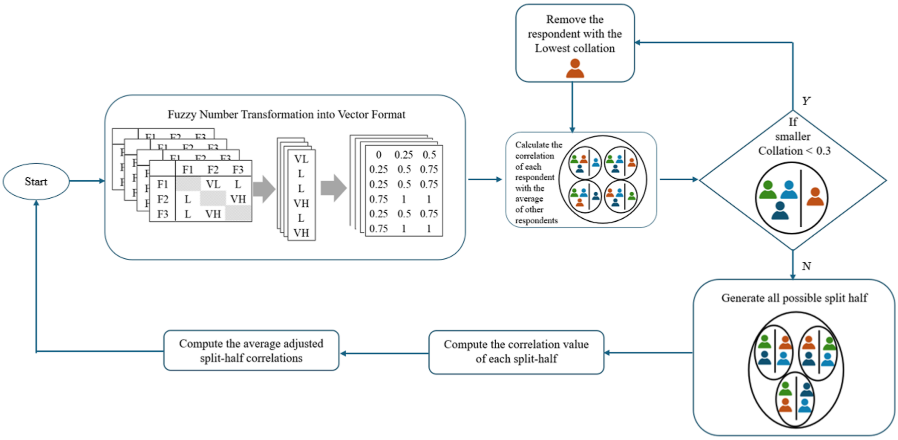


Figure 3. The detailed of consistency rate calculation. Source: Authors’ own work

(2) Each expert's response is compared with the average responses of the other participants. Correlation values for all survey responses are calculated based on the average of the group using Eq. (2), with the correlation between X and Y determined using Eq. (3). This measure quantifies the strength of the relationship between each individual survey item and the overall survey results, providing insight into the consistency and alignment of responses within the group.

$$\text{Corrected item} - \text{total correlation}\,(X_i) = \text{corr}\left(X_i, \sum_{j=1}^{22} X_j - X_i\right) \tag{2}$$

$$r = \frac{\sum\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum\left(X_i - \overline{X}\right)^2 \sum\left(Y_i - \overline{Y}\right)^2}} \tag{3}$$

(3) Any calculated correlation values from the previous step that fall below 0.3 are addressed by removing the expert with the lowest correlation. The process then reverts to Step 2 with the updated list of experts. This iterative procedure is repeated as necessary until all corrected item-total correlation values meet or exceed the threshold of 0.3. By applying this approach, only reliable and consistent expert responses are retained, ensuring the robustness of the data for subsequent analysis.

(4) Generate all possible split-halves of the dataset using an appropriate method (e.g. the MATLAB function nchoosek). For each split-half, compute the correlation values and adjust these correlations using the Spearman-Brown formula, as expressed in Eq. (4), where r represents the estimated correlation between the two halves. Finally, calculate the average of all adjusted split-half correlations to determine the overall consistency of the dataset.

$$r_{\text{Spearman-Brown}} = \frac{2r}{1+r} \tag{4}$$

In step 4, if the number of remaining experts from step 3 exceeds 15, the number of possible split-half combinations will increase exponentially. To address this, the required number of half combinations (n) can be calculated using Eq. (5), where $Z_{\alpha/2} = 1.96$, p represents the expected response rate, and $q = 1 - p$. The final required number of half combinations is then determined by Eq. (6). This method ensures an efficient evaluation process while preserving statistical validity.

$$n = \frac{Z_{\alpha/2}^2 \cdot p \cdot q}{\text{error}^2} \tag{5}$$

$$n_{\text{corrected}} = \frac{n}{1 + \frac{n-1}{n_{\text{population}}}} \tag{6}$$

The selected 10 expert respondents demonstrated a high level of consistency in their evaluations, meeting the predefined threshold for inclusion in the analysis. This ensured the reliability of the aggregated responses and minimised the impact of subjective biases on the study's findings. As shown in Table 4, the final selected respondents' profiles reflect their expertise and relevant backgrounds, ensuring the credibility and robustness of the data used in the analysis.

Table 4. Profile of selected experts after consistency rate calculation

Experts	Position	Gender	Highest qualification	Work experience
Expert 1	Earthmoving equipment production manager	Male	Bachelor's degree	33
Expert 5	Safety manager	Male	Bachelor's degree	25
Expert 7	Project manager	Male	Master's degree	20
Expert 9	Safe work design strategist	Female	Doctorate degree	20
Expert 11	Safety manager	Male	Post Graduate Certificate	15
Expert 13	Safety manager	Male	Diploma	12
Expert 15	Site supervisor	Male	Master's degree	8
Expert 16	Safety manager	Male	Master's degree	6
Expert 17	Site engineer	Male	Master's degree	5
Expert 18	Safety manager	Male	Diploma	5

Source(s): Authors' own work

Step 4: Aggregating the direct-relation matrices.

An average matrix is constructed by aggregating the direct matrices from multiple respondents. Each element in this matrix represents the mean of the corresponding elements across the individual direct matrices provided by the respondents (Tzeng *et al.*, 2007). The average normalised direct relation fuzzy matrix (A_z) for all experts' input is calculated as follows:

$$A_z = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \tag{7}$$

Where $p_{ij} = \left(\sum_{k=1}^{K} Z_{ij}^{(k)}\right) / K$)

Step 5: Normalising the direct relation matrix.

The initial direct influence matrix (N_{ij}) is derived by normalising the average matrix (A_z), ensuring that all principal diagonal elements are zero. Matrix N illustrates the initial influence that each element exerts on and receives from others.

$$\widetilde{N_{ij}} = \frac{\widetilde{A_{ij}}}{r} = \left(\frac{l_{ij}^{k}}{r}, \frac{m_{ij}^{k}}{r}, \frac{u_{ij}^{k}}{r}\right) \tag{8}$$

Where $r = \max_{ij}\{\max_i \sum_{j=1}^{n} u_{ij}, max_j \sum_{i=1}^{n} u_{ij}\}\ i, j \in \{1, 2, 3, \ldots, n\}$

Step 6: Developing the total (direct–indirect) relation matrix.

Eq. (9) is used with all the fuzzy values to compute the total relation matrix. Once the normalised fuzzy direct-relation matrix $\widetilde{N} = (N^l, N^m, N^u)$ is obtained, where $N^l = [n_{ij}^{l}]_{n \times n}$, $N^m = [n_{ij}^{m}]_{n \times n}$, $N^u = [n_{ij}^{u}]_{n \times n}$, the fuzzy total-relation matrix $\widetilde{T} = [\widetilde{t}_{ij}]_{n \times m}$ where $\widetilde{t}_{ij} = (t_{ij}^{l}, t_{ij}^{m}, t_{ij}^{u})$, is derived as follows:

(1) The lower bound matrix $T^l = [t_{ij}^{l}]_{n \times n}$ is calculated as $N^l(I - N^l)^{-1}$

(2) The middle-bound matrix $T^m = [t_{ij}^{m}]_{n \times n}$ is calculated as $N^m(I - N^m)^{-1}$

(3) The upper bound matrix $T^u = [t^u_{ij}]_{n\times n}$ is calculated as $N^u(I - N^u)^{-1}$

Where I represents the identity matrix. These computations are executed in Microsoft Excel utilising the "Minverse" and "Mmult" functions.

$$T = \begin{bmatrix} t_{11} & t_{12} & \dots & t_{1n} \\ t_{21} & t_{22} & \dots & t_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ t_{n1} & t_{n2} & \dots & t_{nn} \end{bmatrix} = N \times (I - N_{nd})^{-1} \tag{9}$$

Step 7: Converting the values of the total relation matrix into crisp values

Defuzzification of the total relation matrix T values are performed to generate the total relation matrix with crisp values. This process involves applying the defuzzification method using Eq. (10) and (11) (Ocampo *et al.*, 2018).

$$D_T = \left(d_{T\,ij}\right)_{n\times n} \tag{10}$$

$$d_{T\,ij} = \left(l_{t\,ij} + 4m_{tij} + u_{tij}\right)/6 \tag{11}$$

Step 8: Set threshold value and obtain the Impact Relations Map (IRM)

Tzeng *et al.* (2007), recommend simplification of the structure of elements in matrix D_T, by setting a threshold value TS, to filter the most significant effects represented by the elements of the matrix. Each element $d_{T\,ij}$ in matrix D_T indicates the degree to which element i influences element j. If all elements from matrix D_T are converted into an Impact-Relation Map (IRM), the resulting map would be overly complex, making it difficult to extract meaningful information for decision-making. Only those elements in matrix D_T with influence levels exceeding the threshold are selected and included in the final IRM. There are various methods to calculate thresholds in the DEMATEL method, each presents unique challenges in balancing the trade-off between providing more or less relational information (Apaydın and Aladağ, 2022). Methods providing more information often complicate IRM with trivial relations, while those offering less information risk omitting significant relationships, potentially compromising analytical accuracy and clarity (Si *et al.*, 2018). In this paper, the third quartile was used as a threshold to identify relationships that are above the median but below the extreme outliers (Si *et al.*, 2018). The total relation matrix S, after removing the minor influences, is shown as follows:

$$TS = The\ Third\ Quartile\ of\ Total\ Relation\ Matrix \tag{12}$$

$$S_{ij} = \begin{cases} d_{T\,ij}\, d_{T\,ij} \geq TS \\ 0\ Others \end{cases} \tag{13}$$

$$S = \left(s_{ij}\right)_{n\times n} \tag{14}$$

Step 9: Generating Impact Relations Map (IRM)

Eq. (15) and (16) are utilised to compute the two influence indexes from the total relation matrix. The two influence indices D_i and R_i are instrumental in determining the centrality and causality levels of the factors under analysis. The first index D_i represents the influence exerted by one factor on others, referred to as the dispatcher. Similarly R_i reflects the influence received by a factor from other surrounding criteria, referred to as the receiver (Alshahrani *et al.*, 2024).

$$D_i = \sum\nolimits_{j=1}^{n} DT_{ij} \tag{15}$$

$$R_j = \sum\nolimits_{i=1}^{n} DT_{ij} \tag{16}$$

Step 10: The Centrality Degree (CE) and Causality Degree (CA)

The Centrality Degree (CE) and Causality Degree (CA) have been computed using Eq. (17). CE quantifies the relative importance of the factors, while CA determines the cause-and-effect relationships among them. Criteria with positive CA values are classified within the cause group, whereas those with negative CA values are assigned to the effect group (Alshahrani *et al*., 2024).

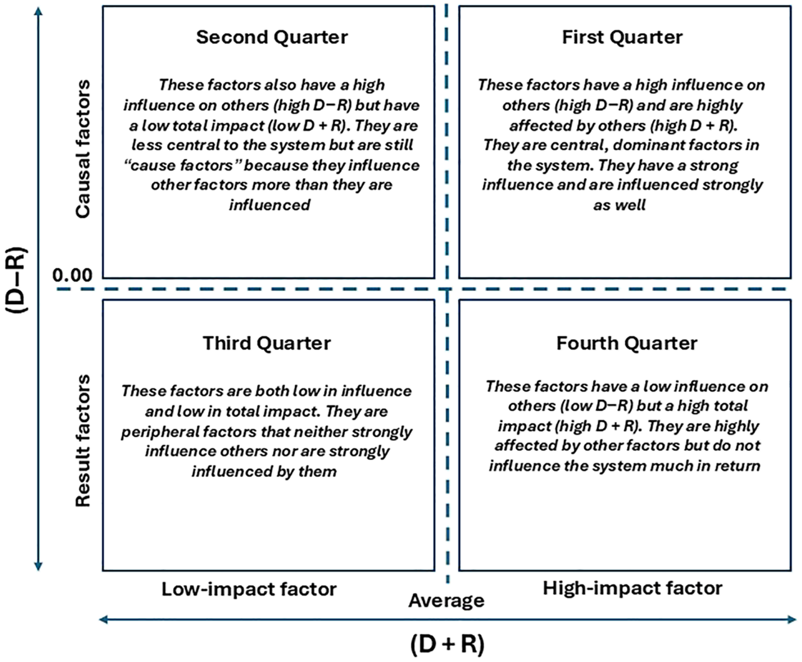
$$\mathrm{CE} = \left(\mathrm{D_i} + \mathrm{R_j}\right)$$

$$\mathrm{CA} = \left(\mathrm{D_i} - \mathrm{R_j}\right) \tag{17}$$

As a result, the causal diagram was divided into four distinct quarters (first, second, third, and fourth) based on the values of "$D - R$" and "$D + R$" (Figure 4) (Mohandes *et al*., 2022).

3.3 Sensitivity analysis

To calculate the probability of a change in the factor region within the DEMATEL model, two key parameters must first be defined: N, representing the number of iterations, and W, representing the range of experts' weights. In this paper, *N* is set to 1,000 iterations, and W is set within the range of [75, 100]. For each participant, their weight is denoted by w, meaning their influence is considered w times in the model. At the start of the process, the iteration index



These factors also have a high influence on others (high D−R) but have a low total impact (low D + R). They are less central to the system but are still "cause factors" because they influence other factors more than they are influenced

These factors have a high influence on others (high D−R) and are highly affected by others (high D + R). They are central, dominant factors in the system. They have a strong influence and are influenced strongly as well

These factors are both low in influence and low in total impact. They are peripheral factors that neither strongly influence others nor are strongly influenced by them

These factors have a low influence on others (low D−R) but a high total impact (high D + R). They are highly affected by other factors but do not influence the system much in return

Figure 4. Impact-relation map (IRM) divided into four quarters for causal analysis. Source: Authors' own work

i is initialised to 1. Then, for each iteration, a random weight is assigned to each participant, and the DEMATEL model is executed based on these weights. After running DEMATEL, the region of each factor is determined and recorded. Once all 1,000 iterations are complete, the factor regions from each iteration are compared. The probability of change for each factor is then calculated by counting the number of iterations in which a change in the region occurs, relative to the total number of iterations (1,000). Figure 5 illustrates the process of sensitivity analysis conducted on the findings.

4. Results

The literature review comprehensively identified the main and subcategories of risk factors contributing to EEOs as summarised in Table 5, to establish a comprehensive and contextually relevant foundation for the study. While the FDEMATEL method has been specifically applied to evaluate safety in EEOs, the majority of identified risk factors are not unique to these operations but are broadly reflective of general conditions and challenges inherent to construction activities. This overlap underscores the systemic nature of the risks and highlights the applicability of the findings to Australian construction operations as a whole.

The cause-and-effect relationships among risk factors were analysed as described above. This analysis provides insights into the influence and dependency levels of the identified causes, helping to distinguish between key drivers and outcomes within the system. The total direct–indirect matrix of all identified causes was calculated prior to the exclusion of minor influences (step 6). Threshold values were subsequently determined for each group to filter out these minor effects. The refined direct–indirect matrix highlights zero values corresponding to the isolated influences (step 8). The cause-and-effect relationships among all causes are illustrated in Figure 6 derived from the values presented in Table 6.

5. Sensitivity analysis

Sensitivity analysis was employed to validate the reliability and strength of the obtained results (Guo *et al.*, 2024).The sensitivity analysis, performed through 1,000 trials with expert weightings varied between 0.75 and 1, reveals that most factors exhibit 0% variation, offering significant insights into the reliability and stability of their positions within the Impact-Relation Map (IRM). G2 (47%), EN (33%), and EQ (7) (29%) exhibited the highest probability of zone variation, indicating significant sensitivity to changes in experts' weightings. CS10 (21%) and CS (13%) showed moderate variation, suggesting some susceptibility to expert input shifts. S (9%) and W12 (7%) demonstrated minimal variation, reflecting a relatively stable position with slight responsiveness to modifications. The overall aggregation value (3%) further highlights the general robustness of the results, with most factors remaining stable despite expert weight variations. These findings underscore the reliability of the aggregated results while highlighting a few factors that require further examination to better understand their interrelations and ensure comprehensive decision-making.

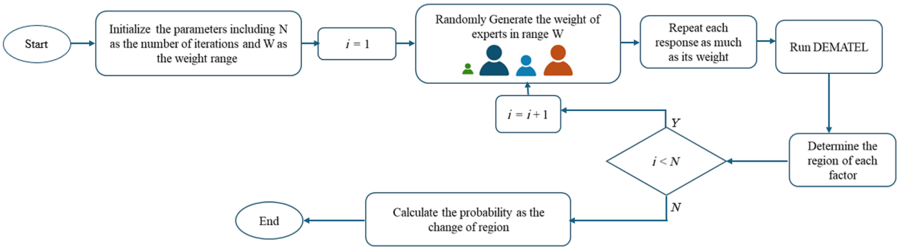


Figure 5. The detailed of sensitivity analysis. Source: Authors' own work

Table 5. Risk factors contributing to accidents in earthmoving equipment operation on Australian construction sites were identified through a review of literature and interviews with experts

The main category of risk factors (Code)	Sub-risk factors (code)	References 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Interview
Government and regulatory association (G)	Safety regulation (G1)		✓		✓					✓				✓		✓	✓	✓	✓	
	Safety supervision (G2)										✓	✓				✓	✓	✓	✓	
	Regulatory training requirements/standards (G3)		✓								✓	✓	✓	✓		✓		✓		
	Authorities'/regulators' permit condition (G4)															✓		✓		
	Verification of competency (G5)									✓				✓		✓	✓			
	Construction equipment registration (G6)															✓		✓		
Commercial management (C)	Client management (C1)				✓			✓					✓			✓				
	Procurement management (C2)		✓					✓								✓				
	Budget (C3)											✓				✓			✓	
Stakeholder safety management (S)	Safety management plan of the principal contractor (S1)								✓							✓	✓	✓	✓	
	Incentive and disciplinary measures of principal contractors for safety management (S2)																	✓		*
	Accident investigation plan by principal contractor (S3)						✓		✓			✓						✓		
	Safety management plan of subcontractor (S4)										✓	✓				✓	✓	✓	✓	
	Safety plan of equipment designers (S5)						✓		✓		✓	✓				✓	✓		✓	
	Qualifications of manufacturers (S6)	✓		✓	✓	✓	✓	✓	✓		✓			✓	✓	✓	✓	✓	✓	
	Safety training by contractors (S7)	✓	✓	✓	✓	✓	✓		✓			✓	✓	✓	✓	✓	✓	✓	✓	
	Equipment maintenance plans by contractors (S8)		✓							✓		✓				✓	✓	✓	✓	
Construction site management (CS)	Site supervision (CS1)				✓		✓				✓	✓		✓	✓	✓	✓	✓	✓	
	Site isolation and warning region setting (CS2)			✓			✓		✓		✓	✓		✓		✓	✓		✓	
	Implementation of safety plan (CS3)															✓	✓	✓		
	Schedule Pressure (CS4)										✓	✓				✓				
	Traffic management plan (CS5)		✓				✓				✓	✓				✓	✓		✓	
	Requirements to submit Safe Work Methods (SWMs) (CS6)										✓					✓	✓		✓	
	Coordination and planning of multiple operations (CS7)																✓		✓	*
	Obstacles and congested site (CS8)																✓		✓	
	Utility-related problems (CS9)							✓		✓		✓				✓	✓			
	Change management (CS10)																			*

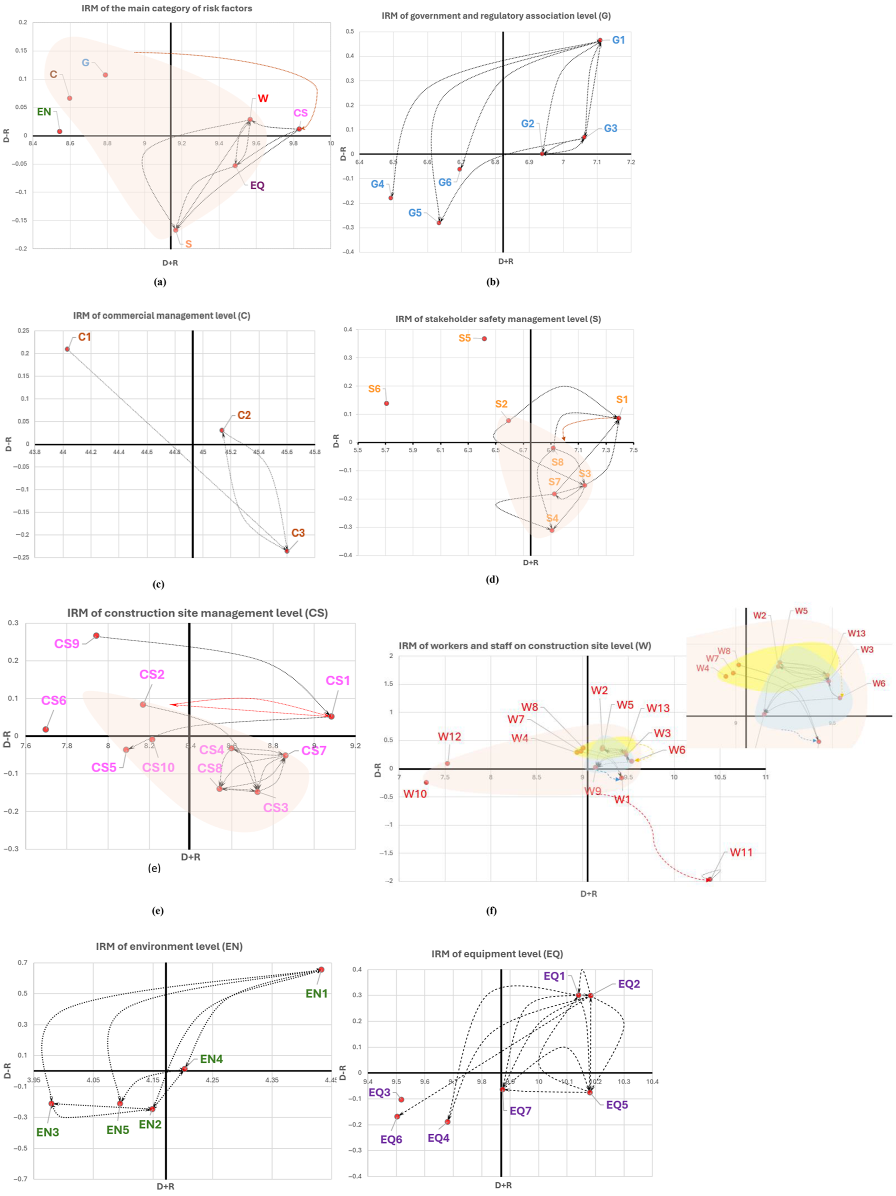
(*continued*)

Table 5. Continued

The main category of risk factors (Code)	Sub-risk factors (code)	References 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Interview
Workers and staff on construction site (W)	Job stress of workers (W1)	✓														✓		✓		
	Workers' knowledge/experience (W2)															✓	✓	✓	✓	
	Lack of hazard/situational awareness of workers (W3)															✓	✓	✓	✓	
	Supervisor's safety inspection (W4)			✓		✓	✓		✓					✓		✓	✓		✓	
	Supervisor's safety commitment (W5)																	✓	✓	*
	Supervisor's safety instruction (W6)						✓										✓		✓	
	Supervisor's character (W7)	✓																✓		*
	Operators' character (W8)	✓												✓				✓		*
	Operators' proficiency (W9)	✓								✓							✓		✓	
	The physical and health quality of the Operator (W10)																			
	Personal protective equipment (PPE) (W11)													✓			✓		✓	
	Operator's employment source (W12)															✓		✓		
	Operation communication (W13)				✓		✓		✓		✓	✓		✓	✓	✓	✓		✓	
Environment (EN)	Weather condition (EN1)										✓	✓				✓	✓	✓	✓	
	Poor visibility (EN2)								✓	✓	✓	✓		✓		✓	✓	✓	✓	
	Site Layout (EN3)						✓		✓		✓	✓		✓		✓	✓	✓	✓	
	Ground condition (EN4)					✓		✓			✓	✓			✓	✓	✓	✓	✓	
	Soil condition (EN5)										✓	✓				✓	✓	✓	✓	
Equipment (EQ)	Safety reliability of attachment of equipment (EQ1)				✓	✓	✓	✓		✓	✓	✓			✓		✓	✓	✓	
	Safety stability of main structural bodies of the equipment (EQ2)					✓		✓						✓	✓	✓		✓		
	Ergonomic level of operator's cab (EQ3)									✓									✓	
	Failure/disorder of the control system (e.g. hydraulic system, error in software) (EQ4)									✓							✓		✓	
	Task-related malfunction (EQ5)		✓	✓			✓					✓		✓	✓	✓	✓		✓	
	Operation aid (e.g. digital display) (EQ6)										✓									
	Blindspot (EQ7)			✓					✓		✓	✓	✓	✓					✓	

Note(s): 1-Edwards *et al.* (2002); 2- Hinze *et al.* (2005); 3- Riaz *et al.* (2006); 4- Edwards and Holt 2008); 5-Edwards and Holt (2010); 6- Riaz *et al.* (2011); 7-Edwards and Holt (2011); 8- Hinze and Teizer (2011); 9-Edwards and Love (2016); 10- Lingard *et al.* (2013a); 11- Lingard *et al.* (2013b); 12- Hinze *et al.* (2017); 13- Kazan and Usmen (2018); 14- Edwards *et al.* (2019); 15- Lingard *et al.* (2021); 16- Safe Work Australia (2021); 17- Sadeghi *et al.* (2023) 18-Safe Work Australia (2024a); and * indicates the sub-risk factors identified by the selected experts during the interview process

Source(s): Authors' own work



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Figure 6. Impact-relation maps (IRM) of main category of risk and sub-risk factors in EEOs. Source: Authors' own work

6. Discussion

This section discusses the main findings of the study, focusing on the various categories of EEOs safety management systems.

Table 6. The cause-and-effect analysis

The main category of risk factors (Code)	Sub-risk factors (code)	D	R	CE (D + R)	CA (D-R)	Located quarter in IRM	Relation
Main category	Government and regulatory association (G)	4.448	4.341	8.789	0.107	Quarter 2	Cause
	Commercial management (C)	4.332	4.266	8.598	0.066	Quarter 2	Cause
	Stakeholder safety management (S)	4.500	4.667	9.167	−0.167	Quarter 4	Effect
	Construction site management (CS)	4.921	4.910	9.831	0.011	Quarter 1	Cause
	Workers and Staff on Construction Site (W)	4.798	4.769	9.567	0.029	Quarter 1	Cause
	Environment (EN)	4.276	4.269	8.545	0.007	Quarter 2	Cause
	Equipment (EQ)	4.717	4.770	9.487	−0.053	Quarter 4	Effect

The main category of risk factors (Code)	Sub-risk factors (code)	D	R	CE	CA	Located quarter in IRM derived from the findings	Relation
Government and regulatory association (G)	Safety regulation (G1)	3.788	3.323	7.111	0.465	Quarter 1	Cause
	Safety supervision (G2)	3.469	3.469	6.938	−0.001	Quarter 1	Effect
	Regulatory training requirements/standards (G3)	3.565	3.499	7.064	0.066	Quarter 1	Cause
	Authorities'/regulators' permit condition (G4)	3.156	3.338	6.494	−0.182	Quarter 3	Effect
	Verification of competency (G5)	3.176	3.459	6.636	−0.283	Quarter 3	Effect
	Construction equipment registration (G6)	3.316	3.381	6.697	−0.065	Quarter 3	Effect
Commercial management (C)	Client management (C1)	22.123	21.914	44.038	0.209	Quarter 2	Cause
	Procurement management (C2)	22.584	22.555	45.139	0.029	Quarter 1	Cause
	Budget (C3)	22.683	22.921	45.604	−0.238	Quarter 4	Effect

(*continued*)

Table 6. Continued

The main category of risk factors (Code)	Sub-risk factors (code)	D	R	CE	CA	Located quarter in IRM derived from the findings	Relation
Stakeholder safety management (S)	Safety management plan of the principal contractor (S1)	3.7394	3.654	7.394	0.085	Quarter 1	Cause
	Incentive and disciplinary measures of principal contractors for safety management (S2)	3.3365	3.259	6.595	0.078	Quarter 2	Cause
	Accident investigation plan by principal contractor (S3)	3.4967	3.649	7.146	−0.152	Quarter 4	Effect
	Safety management plan of subcontractor (S4)	3.2990	3.611	6.910	−0.312	Quarter 4	Effect
	Safety plan of equipment designers (S5)	3.3927	3.026	6.419	0.366	Quarter 2	Cause
	Qualifications of manufacturers (S6)	2.9232	2.786	5.709	0.138	Quarter 2	Cause
	Safety training by contractors (S7)	3.3719	3.554	6.926	−0.182	Quarter 4	Effect
	Equipment maintenance plans by contractors (S8)	3.4492	3.469	6.9185	−0.020	Quarter 4	Effect
Construction site management (CS)	Site supervision (CS1)	4.567	4.516	9.083	0.051	Quarter 1	Cause
	Site isolation and warning region setting (CS2)	4.128	4.044	8.171	0.084	Quarter 2	Cause
	Implementation of safety plan (CS3)	4.289	4.437	8.726	−0.148	Quarter 4	Effect
	Schedule pressure (CS4)	4.284	4.316	8.600	−0.033	Quarter 4	Effect
	Traffic management plan (CS5)	4.026	4.063	8.090	−0.037	Quarter 3	Effect
	Requirements to submit safe work methods (SWMs) (CS6)	3.858	3.841	7.699	0.018	Quarter 2	Cause
	Coordination and planning of multiple operations (CS7)	4.404	4.456	8.861	−0.052	Quarter 4	Effect
	Obstacles and congested site (CS8)	4.200	4.340	8.540	−0.140	Quarter 4	Effect
	Utility-related problems (CS9)	4.104	3.838	7.942	0.266	Quarter 2	Cause
	Change management (CS10)	4.103	4.112	8.215	−0.009	Quarter 3	Effect

(*continued*)

Table 6. Continued

The main category of risk factors (Code)	Sub-risk factors (code)	D	R	CE	CA	Located quarter in IRM derived from the findings	Relation
Workers and Staff on Construction Site (W)	Job stress of workers (W1)	4.626	4.804	9.430	−0.178	Quarter 4	Effect
	Workers’ knowledge/experience (W2)	4.782	4.438	9.220	0.345	Quarter 1	Cause
	Lack of hazard awareness of workers (W3)	4.862	4.619	9.481	0.243	Quarter 1	Cause
	Supervisor’s safety inspection (W4)	4.613	4.335	8.948	0.278	Quarter 2	Cause
	Supervisor’s safety commitment (W5)	4.801	4.427	9.228	0.374	Quarter 1	Cause
	Supervisor’s safety instruction (W6)	4.833	4.707	9.539	0.126	Quarter 1	Cause
	Supervisor’s character (W7)	4.643	4.343	8.986	0.300	Quarter 2	Cause
	Operators’ character (W8)	4.686	4.329	9.015	0.357	Quarter 2	Cause
	Operators’ proficiency (W9)	4.580	4.566	9.146	0.014	Quarter 1	Cause
	The physical and health quality of the Operator (W10)	3.523	3.777	7.300	−0.255	Quarter 3	Effect
	Personal protective equipment (PPE) (W11)	4.211	6.185	10.396	−1.974	Quarter 4	Effect
	Operator’s employment source (W12)	3.809	3.724	7.534	0.085	Quarter 2	Cause
	Operation communication (W13)	4.879	4.595	9.474	0.285	Quarter 1	Cause
Environment (EN)	Weather condition (EN1)	2.544	1.889	4.433	0.655	Quarter 1	Cause
	Poor visibility (EN2)	1.951	2.198	4.149	−0.247	Quarter 3	Effect
	Site Layout (EN3)	1.885	2.095	3.980	−0.211	Quarter 3	Effect
	Ground condition (EN4)	2.108	2.095	4.203	0.013	Quarter 1	Cause
	Soil condition (EN5)	1.942	2.153	4.095	−0.211	Quarter 3	Effect
Equipment (EQ)	Safety reliability of attachment of equipment (EQ1)	5.221	4.920	10.141	0.301	Quarter 1	Cause
	Safety stability of main structural bodies of the equipment (EQ2)	5.241	4.942	10.183	0.298	Quarter 1	Cause
	Ergonomic level of operator’s cab (EQ3)	4.707	4.810	9.517	−0.103	Quarter 3	Effect
	failure/disorder of the control system (e.g. hydraulic system, error in software) (EQ4)	4.745	4.935	9.680	−0.189	Quarter 3	Effect
	Inappropriate application of equipment for tasks being performed/ task-related malfunction (EQ5)	5.053	5.128	10.181	−0.075	Quarter 4	Effect
	Operation aid (e.g. digital display) (EQ6)	4.667	4.836	9.503	−0.169	Quarter 3	Effect
	Blindspot (EQ7)	4.905	4.968	9.873	−0.063	Quarter 4	Effect

Source(s): Authors’ own work

6.1 The main categories of safety management system

As shown in Figure 6(a), in the safety management of EE, construction site management (CS) and workers (W) are positioned in the first quarter, indicating their central and dominant roles within the system. They exhibit high influence on other elements while being strongly influenced themselves, highlighting their pivotal role in interrelationships. CS and W not only exert mutual influence but also collectively shape practices within stakeholders in the S level, influencing how stakeholder-related mechanisms (e.g. safety management plan of the principal contractor (S1)) are developed and enacted. Their embedded operational decisions and interactions serve as upstream determinants of downstream stakeholder actions. Furthermore, the observed influence of the government level (G) on CS underscores how regulatory decisions cascade into construction management processes, ultimately shaping outcomes at the worker level through policies, procedural requirements, and compliance expectations. This interconnectedness explains why technological developments in construction safety often prioritize construction site (CS) monitoring (Soltanmohammadlou *et al.*, 2024b), given its central role as the operational bridge between regulatory directives and frontline activities. Such prioritisation is not only logical but necessary, as CS serves as the point of convergence between policy formulation and physical task execution. However, the environment (EN) is isolated, acting as an external and uncontrollable variable, such as weather conditions, that affects construction operations independently, without being shaped by internal processes, serving instead as a broader contextual influence. In the Australian construction industry, workforce involvement is crucial for a strong safety culture, as their hands-on experience offers insights often overlooked by management. A bottom-up approach leverages these insights to identify hazards and suggest practical safety improvements, ensuring effective and lasting safety strategies (Biggs *et al.*, 2013; Newaz *et al.*, 2019). However, top-down rules often fail to address real-world complexities, whereas involving workers in rule development and maintaining continuous dialogue with management ensures relevance and adaptability (Hale and Borys, 2013a, b). In EEOs, subcontractors act as key sources of safety information in EEOs (Rashidi *et al.*, 2024), supporting a bottom-up approach that refines safety rules dynamically to align with real-world operations (Hale and Borys, 2013a, b). This approach ensures a balanced and practical response to equipment-related hazards, including location-based risks (e.g. movement between zones) and state-based risks (e.g. task-specific actions) (Taher *et al.*, 2019).

6.2 Government and regulatory association (G)

At the G level, safety regulation (G1) holds a predominant position, influencing all other factors in its category (Figure 6 (b)). G1 serves as the central mechanism of Australian construction safety management, ITIS Regulations 2011; Safe Work Australia, 2024b) require PCBUs and supervisors to monitor site operations, identify hazards, and enforce compliance (Safe Work Australia, 2024b). However, the WHS Act and Regulations are flexible and open-ended, lacking specific guidance on ITIS delivery. Similarly, codes of practice provide general compliance advice but offer limited direction and rarely address specific ITIS methods (Bluff, 2019). In Australia, ensuring construction safety is not the sole responsibility of an individual or organisation but requires coordinated efforts across all levels of the system, similar to other complex sociotechnical systems (STSs) (Woolley *et al.*, 2018). However, this integrated approach is rarely fully realised in practice, leading to a gap where those creating construction safety laws may lack critical information needed for informed decision-making.

Regulatory training requirements/standards (G3) are positioned in the first quarter, exerting significant influence on safety regulation (G1), safety supervision (G2), and verification of competency (VOC) (G5). Despite this, the actual implementation of training and competency processes is compromised by the inconsistent performance of Registered Training Organisations (RTOs), which are often poorly regulated. Previous research has identified issues such as low instructional standards, fraudulent practices (e.g. sale of VOC certifications), and inadequate assessment processes (Lingard *et al.*, 2021), all of which undermine the reliability of competency validation in practice.

Despite G5 being in the third quarter with low influence and impact, prioritising VOC remains critical. According to the verification of competency – mobile plant fact sheet, a standardised checklist aligned with the nationally recognised training package should cover hazard identification, risk controls, operator manual requirements, and emergency responses (Office of the Federal Safety Commissioner, 2021). This research highlights that current VOC implementation may not consistently provide reliable evidence of operator competency, revealing key areas of concern:

1. The VOC process lacks a feedback loop to evaluate operator performance over time, which is critical in equipment-intensive and project-specific earthwork operations such as cleaning, excavation, compaction, and grading. Without a mechanism to address skill gaps, refine criteria, or adapt RTO requirements, the VOC process remains static. As a result, it does not ensure operation-specific competency or enable continuous improvement.
2. Without a reliable and standardised VOC process, PCBUs struggle to ensure operator competency for project/task-specific and evolving operational demands. Additionally, this limits PCBUs' ability to address skill gaps and improve safety performance effectively.

Expert interviews confirmed that the VOC process may involve subjective assessments of operator competency and issues such as misalignment with machinery types and associated risks, the use of multiple machines in earthmoving operations, and gaps in task-specific training. This highlights the need for task- and equipment-specific training and evaluation mechanisms to ensure operators have the necessary skills and adaptability for safe and effective performance in diverse operational contexts.

6.3 Commercial management (C)

Figure 6(c) shows procurement management (C2) as a central and dominant factor within the system. While procurement management was not explicitly linked to accident causes in the Australian construction industry (Lingard *et al.*, 2013a), this analysis confirms its influence on other risk factors. C2 plays a pivotal role in ensuring EE safety by influencing the selection of high-quality machinery that meets safety standards (Edwards and Holt, 2011) and aligning with manufacturer performance for optimal safety and efficiency (Soltanmohammadlou *et al.*, 2024a). However, decision-makers often prioritise cost and manufacturer reputation, shaped by client experience, after considering operational and environmental factors (Edwards and Holt, 2011). Budget constraints may lead to compromises on equipment quality and safety features, increasing risks. Additionally, adequate resources must be allocated not only for advanced machinery acquisition but also for workforce training on operational requirements. Technical standards, task step definitions, and hazard identification require further attention to ensure the safe and efficient integration of advanced machinery (Soltanmohammadlou *et al.*, 2024a). EEOs account for a significant portion of project expenses, making up 20% of total costs in construction projects and up to 30% in highway construction (Shehadeh *et al.*, 2022). The position of client management (C1) highlights its influence on work health and safety (WHS) performance in construction through management actions (Lingard *et al.*, 2019) such as budgets, schedules, goals, performance criteria, project delivery methods, contracting approaches, and team selection (Gibb *et al.*, 2014). In Australian construction projects, government agencies as clients play a key role in fostering positive safety cultures through procurement practices (Kiani Mavi *et al.*, 2024; Lingard *et al.*, 2019). Understanding how performance measurement and management interact at the client-contractor interface is crucial for positive WHS outcomes, as clients are key actors in shaping safety practices in the Australian construction industry (Lingard and Pirzadeh, 2025). Clients are not passive overseers but active agents capable of embedding safety into procurement frameworks, thereby enabling system-level safety improvements.

6.4 Stakeholder safety management (S)

Shifting the focus to the stakeholder safety management (S) sub-risk factors (see Figure 6(d)), the safety management plan of the principal contractor (S1) has influence on, accident investigation plan by principal contractor (S3), safety management plan of subcontractor (S4), safety training by contractors (S7), and equipment maintenance plans by contractors (S8), highlighting its pivotal role in driving coordinated safety practices across contracting tiers. Indeed, in interviewing the experts for validation of risk factors, most participants concurred that S1 acts as an umbrella, aligning subcontractor safety plans under a unified system to promote consistency while reducing administrative burdens. They also mentioned that for the safe operation of EE, it is essential to address several key aspects. Insufficient prequalification can increase the risk of unskilled or unqualified sub-contractors being permitted on-site, compromising safety. Clearly defining sub-contractor responsibilities before site commencement is crucial to ensure accountability and compliance. Additionally, outlining comprehensive requirements for site acceptance enhances clarity and establishes necessary safety benchmarks.

Each of the PCBUs such as the principal contractors and EE subcontractors should have flow of information about the risk management of these kinds of operations. Owing to the fact that principal contractors are tasked with bridging the gap between regulatory expectations and on-site realities, necessitating proactive engagement with subcontractors and the implementation of robust safety systems (Biggs and Biggs, 2013; Biggs *et al*., 2013; Loosemore and Andonakis, 2007). Moreover, subcontractors possess valuable tacit knowledge of safe practices, often acquired informally through hands-on job experience. Because of this importance, the safety management plan of subcontractor (S4) is highly affected by S1. To encapsulate, in this level, if sufficient attention is directed toward S1, it is likely to result in substantial improvements in other sub-risk factors. Another noteworthy finding is the position of incentive and disciplinary measures of principal contractors for safety management (S2), represents a factor with significant influence on other elements within the system. Providing rewards and incentives for good safety performance, such as active participation in safety talks, reporting near misses, and identifying unsafe conditions, fosters a safety culture (Jalil Al-Bayati *et al*., 2023). However, experts during the risk factors validation interviews criticised traditional methods like toolbox talks for failing to resolve recurring issues and advocated for rewarding proactive behaviour while ensuring fair accountability for negligence. This approach promotes collective responsibility and aligns with evolving regulations, such as the “chain of responsibility” or which holds senior leaders accountable for endangering workers and underscores the need for ethical governance and adoption of emerging safety technologies (Khorrami Shad *et al*., 2024) . Specifically, the training of subcontractors for operators of EE is essential to facilitate shared decision-making for operations requiring the coordination of a fleet of equipment (Rashidi *et al*., 2024). The positions of the safety plan of equipment designers (S5) and qualifications of manufacturers (S6) highlight their foundational roles rather than acting as drivers of interconnected sub-risk factors. Subcontractors of EE rely heavily on manufacturer-provided equipment characteristics, making it essential that these properties are clearly documented in the equipment manufacturer’s handbook to support contractors in work improvement (Alshboul *et al*., 2024).

6.5 Construction site management (CS)

Figure 6(e) highlights site supervision (CS1) as a central factor in managing sub-risk factors in earthmoving and other construction operations. CS1 connects and supports site isolation and warning region setting (CS2), safety plan (CS3), schedule pressure (CS4), traffic management plan (CS5), coordination and planning of multiple operations (CS7), obstacles and congested site (CS8), and change management (CS10). CS1 is closely linked to the role of the direct supervisor, responsible for assigning tasks and ensuring safety and operational procedures. The hazards of EEOs vary based on machinery combinations, project types, tasks, and sub-tasks, each requiring onsite coordination (Alshboul *et al*., 2024; Taher *et al*., 2022). The role of CS1 underpins the practical enforcement of critical controls such as isolation zones, task sequencing, and traffic planning, particularly essential in EEOs where spatial constraints and task interdependencies are high. The central positioning of CS1 reflects its role as a mediating function that not only interprets safety protocols but dynamically adjusts them in response to site conditions, acting as the interface between planning intentions and real-time operational demands. In Australia, frontline supervisors play a pivotal role in managing high-risk workers and implementing leadership-level safety strategies (Biggs *et al*., 2013). Utility-related problems (CS9) have a high influence on other sub-risk factors (high D-R), emphasising the role of Dial Before You Dig (DBYD) in Australia. DBYD acts as a critical boundary object, fostering consensus for safe practices, ensuring infrastructure integrity and public safety, and facilitating data transfer about existing buried infrastructure between utility companies and those planning excavation work (Moshtaghian and Noorzai, 2023) in sociotechnical systems.

While Safe Work Methods (SWMs) (CS6) is located in the second quarter with high influence, its lack of direct connections to other risk factors suggests a fragile integration into broader site safety systems—where changes in related practices may not be adequately captured or adjusted. In the Australian context, SWMs are legally mandated for high-risk construction work (HRCW), such as excavation with intense equipment operation, and must be completed in writing (Zhu *et al*., 2024). However, discrepancies exist between SWMs as imagined and as performed, as they are often developed by back-office employees, consultants, or head contractors with little input from workers, leading to low engagement and minimal updates during high-risk tasks (Bluff, 2019). Addressing HRCW gaps, such as excavations exceeding 1.5 m involving EE, requires comprehensive hazard assessments, including risks from multiple machines and tasks. PCBUs are legally required to engage workers in managing WHS risks, but socio-psychological barriers, such as low literacy and non-English-speaking backgrounds, hinder hazard identification and SWMs compliance (O’Neill *et al*., 2022). SWMs are widely recognized by WHS regulators and contractors as lacking practical impact, yet they remain unchallenged. Until workers and practitioners expose these flaws, the system will persist, reinforcing the “tick and flick” approach to documentation (Lingard *et al*., 2021).

6.6 Workers and staff on construction site (W)

Figure 6(f) highlights human-related sub-risk factors in the first quarter, including supervisor’s safety commitment (W5), workers’ knowledge/experience (W2), operation communication (W13), lack of hazard/situational awareness of workers (W3), supervisor’s safety instruction (W6), and operators’ proficiency (W9). Refining these factors would lead to corresponding improvements in the cluster. Expert interviews confirmed that W5 acts as a canopy for the supervisor’s safety inspection (W4) and supervisor’s safety instruction (W6), influencing on-site safety management and safety culture. However, the high D + R value of Supervisor’s safety instruction (W6) demonstrates its pivotal function in shaping interconnected workforce-related risk factors, positioning it as a central mechanism through which broader safety outcomes can be effectively influenced. Supervisors who provide consistent guidance, engage in safety practices and respond to concerns reinforce safety awareness and help apprentices apply up-to-date safety knowledge (W2) from TAFE to on-site operation. A strong supervisor-worker relationship allows workers to raise safety issues, contribute to SWMs, and discuss personal challenges (Oswald *et al*., 2022). Effective safety instructions (W6) depend on supervisors’ qualifications, which are particularly crucial in HRCW, such as excavation (Tang *et al*., 2019; Winge *et al*., 2019). Minimal supervision and inadequate instruction (W6) contributed to the serious injuries of two young, inexperienced workers on their first day at a construction site in NSW (Loosemore and Andonakis, 2007).

The high injury risk among inexperienced workers is attributed to a lack of workers' knowledge and experience (W2), hazard awareness (W3), ability to handle unexpected events, understanding of workplace safety policies, and greater exposure to hazardous conditions (Breslin *et al.*, 2019). The lack of hazard/situational awareness of workers (W3) is influenced by the repetitive nature of EEOs, which reduces attention and varies based on awareness levels (Hussain *et al.*, 2024). Construction equipment operation relies on cognitive functions such as selective attention, situational awareness, and spatial cognition, further affected by individual factors like experience, fatigue, and working memory, as well as external conditions such as pedestrian workers and other equipment (Cheng and Teizer, 2014; Fang and Cho, 2017). These operations require shared hazard/situational awareness (W3), along with individual recognition of skills, knowledge, and their contribution to team efforts (Harris *et al.*, 2024).

Effective operation communication (W13) enhances the safety climate (Kima *et al.*, 2024) and outcomes in EEOs, such as excavator crews. Communication failures contributed to 17% of 81 fatal plant and machinery incidents on Australian construction sites (Lingard *et al.*, 2013b). Improved operational communication (W13) has the potential to enhance multiple interconnected worker-related factors in EEOs, including reducing job stress of workers (W1), strengthening workers' knowledge and experience (W2), increasing situational awareness (W3), reinforcing supervisors' safety commitment (W5) and instruction (W6), improving operators' proficiency (W9), and ensuring more effective use of personal protective equipment (W11). Improved operational communication fosters clearer task expectations, facilitates timely feedback, and supports informed decision-making on-site. As coordination among workers and supervisors improves, it creates a more supportive environment that indirectly benefits EE's operators, who frequently rely on such interactions for safe and effective task execution (Mehmood *et al.*, 2024). Although operators' proficiency (W9) requires adequate training and competency in handling EE and attachments. While formal licenses are not always required, reliance on the VOC process (see section 6.2) raises concerns about assessment consistency, leading to gaps in safety practices, this collective communication reduces cognitive load, enhances situational awareness, reinforces supervisory guidance, encourages proper use of protective equipment, and supports overall task proficiency across the crew (Zamani *et al.*, 2020). Finally, W11 (Personal Protective Equipment) emerges as a risk factor highly influenced by other risk factors within the workforce group. It also exerts cascading influence, meaning that its proper or improper use can significantly affect overall safety performance.

6.7 Environment (EN)

Figure 6(g) highlights weather condition (EN1) as the central factor at the environment level, influencing all other environmental risk factors. This prominence reflects its recurring presence in the literature, where it is often noted for its impact on the physiological and psychological well-being of construction workers in the Australian context (Alashwal and Moustafa, 2022). Increased injury rates have been linked to the frequent operation of heavy machinery and power tools, especially when combined with prolonged exposure to direct sunlight. (Xiang *et al.*, 2014). EEOs in road and highway projects expose workers to heat-generated process such as hot asphalt and paving (Fatima *et al.*, 2023; Taher *et al.*, 2022). Repetitive tasks, combined with weather conditions, further exacerbate fatigue among operators and pedestrian workers. Weather conditions significantly impact safety in Australia, with operators often pressured to work in unsafe conditions to meet deadlines (Lingard *et al.*, 2021). The willingness to halt work in adverse weather varies, influenced by judgement, personality, and employment arrangements. While reputable companies follow safety standards, others may encourage unsafe practices and increasing risks. Heat-related policies in Australian construction remain underdeveloped and require improvement (Fatima *et al.*, 2023). Ground condition (EN4) is another key risk factor, affecting EEOs near the operation of construction equipment like cranes. Unstable ground and underground services pose significant hazards, especially when multiple crews prioritise deadlines over safety (Lingard *et al.*, 2021).

6.8 Equipment (EQ)

Figure 6(h) highlights Safety reliability of attachment of equipment (EQ1) and safety stability of main structural bodies of the equipment (EQ2) as central factors within the equipment level, showing strong mutual influence. These two interrelated factors collectively impact other equipment-related risks, including failure or disorder of the control system (EQ4), Inappropriate application of equipment for tasks being performed (EQ5), and Blindspot issues (EQ7), indicating that deficiencies in structural stability or attachment reliability can propagate to systemic malfunctions. These two ITIS risk factors align with safety plan of equipment designers (S5) and qualifications of manufacturers (S6) at the stakeholder management level, underscoring their role in equipment design, operational standards, and compliance with OEM recommendations (Edwards *et al.*, 2019). EE classification varies (Taher *et al.*, 2022), but the use of excavators as cranes introduces significant safety hazards, often overlooked by stakeholders. Improper load connection methods and non-compliance with manufacturer guidelines highlight the need for adhering to protocols and integrating proper equipment usage into risk management (Edwards and Holt, 2010). Additionally, assessing excavator stability under dynamic load conditions instead of relying solely on tilt-table performance data can enhance equipment selection and stability considerations (Edwards and Holt, 2009, 2011). Inappropriate application of equipment for tasks (EQ5) is positioned in the fourth quarter, reflecting high dependency on other risk factors. This highlights the importance of a well-defined step-by-step breakdown of tasks and sub-tasks to ensure proper equipment selection, reducing risks and improving operational safety (Soltanmohammadlou *et al.*, 2024a). Reassigning an excavator’s function alters its classification, changing associated hazards and risk factors (Taher *et al.*, 2022).

7. Implications

7.1 Technological implications

A clear understanding of cause-and-effect relationships within EEOs reveals that, although the most influential factors lie at the construction site management and workforce levels, both maintain a reciprocal relationship with stakeholder safety management level. The stakeholder management level often serves as the central hub for executing corrective measures, where tangible actions are taken not only to increase awareness but also to translate knowledge into practical improvements (e.g. safety management plans by contractors) (Woolley *et al.*, 2018). Technological interventions across these interconnected levels can support vertical, horizontal, and end-to-end integration of safety management by aligning frontline practices, supervisory actions, and strategic oversight as part of a unified system. This opens the avenue for combining technological solutions to integrate the core functionalities of anticipation, prevention, response, and AI-driven learning within a multi-layered risk management system (Soltanmohammadlou *et al.*, 2024b) that supports task-specific operation in EEOs, human-cantered vulnerabilities, and regulatory compliance simultaneously.

Technologies such as Building Information Modelling (BIM), when integrated meaningfully, can support this multi-level coordination by offering a shared digital environment where regulatory requirements, site-specific conditions, and operational sequences are visualized, simulated, and adjusted in real-time. When we return to the risk factors identified in this research, it becomes clear that technologies must align closely with real-time, task-based risk management. For example, SWMS as documents often remain static in excavation operation, BIM transforms this paradigm by linking these static plans with dynamic site conditions through real-time visualization and data integration. For instance, BIM empowers supervisors to embed SWMS directly within the 3D model environment, enabling the spatial mapping of specific workspaces, tasks, and hazard zones in alignment with the construction schedule via the Work Breakdown Structure (WBS) in EEOs (Moon and Seo, 2017). Through 4D BIM, principal contractors can simulate safety-critical sequences, such as excavation near temporary structures, and proactively adjust timelines or site layouts to mitigate risks, as demonstrated in the study by Abed *et al.* (2020). Supervisor instructions can be dynamically linked to model-based alerts and digital workflows, ensuring that high-risk scenarios, such as potential trench collapses or activity clashes in EEOs (Abed *et al.*, 2020; Khan *et al.*, 2019), are communicated in real time through visual and data-rich interfaces. Integrating ontology-based knowledge of earthwork operations into BIM has the potential to illuminate the entire excavation lifecycle by transforming BIM from a geometric modelling tool into a semantic, system-aware platform.

The Earthwork Ontology (Taher *et al.*, 2022) enables formal representation of critical concepts such as equipment types, micro-tasks, hazard categories, soil classifications, and regulatory requirements. This structured knowledge allows BIM systems to reason about cause-effect relationships across phases and actor levels, improving hazard detection, excavation planning, and compliance validation. When combined with monitoring technologies like computer vision (for behaviour, task, pattern, and activity recognition), sensor-based systems (for real-time monitoring), and digital twins (for simulation and feedback), BIM becomes the backbone of an integrated safety management system. These connections allow for vertical integration (from policy to site operation), horizontal integration (across project stages and stakeholder roles), and end-to-end integration (from planning through operation and post-excavation review) (Khan *et al.*, 2019).

7.2 Research and managerial implications

Understanding cause-and-effect relationships among risk factors enables proactive risk mitigation. For safety managers, this means gaining clearer insights into where interventions should be prioritized within EEOs. This study introduces those focal areas by accounting for context-based influences and identifying reflective zones where upstream causes manifest. Additionally, the empirical representation of causal risk factors, informed by expert insights, serves as an inductive guide for earthmoving operation planners and managers to understand risk factors based on project conditions and policy settings. This has direct implications for improving safety documents, such as codes of practice, SWMs, and VOC. Policy reforms should emphasize collaborative SWMS development with frontline workers and VOC should be reclassified and regulated as a structured certification process tailored to specific equipment types and task complexities within EEOs. The emergence of supervisory factors across various levels, such as site supervision (CS1) and supervisor safety commitment (W2), as causal elements presents an opportunity for stakeholders to enhance supervisory safety leadership characteristics and practices (Oswald *et al.*, 2022). For example, the emergence of supervisory factors across various levels, such as site supervision (CS1) and supervisor safety commitment (W2), as causal elements highlight the need for stakeholders to enhance supervisory safety leadership characteristics and practices.

The study’s findings also prompt critical inquiries into WHS practices, particularly regarding codes of practice for HRCW, such as excavation, which relies heavily on comprehensive and high-level safety instructions. The study highlights the need to address EEO hazards through a structured ITIS delivery. When training processes are aligned with task-specific safety requirements, contractors are better equipped to meet both operational goals and compliance expectations. Moreover, environmental influences such as weather have drawn attention to the issue of providing more weather-responsive regulations by government agencies, where weather is identified as the primary environmental risk in construction operations.

8. Future research and limitations

Future research could prioritize the most influential factors and further investigate their interconnections to gain a deeper understanding of their impact. Additionally, future studies should focus on developing Decision Support Systems (DSS) and Expert Systems (ES) to facilitate data-driven safety interventions. Applying the Hierarchical DEMATEL method for analysing complex systems (Du and Li, 2021) is essential for addressing the challenges experts face in evaluating relationships between multiple factors. In Australian construction safety research, MCDM methods remain underexplored, with existing studies predominantly qualitative. This research paves the way for integrating additional MCDM models, such as AHP, ANP, or fuzzy TOPSIS, allowing researchers to compare results across methodologies for a more thorough examination of risk factor behaviour. This research also offers a structured foundation for exploring the dynamics of risk factors in EEOs through a systems ergonomics lens, particularly using the Event Analysis of Systemic Teamwork (EAST) framework, which analyses systems across task, social, and information networks. The identification of dominant causal factors paves the way for a longitudinal ethnographic study and network-based inquiries that capture how safety is shaped through interactions among roles, tasks, and flows of information.

This research has several limitations that should be acknowledged. First, its geographic focus is limited to the Australian construction context, which may affect the broader applicability of the findings to other regions with different regulatory or operational environments. Second, the use of purposive sampling, while appropriate for targeting expert insights, may limit the generalizability of the results. Moreover, it does not differentiate between organizational sizes, small, medium, and large enterprises, which may exhibit distinct safety capacities and practices, particularly in WHS system maturity. As a final point, the analysis does not account for the temporal evolution of causal risk factors, leaving the dynamic nature of risk interactions underexplored.

9. Conclusions

This study was driven by the need for formal risk modelling in EEOs to streamline hazard recognition, evaluation, and risk assessment, ensuring more targeted and effective interventions within the Australian construction context. In Australian construction safety research, no prior study has examined the importance of existing causes and their interrelationships within a system while addressing the uncertainty inherent in construction activities, particularly in EEOs. This research conducted a meticulous investigation, integrating a one-step qualitative approach, which validated expert identification of EEO risk factors, with a quantitative three-step methodology. The quantitative approach combines corrected item-total correlation and split-half methods to calculate response consistency within the FDEMATEL framework, followed by rigorous sensitivity analysis to ensure robustness and reliability. The results uncover cause-and-effect relationships of risk factors across each level of (Rasmussen, 1997) RMF using a systems thinking approach, culminating in an Impact Relations Map (IRM) that classifies risk factors based on their causal and effect-driven roles. This understanding provides a foundation for guiding the integration of targeted technologies to address causal factors more effectively and enhance system-wide safety interventions.

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