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# Comprehensive factor analysis and risk quantification study of fall from height accidents

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ABSTRACT

Working at heights poses frequent and significant risks, demanding scientific approaches for investigating fall-from-height (FFH) incidents and proposing preventive measures to enhance building safety. Nevertheless, ongoing research on analyzing the causal factors behind fall-from-height accidents lacks a comprehensive qualitative and quantitative assessment of the interplay between these factors. To bridge this gap, this study introduces an integrated risk analysis model. Utilizing incident reports and leveraging the multi-case rootedness theory, the model initially identifies influential elements. Subsequently, employing the Grey Decision Making Laboratory (Grey-DEMATEL) and Interpretive Structural Modeling (ISM) techniques, a hierarchical network is constructed, followed by the transformation of this hierarchical network model into a Bayesian Network (BN) model using GeNie2.0 software. Ultimately, the study was based on data from 420 accident cases and analyzed the causes and diagnosis of the accidents. The findings indicate that A5 (Low-security awareness) is the most significant factor contributing to falls from great heights and that the connection between the components is dynamic and non-linear rather than simply independent and linear. Furthermore, the study established a likelihood of occurrence of such incidents of up to 57 % and ranked the probability of occurrence of each contributing component in the case of a fall from height. This study presents a scientifically valid method for analyzing fall-from-height accidents. Experimental results confirm the model's applicability, empowering contractors to improve safety management by accessing precise risk information and prioritizing preventive measures against interrelated accidents. The model facilitates informed decision-making for contractors to effectively mitigate fall-from-height risks and establish a safer working environment.

## 1. Introduction

In our technologically and industrially advanced society, the construction industry assumes a prominent position, making a substantial contribution to the gross domestic product (GDP) and serving as a pivotal driver of socio-economic development [1,2]. As outlined in the "Statistical Analysis of Construction Industry Development in 2022″ by the China Construction Industry Association, the number of construction enterprises in China has surged from 62 in 1952 to 143,621 by the conclusion of 2022. This proliferation of

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construction enterprises has concomitantly led to a proportional escalation in the industry's output value, thereby significantly enhancing its contribution to the national economy [3].

However, such progress in the industry often goes hand in hand with occupational accidents and health-related issues, and the construction sector is no exception. It currently grapples with a concerning frequency of construction safety incidents [4,5]. Notably, data from the Ministry of Housing and Construction of China reveals that falls from heights (FFH) have consistently accounted for a substantial share of construction accidents in recent years. These FFH incidents result in casualties and property damage, emphasizing their gravity. Within construction, FFH accidents are both frequent and severe, demanding global attention. Beyond jeopardizing workers' physical well-being and safety, these occurrences significantly impede construction project timelines and escalate costs. Consequently, a thorough exploration of the causes behind FFH accidents, a scientific quantification of risk intensity, and the proposition of preventive measures are all of paramount significance [6].

Existing research in FFH analysis has focused on accident factor relationship analysis and prediction. To delve more profoundly into the causal elements of FFH, endeavors have been undertaken to formulate models and techniques, including fault tree analysis (FTA), statistical analysis, and machine learning approaches [6–11]. Nonetheless, these studies frequently lack a comprehensive exploration of FFH incidents, omitting a thorough qualitative and quantitative examination of the intricate causal interconnections between factors. In reality, the contributory factors to FFH are abundant and intricately interrelated, demanding a combined qualitative and quantitative strategy to unveil the interplay among diverse accident causes.

To tackle this challenge, this study introduces an innovative amalgamation of the Grey Decision Experimentation Technique (Grey-DEMATEL), Interpretative Structural Model (ISM), and Bayesian Networks (BN) to effectively dissect and quantify the underlying relationships among the causal determinants of FFH.

Furthermore, conventional methods for extracting causal factors, such as expert reviews, brainstorming, and questionnaire surveys, often carry subjectivity and overlook the interdependency and feedback loops between factors [11]. To surmount this limitation, this article adopts the multi-case rooting theory for factor extraction, augmenting the objectivity of factor identification [12].

In conclusion, this study employs a combination of theoretical analysis and the examination of actual accident instances to identify the causal factors contributing to falls from heights (FFH). To achieve this, the research utilizes the Grey Decision Laboratory Technology (Grey-DEMATEL), which offers enhanced transparency and addresses the limitations observed in traditional DEMATEL methodologies [13–16]. Additionally, the study employs the Interpretive Structural Modeling (ISM) approach to explore the underlying structural interactions among various components and uncover immediate, transitional, and foundational causes [17–19]. Subsequently, the hierarchical ISM model is integrated into the Bayesian Network (BN), with real accident case data being transformed into conditional probability distributions. Through the BN, the study quantifies the strength of correlations between variables. As a result, this integrated analytical framework, known as Grey-DEMATEL-ISM-BN, not only presents an effective method for risk management about falls from heights but also offers a theoretical pathway for future advancements in this field.

## 2. Literature review

This section will review the literature related to construction safety management and fall-from-height accidents (FFH) in construction.

### 2.1. Review of literature related to construction safety management

Globally, research about construction safety management primarily centers on averting construction safety incidents via diverse approaches, encompassing accident causation analysis, evaluation, and the application of construction safety. Among these, accident causation analysis assumes a pivotal role within the safety research realm. For instance, Suraji et al. [20]. employed an accident causality model as a conduit to spotlight intricate interactions among factors. Zubaida et al. [21]. employed questionnaire-based research, concluding that the awareness of construction personnel predominantly shapes safety outcomes on construction sites, followed by effective on-site communication. Drawing from an analysis of 176 accidents within the Norwegian construction industry, Winge et al. [22]. established that accident types vary across building losses and building types. Employing Principal Component Analysis (PCA), Chiang et al. [23]. undertook a comprehensive factor analysis of fatal construction accidents in Hong Kong, intending to furnish future solutions for global construction safety management.

### 2.2. A review of studies analyzing the causes of falls from height accidents (FFH)

The issue of falls-from-height accidents (FFH), a profoundly researched topic within the construction process, has garnered significant attention from experts and scholars in recent years. Different theories, models, and research perspectives have been harnessed to conduct thorough investigations into FFH, aiming to formulate corresponding preventive and control measures. As an example, Hora et al. [24]. employed the TOH method to deeply analyze FFH stemming from scaffolding, revealing that accident-causing factors encompass technical, organizational, and human elements, with organizational factors wielding dominant influence. Developing a fuzzy AHP risk assessment model for FFH, Shi et al. [8]. ultimately affirmed the congruence of their evaluation outcomes with real-world conditions. Chi et al. [25]. opted for the fault tree analysis method to comprehensively scrutinize the causal components of FFH in the building sector. Drawing from the dataset of 23,057 FFH cases provided by the National Institute for Occupational Safety and Health (NIOSH), Yahia et al. [6]. delved into FFH trends through frequency analysis, correlations between accident factors and injury levels, and logistic regression analysis. These efforts culminated in the creation of a predictive model capable of diagnosing fatal and non-fatal accidents.

### 2.3. Research gaps and contributions

According to the aforementioned literature, several methods have been proposed in existing research to study falls-from-height accidents (FFH), including statistical analysis [6], machine learning [7], expert systems [8], and fault tree analysis (FTA) [9]. However, these methods have the following limitations in their ability to identify causal relationships among the factors that lead to accidents:

1. Statistical analysis methods may assume that relationships are linear or additive, while causal relationships are usually nonlinear or interactive [26];
2. Machine learning methods that rely on large data sets to identify associations [26];
3. Expert systems approaches rely on the knowledge and experience of subject matter experts to identify the factors that contribute to building fall accidents [26];
4. FTA fails to provide a comprehensive understanding of the underlying causes of an issue and may overlook potential contributing factors that are not directly related to the problem [26].

In conclusion, typical factor analysis methods or models are incapable of thoroughly analyzing and quantifying the causative components of FFH, and previous research lack a comprehensive investigation on the causal factors of FFH. Given this, the research incorporates the Grey-DEMATEL-ISM-BN technique in a new way to find and quantify hidden interactions and complicated correlations among components, which has not been tried in previous works [27]. It aims to conduct a more comprehensive and systematic causal analysis of FFH, which is of great significance to the safety production of building construction, and to summarize the general rules of FFH on this basis. The core contributions of the article are as follows:

1. FFH poses a significant risk to construction projects, leading to casualties. Through comprehensive analysis methods, this article identifies patterns and potential risk factors, providing a scientific foundation for enhancing worker safety and reducing accident rates.
2. FFH can have significant cost consequences for the business, including cleanup, repairs, and compensation. However, by using BN analysis on real-world accident instances, this study is able to forecast accident likelihood, allowing for prompt preventative steps and lowering possible economic losses.
3. This article investigates and analyzes FFH causal links, finds inadequacies and weaknesses in the building process, and uses this information to offer specific suggestions.

## 3. Construction falls from height accidents (FFH) causative factor index system construction

### 3.1. Causal factor extraction based on multi-case rooting theory

Falls-from-height accidents (FFH) are highly comprehensive safety accidents, which are not caused by a single factor. Therefore, the objectivity, reliability, and comprehensiveness of the selection of causal factors will directly affect the reliability of the research results [28].

(1) Access to accident investigation reports

This study draws upon primary data sourced from accident investigation reports accessible on the websites of diverse departments, including the State Administration of Work Safety, the State Ministry of Housing and Urban-Rural Development, as well as provincial and municipal administrative bodies [29–31]. To uphold both the representativeness and objectivity of the reports, the study adheres to specific screening principles: (1) The accident investigation reports must originate from authoritative organizations, guaranteeing their accuracy and reliability; (2) These reports should comprehensively elucidate the environmental conditions during the accident, the accident progression, outcomes, causal analysis, and safety management recommendations. The study meticulously examined 420 instances of FFH taking place in different regions of China from 2012 to 2023. The sample encompasses 380 common FFH cases and 40 significant incidents, encompassing diverse FFH types, such as falls from holes and scaffolding [32].

(2) Extraction of causal factors

Data-driven, through the mobile Internet or other related software as a means to collect massive data, data organization, and the formation of information, and then integrate and refine the relevant information [33]. Based on this concept, this study started with a data-driven strategy to extract 27 accident factors. These factors were derived from 420 construction-related fall from height (FFH) investigation reports. The study then combines the relevant factors and assesses their frequency and prevalence using multi-case root cause theory. The results of the factor extraction are shown in Exhibit 1, which resulted in the identification of 23 accident factors.

(3) Construction of causative factor framework

The article numbered the causal factors by multi-case rooting theory, which led to the framework of causal factors for falls-from-height accidents (FFH), as shown in Fig. 1.

### 3.2. Description of causative factors of fall from height accidents (FFH)

In summary, the article refers to the element classification of trajectory intersection theory and classifies the causal factors of FFH into four categories, such as “human - material - environment - management".

(1) Human factors

A1. Violation of work rules and operating errors.

Violation of regulations and operational errors are actions by construction personnel that do not follow relevant laws or regulations, resulting in potential safety risks.

A2. Command violation, command error.

Command violation, command error will directly affect the operation of the builder, which in turn brings risk to the site safety management.

A3. Lack of safety operation skills and knowledge.

Lack of safety skills and knowledge of construction workers to carry out construction work at height.

A4. Improper use of protective equipment.

Construction workers do not use protective equipment in accordance with the appropriate safety regulations.

A5. Low security awareness.

When the lower the safety awareness of site personnel, the more likely it is that violations will occur, thus causing harm.

A6. Mental or physical discomfort of workers.

The psychological or physical condition of workers working at heights is directly related to the quality of the project.

(2) Material factors

B7. Inadequate safety due to lack of timely maintenance and repair of equipment.

When the machinery and equipment is not maintained and serviced in a timely manner, it will lead to a lack of safety in its use, resulting in potential safety hazards.

B8. Insufficient safety of the support system.

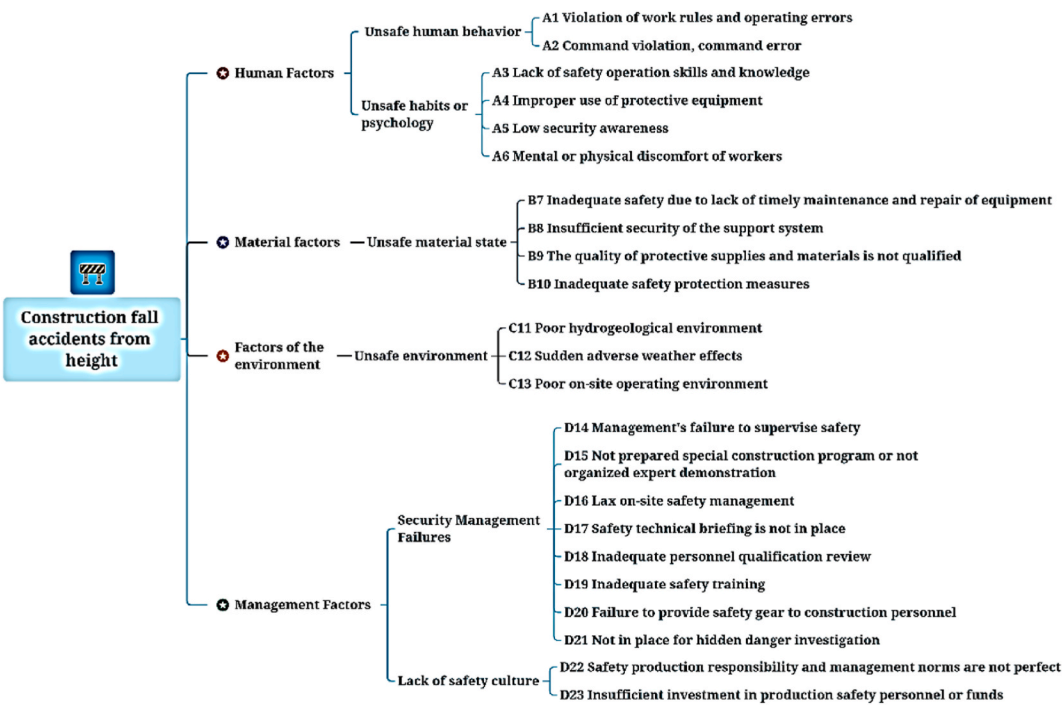



**Fig. 1.** Factor framework structure diagram.

However, in the process of construction, due to problems such as operator error, the support system cannot meet the use standards, i.e., the degree of safety is insufficient.

B9. The quality of protective supplies and materials is not qualified.

In addition to mechanical equipment, the quality of protective supplies and materials also directly affects the quality and safety of the entire construction process.

B10. Inadequate safety protection measures.

In such a complex environment, there are many potential risks. Construction accidents caused by inadequate safety precautions, etc., can be seen everywhere.

(3) Environmental factors

C11. Poor hydrogeological environment.

Having good natural geological conditions at the construction site is a prerequisite to ensure construction safety.

C12. Sudden adverse weather effects.

In addition to hydrological and geological conditions, sudden adverse weather effects may cause FFH, such as typhoons, thunderstorms, etc.

C13. Poor on-site operating environment.

The good or bad working environment on site will directly affect the working condition of construction workers.

(4) Management factors

D14. Management's failure to supervise safety.

Management's failure to supervise safety refers to the construction site management's failure to fulfill its own responsibilities, resulting in a lack of safety supervision on site.

D15. Lacking a well-prepared construction plan or an organized expert demonstration.

Preparing a special construction plan and organizing expert demonstrations are necessary to ensure the quality and safety of a construction project. Without these measures, the risk of accidents increases.

D16. Lax site safety management.

Slack site safety management refers to the lack of safety management personnel on site resulting in disorderly safety.

D17. Safety technical briefing is not in place.

A safety technical briefing specifies the work supervisor's requirements for a construction project, including potential hazards, danger sources, construction techniques, necessary safety measures, and procedures.

D18. Inadequate personnel qualification review.

Inadequate personnel qualification review is likely to lead to unqualified personnel on the job, thus leading to accidents.

D19. Inadequate safety training.

Systematic safety training is a prerequisite for strengthening personnel safety awareness, improving the quality of all personnel safety capabilities, and ultimately improving safety behavior.

D20. Failure to provide safety gear to construction personnel.

Failure to provide safety gears to construction workers will result in the workers not being able to wear the safety gears properly, thus laying a potential risk for accidents to occur.

D21. Hidden danger investigation has not been properly executed.

Timely inspection of construction hazards can effectively prevent the occurrence of construction fall accidents from heights.

D22. Inadequate safety production responsibility and management norms.

Imperfect safety production responsibility and management norms refer to the unclear safety production responsibility of each main unit at the construction site and the lack of perfect management norms for control.

D23. Insufficient investment in production safety personnel and funds

Insufficient production safety personnel and capital investment refers to the lack of production safety personnel on the project site or insufficient project funds.

## 4. Methodology

Currently, Grey-DEMATEL, ISM, and BN are usually used alone or in combination in the literature, while fewer studies are using all three methods simultaneously. In this paper, we suggest the following reasons for combining Grey-DEMATEL, ISM, and BN for the causal analysis of fall-from-height (FFH) accidents: by combining these three methods, we can make up for the deficiencies of their respective methods and improve the comprehensiveness and credibility of the analysis. Grey-DEMATEL can eliminate the limitations of traditional DEMATEL and deal with the problem of incomplete data; ISM can reveal causality and structural hierarchy; and BN can deal with uncertainty and quantify factor relationships [16,34].

In conclusion, the combined use of the three methods can lead to more comprehensive and accurate results in analyzing the causal factors of FFH. The framework of the analysis methodology is shown in Fig. 2 below.

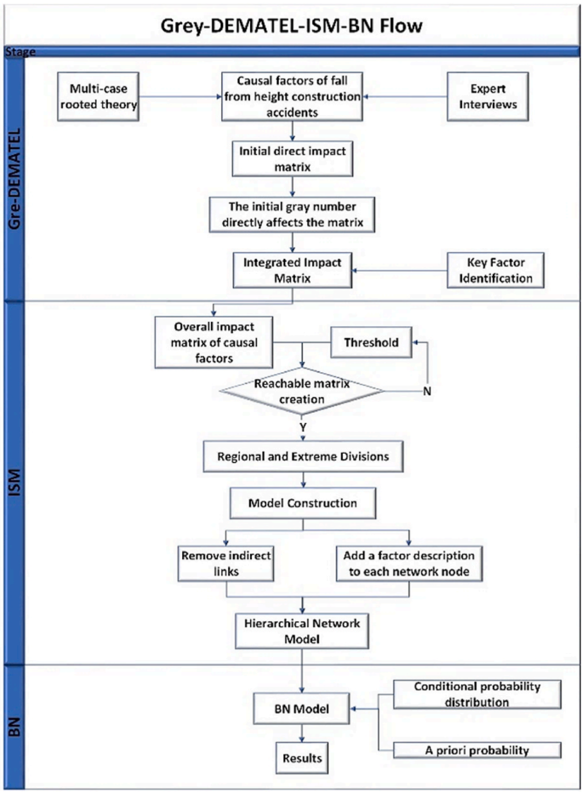



**Fig. 2.** Analysis method framework diagram.

### 4.1. *Causal analysis of fall from height accidents (FFH) based on grey-DEMATEL-ISM*

Although the traditional DEMATEL method makes full use of experts' experience and knowledge in scoring, it still has the defect of assigning too definite values, so the article introduces grey number theory to solve this problem and make the evaluation results more consistent with the actual [15,35,36].

The flow of the causal analysis of fall-from-height accidents (FFH) based on Grey-DEMATEL-ISM is as follows (all calculations below are done by MATLAB) [15]:

(1) Determination of FFH causal factors. The article collects and studies 420 cases of FFH to propose several causal factors, identifies the causal factors to be studied, and clarifies the meaning of each factor based on expert judgment and literature analysis.
(2) To construct the initial direct impact matrix P, this paper identified 23 causal factors contributing to FFH through expert consultation.

Given the intricate interplay among key factors within complex systems, quantification becomes imperative to scrutinize their correlations. This study delved into the direct mutual influence of factor gi on factor gj, taking into account their inherent connections. For the assessment of causal relationship strength, a five-level scale questionnaire survey was conducted and subsequently evaluated by pertinent experts. The scale encompassed categories of very strong influence (4), strong influence (3), weak influence (2), presence of weak influence (1), and absence of influence (0). Twenty questionnaires were disseminated to professors, associate professors at Changsha University of Science and Technology, and safety supervisors at local construction enterprises.

20 questionnaires were distributed to professors, associate professors from Changsha University of Science and Technology, and safety supervisors from local construction enterprises. The paper received 20 replies with a 100 % collection rate, enabling the determination of the direct impact matrix $P = (cij)\ n * m$, where cij represents the direct influence of expert factor gi on factor gj. By adhering to the theory of systems science, effective analysis of the relationships among causal factors was ensured. Background information on the experts is provided in Table 1 below.

(3) The initial direct influence matrix is transformed into a grey number matrix $\theta Y$ by converting the role relationships between different causal factors into corresponding grey numbers through the semantic variables of experts. Due to the differences in work experience, research fields, and subjective knowledge of FFH among different experts and scholars, further differentiated

**Table 1**
Background information on experts.

| Nature of work | Number of people |
|---|---|
| Universities and Research Institutes | 6 |
| Construction company | 5 |
| Design institute | 5 |
| Supervisory firm | 4 |
| Years of experience | Number of people |
| Less than 3 years | 2 |
| 3–5 years | 4 |
| 5 years and above | 14 |
| Professional title | Number of people |
| Junior ranking | 2 |
| Mid-level | 1 |
| Deputy high ranking | 10 |
| High level | 7 |
| Add up the total | 20 |

weights are assigned to the evaluation scores of each expert. The specific weight semantic variables and grey number transformation Ref [15].

(4) Calculation of the grey number direct influence matrix D. The grey number matrix Y is clarified based on Eqs. (1)–(5) and is calculated as follows:

a. Normalization of the upper and lower bounds of the grey number

$$\theta^{-}y_{ij}^{r} = \left(\theta^{-}y_{ij}^{r} - min\ \theta^{-}y_{ij}^{r}\right) \Big/ \Delta_{min}^{max} \tag{1}$$

$$\theta\_y_{ij}^{r} = \left(\theta\_y_{ij}^{r} - min\ \theta\_y_{ij}^{r}\right) \Big/ \Delta_{min}^{max} \tag{2}$$

The interval range of θy interval grey number in Eqs. (1) and (2) $[\theta\_y, \theta^{-}y]$, where $\theta^{-}$ y is the lower interval limit of interval grey number $\theta y$ and $\theta^{-}$ is the upper interval limit of interval grey number θy. $\theta y_{ij}^{r}$ is the evaluation score of expert r on the degree of direct influence of causal factor i on causal factor j for construction fall accidents from height; where $\theta y_{ij}^{r} \in [\theta\_y_{ij}^{r}, \theta^{-}y_{ij}^{r}]$ , $\Delta_{min}^{max} = max\ \theta^{-}y_{ij}^{r} - min\ \theta\_y_{ij}^{r}$.

(4) Calculation of the grey number direct influence matrix D. The grey number matrix Y is clarified based on Eqs. (1)–(5) and is calculated as follows:

b. Perform clarification

$$Z_{ij}^{r} = \frac{\left[\theta\_y_{ij}^{r} * \left(1 - \theta\_y_{ij}^{r}\right) + \left(\theta^{-}y_{ij}^{r} * \theta^{-}y_{ij}^{r}\right)\right]}{\left(1 - \theta^{-}y_{ij}^{r} + \theta\_y_{ij}^{r}\right)} \tag{3}$$

c. Calculate clarity values

$$X_{ij}^{r} = min\ \theta\_y_{ij}^{r} + Z_{ij}^{r} * \Delta_{min}^{max} \tag{4}$$

d. Calculate the weighted matrix D of the r experts, i.e., the grey number direct influence matrix, where $D_{ij}$ is the element of the i-th row and j-th column of the weight matrix.

$$D_{ij} = \mu_1 * D_{ij}^{1} + \mu_2 * D_{ij}^{2} + \ldots + \mu_m * D_{ij}^{m} \tag{5}$$

In equation (5), $\sum_{i=1}^{m} \mu_i = 1$.

Exhibit 2 shows the matrix of the direct impact of the grey number caused by the FFH.

(5) The grey number direct influence matrix is normalized using Equations (6) and (7) to obtain the normalized direct influence matrix M.

$$M = T * D \tag{6}$$

$$T = \frac{1}{\max_{1 \le r \le n} \sum_{j=1}^{m} D_{ij}} \tag{7}$$

Exhibit 3 shows the standardized direct impact matrix for the causes of FFH.

The grey number direct influence matrix only captures the direct relationships between factors in FFH. However, the causal factors exhibit a comprehensive nature, with complexities and obvious nonlinear relationships, leading to accident urgency. Thus, considering only direct relationships is insufficient; it is essential to also account for indirect relationships between factors.

(6) Calculate the integrated impact matrix $S = (s_{ij})_{m*m}$ using Equation (8).

$$S = M * (I - M)^{-1} \tag{8}$$

where $S_{ij}$ denotes the direct influence of factor $g_i$ on factor $g_j$ and the degree of indirect influence; I is the unit matrix. Exhibit 4 presents a comprehensive impact matrix of the causes of FFH.

(7) Using equations (9) and (10) to calculate the degree of influence and the degree of being influenced for each causal factor. The calculation process is as follows.

The degree of factor influence is determined by the sum of the values in each row of the integrated influence matrix S, denoted as $F = (f1, f2, \ldots fm)$. It reflects the combined influence of the corresponding factors in each row on the remaining factors. Similarly, the degree of factor being influenced is determined by the sum of the values in each column of the integrated influence matrix S, denoted as $H = (h1, h2, \ldots hm)$. It represents the combined influence of the corresponding factors in each column on the remaining factors.

$$F = \sum_{j=1}^{m} s_{ij}, j \in 1, 2\ldots..m \tag{9}$$

$$H = \sum_{i=1}^{m} s_{ij}, i \in 1, 2\ldots..m \tag{10}$$

(8) Calculate factor centrality and causal degree. Factor centrality denoted as Oi, is obtained by adding the influence degree and the influenced degree of the factor, indicating its position in the evaluation index system and its magnitude of impact. The causal degree, denoted as Qi, is obtained by subtracting the influence degree and the influenced degree of the factor. If the causal degree is greater than 0, the factor is considered a cause factor, indicating a strong influence on the remaining factors; otherwise, it is regarded as a result factor.

Based on equations (9) and (10) and step (8), the influence, degree of being influenced, centrality, and causality of each causal factor of FFH can be calculated. Refer to Table 2 below for details.

In addition, according to the above table, a causal mapping of the causal factors can be drawn, as shown in the following Fig. 3.

(9) The overall impact matrix B is calculated from equation (11).

$$B = S + I = (b_{ij})_{m \times m} \tag{11}$$

Exhibit 5 presents the overall impact matrix for the causes of FFH.

(10) The reachable matrix E is determined based on the overall impact matrix B (Exhibit 5) of the causal factors of FFH. The formulae are (12)–(15)

In the causal system of FFH, if one factor's influence on another factor exceeds α, then that factor can directly influence the other factor. Conversely, if one factor's influence on another factor is less than α, then the former factor has no influence on the latter. The goal of thresholding is to highlight the major causes of accidents in complex systems without oversimplifying them. The overall impact matrix B can determine the threshold value, which is 0.0497, in steps (9 and 14). Furthermore, the reachability of the components in matrix E for the FFH causative factors may be determined using the method below and the overall effect matrix B.

$$E_{ij} = \{1 | 1 \ge \alpha\}, i, j \in 1, 2\ldots..m \tag{12}$$

$$E_{ij} = \{0 | 1 < \alpha\}, i, j \in 1, 2\ldots..m \tag{13}$$

$$\alpha = s_{ij}^{-} + \partial \tag{14}$$

$$\mathrm{E} = (e_{ij})_{m*m} \tag{15}$$

**Table 2**
The influence, degree of being influenced, centrality, and causality of each causal factor of FFH.

| Causal factors | Degree of influence | Degree of being influenced | Centrality | Center Degree Sorting | Reason degree | Reason degree sorting | Factor Properties |
|---|---|---|---|---|---|---|---|
| A1 Violation of work rules, operating errors | 0.20 | 1.42 | 1.62 | 3 | −1.23 | 21 | Results |
| A2 Command violation, command error | 0.62 | 0.65 | 1.26 | 7 | −0.03 | 11 | Results |
| A3 Lack of safety operation skills and knowledge | 0.89 | 0.48 | 1.37 | 6 | 0.41 | 5 | Reason |
| A4 improper use of protective equipment | 0.19 | 0.82 | 1.01 | 8 | −0.63 | 19 | Results |
| A5 Low security awareness | 1.01 | 0.72 | 1.74 | 1 | 0.29 | 7 | Reason |
| A6 Mental or physical discomfort of workers | 0.39 | 0.43 | 0.82 | 13 | −0.04 | 12 | Results |
| B7 Inadequate safety due to lack of timely maintenance and repair of equipment | 0.16 | 0.76 | 0.92 | 9 | −0.60 | 18 | Results |
| B8 Insufficient safety of the support system | 0.16 | 0.62 | 0.78 | 16 | −0.45 | 17 | Results |
| B9 The quality of protective supplies and materials is not qualified | 0.31 | 0.42 | 0.72 | 18 | −0.11 | 14 | Results |
| B10 Inadequate safety protection measures | 0.20 | 1.30 | 1.50 | 5 | −1.10 | 20 | Results |
| C11 Poor hydrogeological environment | 0.39 | 0.02 | 0.42 | 19 | 0.37 | 6 | Reason |
| C12 Sudden adverse weather effects | 0.40 | 0.03 | 0.42 | 19 | 0.37 | 6 | Reason |
| C13 Poor site working environment | 0.25 | 0.62 | 0.87 | 12 | −0.37 | 16 | Results |
| D14 Management's failure to supervise safety | 1.18 | 0.40 | 1.58 | 4 | 0.78 | 1 | Reason |
| D15 Lacking a well-prepared construction plan or an organized expert demonstration | 0.54 | 0.26 | 0.80 | 14 | 0.28 | 8 | Reason |
| D16 Lax site safety management | 1.17 | 0.47 | 1.64 | 2 | 0.70 | 2 | Reason |
| D17 Safety technical briefing is not in place | 0.50 | 0.40 | 0.90 | 10 | 0.10 | 10 | Reason |
| D18 Inadequate personnel qualification review | 0.48 | 0.28 | 0.76 | 17 | 0.19 | 9 | Reason |
| D19 Inadequate safety training | 0.64 | 0.36 | 1.01 | 8 | 0.28 | 8 | Reason |
| D20 Failure to provide safety gear to construction personnel | 0.34 | 0.38 | 0.72 | 18 | −0.04 | 13 | Results |
| D21 Hidden danger investigation has not been properly executed | 0.26 | 0.54 | 0.80 | 14 | −0.28 | 15 | Results |
| D22 Inadequate safety production responsibility and management norms | 0.72 | 0.18 | 0.89 | 11 | 0.54 | 4 | Reason |
| D23 Insufficient investment in production safety personnel and funds | 0.69 | 0.10 | 0.79 | 15 | 0.58 | 3 | Reason |

where: $s_{\bar{ij}}$ is the mean of all values in matrix B; $\partial$ is the standard deviation of matrix B. Exhibit 6 is reachable matrix of the causes of FFH.

(11) Determine the prior set $R_i$ and the reachable set $V_i$ according to the reachable matrix E. The relevant formulae are (16)–(17):

$$R_i = \{g_i | g_i \in G, s_{ij} \neq 0\}, i \in 1, 2.....m \quad (16)$$

$$V_i = \{g_j | g_j \in G, s_{ij} \neq 0\}, j \in 1, 2.....m \quad (17)$$

Where: G is the set of causal factors $g_i$.

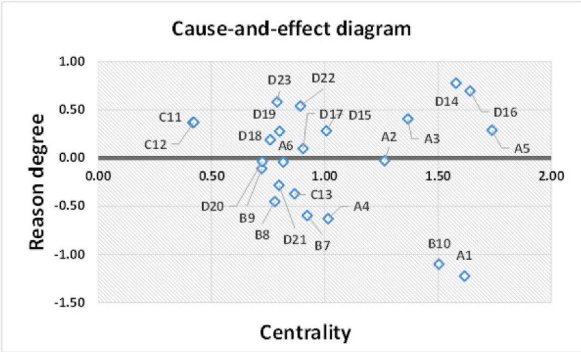
When $V_i = V_i \cap R_i, (i \in 1, 2.....m)$, $Vg_i \in V_i$ are the factors in the highest layer, and then repeat the above process after removing $g_j$ which has been stratified, in order to stratify the causative factors of FFH. Table 3 shows the causes and antecedents of FFH.

(12) Hierarchical mapping of causative factors for FFH.

Based on the reachability set as well as the antecedent set, the hierarchical relationship of causal factors can be determined, which leads to a hierarchical model diagram of FFH (Fig. 4).

### 4.2. Analysis of the causes of falls from height accidents (FFH) based on BN

In line with system theory, construction accidents emanate from the breakdown of the accident system. To more precisely gauge the potency of coupling within accident-causing systems, the analysis employs Bayesian networks. A Bayesian network (BN), alternatively recognized as a probabilistic causal network, constitutes a probabilistic graphical inference model rooted in the Bayesian theory of uncertainty, originating from the pioneering work of Professor Pearl in the United States. The article uses the visualization software GeNie2.0 to convert the multilevel structural model obtained from the Grey-DEMATEL-ISM analysis into a BN model. In addition, to




legend (of a map, etc) : The horizontal axis represents the degree of centrality; the vertical axis represents the degree of cause; and the points in the graph represent the distribution of the factors in the graph

**Fig. 3.** Cause and effect diagram.

**Table 3**
Reachable sets, antecedent sets, and intersection sets.

| Causal factors | Reachability set | Antecedent set | Intersections |
|---|---|---|---|
| A1 | [1] | [1, 2, 3, 5, 6, 11, 12, 13, 14, 15, 16, 17, 18, 19, 22, 23] | [1] |
| A2 | [1,2,4,10,13,20] | [2, 14, 15, 16, 22, 23] | [2] |
| A3 | [1,3,4,7,8,10,17,21] | [3, 6, 11, 12, 14, 16, 18, 19, 22, 23] | [3] |
| A4 | [4,10] | [2, 3, 4, 5, 6, 11, 12, 14, 15, 16, 18, 19, 20, 22, 23] | [4] |
| A5 | [1,4,5,7,10,13,17,21] | [5, 6, 11, 12, 14, 16, 19, 22, 23] | [5] |
| A6 | [1,3–8,10,13,17,21] | [6, 11, 12] | [6] |
| B7 | [7] | [3, 5, 6, 7, 11, 12, 14, 16, 17, 18, 19, 22, 23] | [7] |
| B8 | [8] | [3, 6, 8, 9, 11, 12, 14, 15, 16, 18, 19, 22, 23] | [8] |
| B9 | [8–10] | [9, 14, 16, 22, 23] | [9] |
| B10 | [10] | [2, 3, 4, 5, 6, 9, 10, 11, 12, 14, 15, 16, 17, 18, 19, 20, 22, 23] | [10] |
| C11 | [1,3–8,10,11,13,17,21] | [11] | [11] |
| C12 | [1,3–8,10,12,13,17,21] | [12] | [12] |
| C13 | [1,13] | [2, 5, 6, 11, 12, 13, 14, 15, 16, 19, 22, 23] | [13] |
| D14 | [1–5,7–10,13,14,16–21] | [14, 22, 23] | [14] |
| D15 | [1,2,4,8,10,13,15,20] | [15, 22, 23] | [15] |
| D16 | [1–5,7–10,13,16–21] | [14, 16, 22, 23] | [16] |
| D17 | [1,7,10,17] | [3, 5, 6, 11, 12, 14, 16, 17, 18, 19, 22, 23] | [17] |
| D18 | [1,3,4,7,8,10,17,18,21] | [14, 16, 18, 22, 23] | [18] |
| D19 | [1,3–5,7,8,10,13,17,19,21] | [14, 16, 19, 22, 23] | [19] |
| D20 | [4,10,20] | [2, 14, 15, 16, 20, 22, 23] | [20] |
| D21 | [21] | [3, 5, 6, 11, 12, 14, 16, 18, 19, 21, 22, 23] | [21] |
| D22 | [1–5,7–10,13–22] | [22] | [22] |
| D23 | [1–5,7–10,13–21,23] | [23] | [23] |

ensure the objectivity of the experimental results, the article converted 420 real accident data into comma-separated value format files and imported them into GeNie2.0 to perform BN analyses based on real accident data.

(1) Causal reasoning for FFH

Using the hierarchical network model developed through the Grey-DEMATEL-ISM approach, the study constructed the BN model for FFH by incorporating top-level event nodes (Fig. 5). To heighten the objectivity of research outcomes, this investigation relies on data from 420 real accident cases. A priori probabilities for the intermediate nodes and sub-nodes are computed employing GeNie2.0 software, facilitating forward causal inference.

From Fig. 5, it can be seen that the probability of occurrence of a top event (FFH) is 57 % in the causative system of FFH.

In addition, the article calculates the probability of occurrence of FFH under different circumstances based on established observed events with case inputs, and Table 4 shows the inferred results.

(2) Diagnostic reasoning of FFH

In this paper, the top node is set as the evidence node (i.e., the probability of FFH is 100 %), and the a posteriori probability distribution of the node is derived using the fault diagnosis function of the BN model, as shown in Fig. 6.

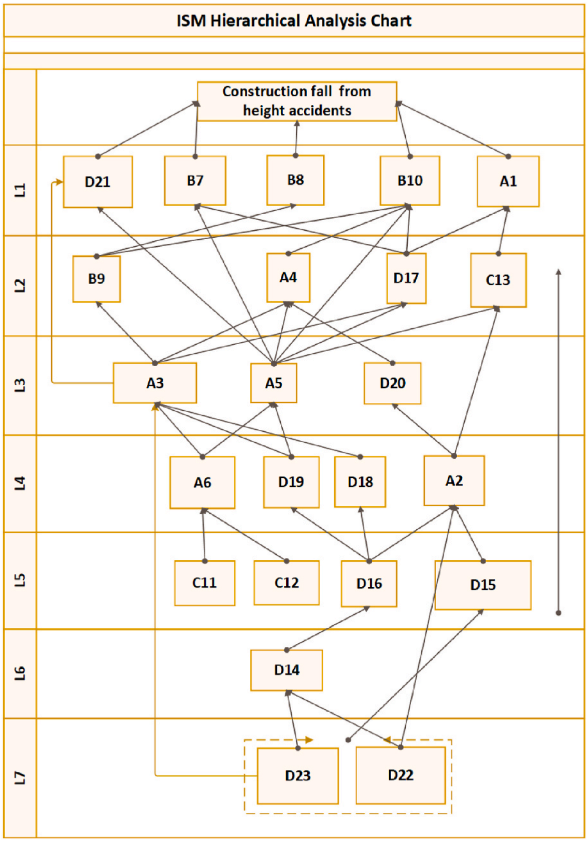



**Fig. 4.** Hierarchical diagram of the causes of FFH.

## 5. Discussion

### *5.1. Causality analysis based on Grey-DEMATEL*

Table 2 elucidates the interrelationships among FFH causal factors. These factors exhibit a broad spectrum of influence, with 10 factors exerting substantial impact. Notably, D14 (Failure of management safety supervision), D16 (Lax site safety management), A5 (Low-security awareness), A3 (Lack of safety operation skills and knowledge), D22 (Inadequate safety production responsibility and management norms), D23 (Insufficient investment in production safety personnel and funds), D19 (Inadequate safety training), A2 (Command violation, command error), D15 (Not prepared special construction program or not organized expert demonstration), and D17 (Safety technical briefing is not in place) emerge as pivotal contributors to falls from height accidents. Evidently, these factors predominantly influence other factors, underscoring the significance of vigilance on the part of managers to monitor shifts in these aspects during construction safety management endeavors. Such attention is instrumental in curbing the incidence of FFH incidents.

In the ranking of the degree of being influenced, A1 (violation of work rules, operating errors), B10(Inadequate safety protection measures), A4 (improper use of protective equipment), B7(Inadequate safety due to lack of timely maintenance and repair of equipment) and A5 (Low-security awareness) ranked in the forefront, indicating that by enhancing its influencers can effectively prevent the occurrence of high construction fall accidents. Among them, A5 (Low-security awareness), A2(Command violation, command error), and A3(Lack of safety operation skills and knowledge) are important influencing and affected factors, from which it can be seen that these factors are the key factors in the causation of falls-from-height accidents, and the improvement of these factors will help to form a virtuous circle of improving the safety level of the construction system at a height.

From the ranking of cause degrees in Tables 2 and it can be seen that the D14 (Failure of management safety supervision), D16 (Lax site safety management), and D23 (Insufficient investment in production safety personnel and funds) are the cause factors that can easily affect other risk factors in the system. In addition, the larger the centrality value, the greater the importance of the factor in the factor system. Based on the ranking of center degrees in Tables 1 and it can be inferred that A5 (Low-security awareness) has the highest degree, followed by D16 (Lax site safety management), A1 (violation of work rules, operating errors), and D14 (Failure of management safety supervision). Therefore, it can be concluded that A5 (Low-security awareness) is the leading cause of FFH, and extra attention should be given to the cultivation of workers' safety awareness during the project construction process.

Upon careful analysis of the data, this study was able to pinpoint the causal relationships among all of the contributing factors to

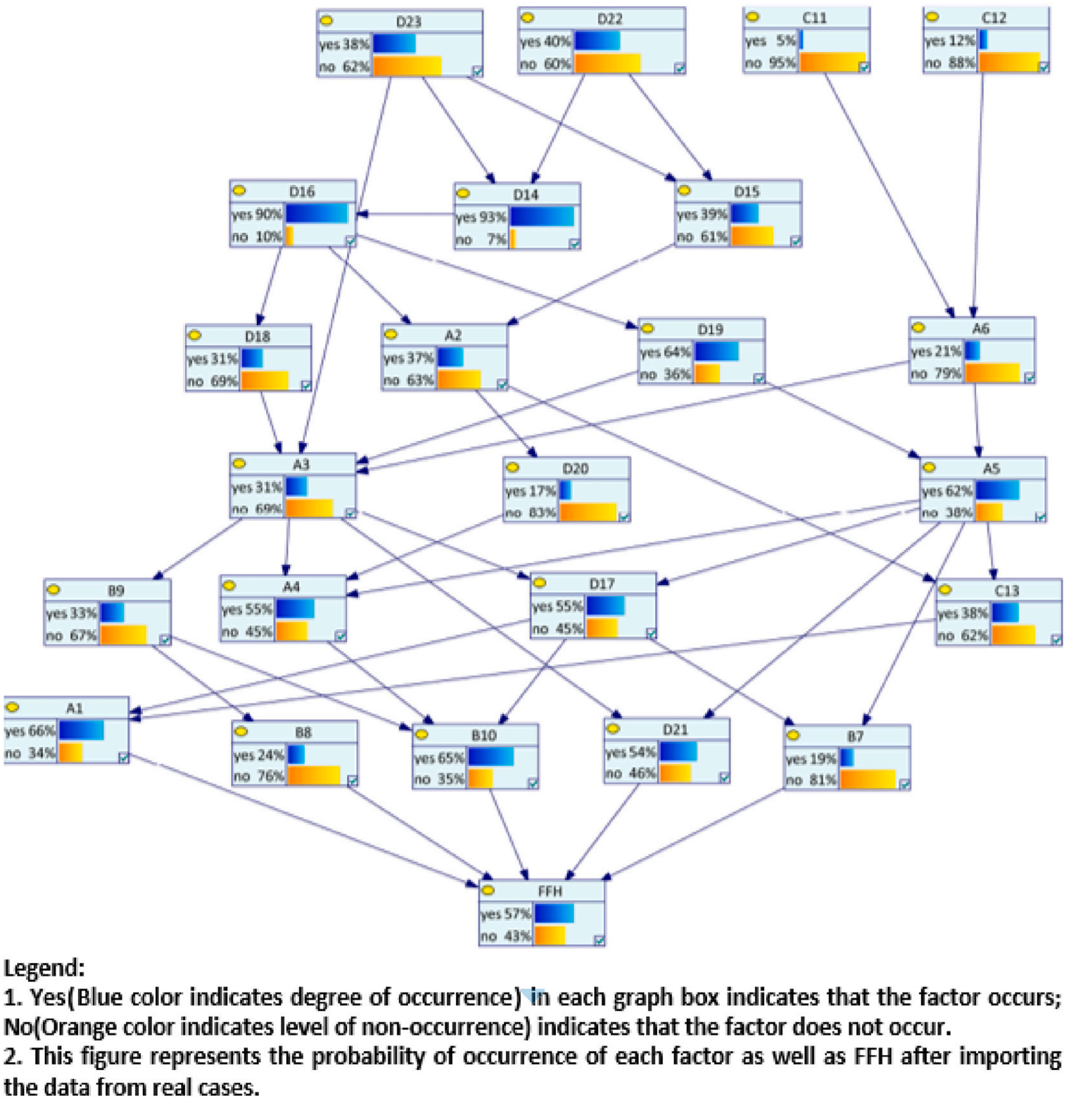



**Fig. 5.** Causal reasoning diagram for FFH.

**Table 4**
Reasoning outcome.

| Probability Type | Root Node Probability | Top event node probabilities |
|---|---|---|
| A priori probability | | 56.72 % |
| Posterior probability | P (D23 = 1) = 1 | 56.74 % |
| | P (D22 = 1) = 1 | 56.74 % |
| | P (D23 = 1) = 0 | 56.70 % |
| | P (D22 = 1) = 0 | 56.71 % |
| | P(C11 = 1) = 1 | 56.73 % |
| | P(C12 = 1) = 1 | 56.73 % |
| | P (D23 = 1) = 1 | 56.99 % |
| | P (D22 = 1) = 1 | |
| | P(C11 = 1) = 1 | |
| | P(C12 = 1) = 1 | |

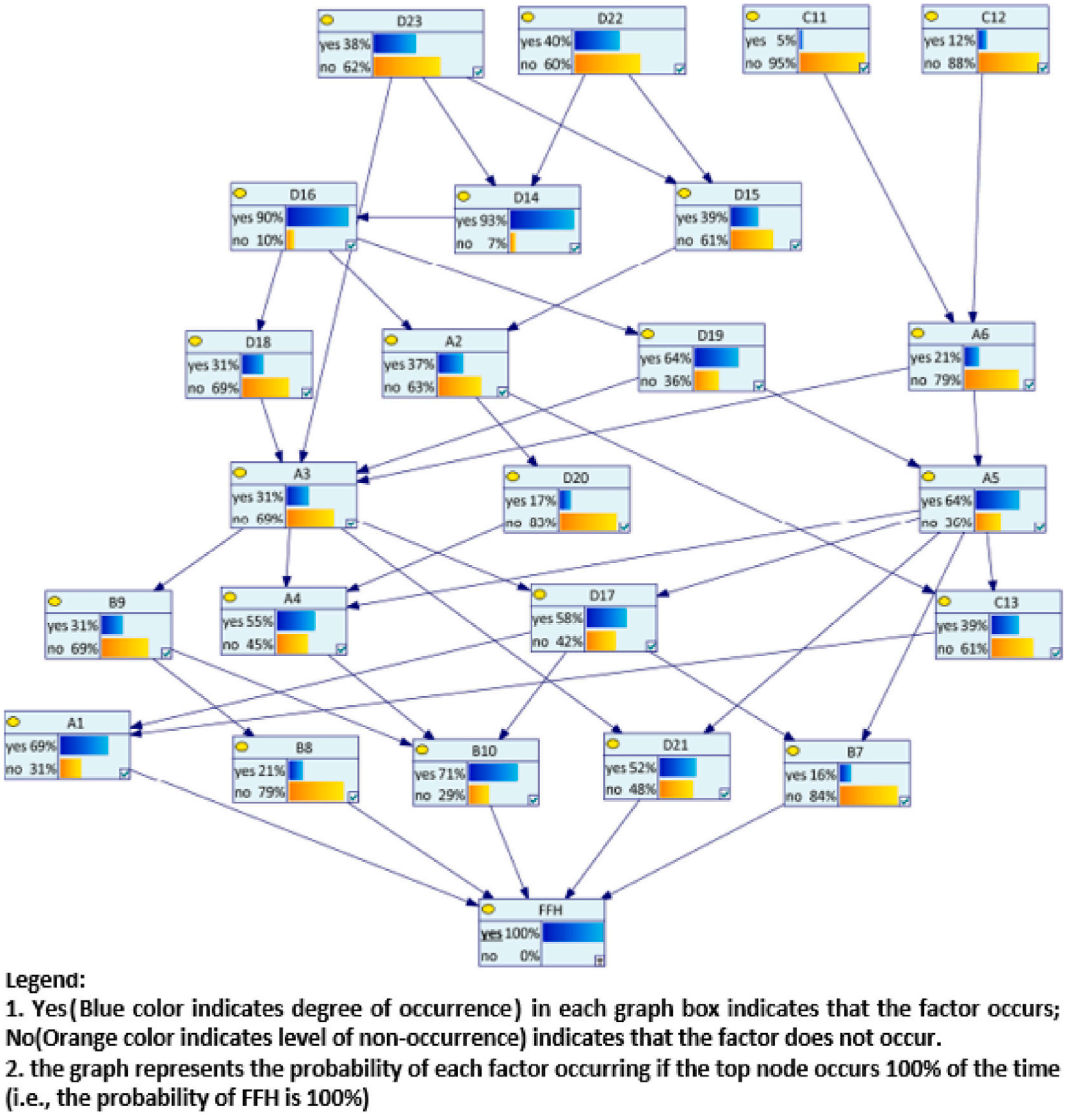



**Fig. 6.** Diagnostic reasoning diagram for FFH.

FFH. With this knowledge, managers can now take precise and targeted measures to prevent accidents by addressing the underlying causes of these incidents. By focusing on the intricate relationships between these factors, managers can effectively reduce the likelihood of accidents occurring and ensure the safety of their construction workers and the profitability of their enterprises.

### 5.2. ISM-based hierarchical relationship analysis

Fig. 4 illustrates the causal system of FFH, organized into 7 layers. The study classifies the causal factors into three groups: direct, transitional, and fundamental factors. Direct causal factors include A1 (violation of work rules, operating errors), B8 (Insufficient safety of the support system), B10 (Inadequate safety protection measures), D21 (Hidden danger investigation has not been properly executed), and B7 (Inadequate safety due to lack of timely maintenance and repair of equipment). These factors directly contribute to FFH occurrences and are influenced by all other causal factors. Preemptive interventions targeting these factors during construction at heights can effectively prevent falls.

D22 (Inadequate safety production responsibility and management norms) and D23 (Insufficient investment in production safety personnel and funds) are underlying factors, termed potential factors. While essential to height safety management, their significance may not be immediately evident. Therefore, vigilant monitoring of these factors is crucial to prevent potential cascading effects on construction safety at heights. All factors, except fundamental and direct ones, belong to the transitional category.

### 5.3. Discussion of the results of the analysis of fall from height accidents (FFH) based on Bayesian networks

(1) Causal reasoning for FFH

As depicted in Fig. 5, the causative system of FFH reveals a 57 % probability of FFH occurrence, indicating a significant risk of system failure and emphasizing the need for enhanced FFH prevention measures.

Moreover, by applying case input, the probability of FFH in different scenarios was calculated based on established observed events. Table 4 inference results demonstrate that the probability of FFH rises when each root node is in an occurrence state (1). Conversely, the probability decreases when in a no-occurrence state (0), with varying magnitudes of change based on the initial probability of occurrence for each root node.

The simultaneous occurrence of root nodes D23, D22, C11, and C12 results in a more significant increase in the probability of FFH compared to the increase caused by a single factor. The lack of restrictions on factor independence leads to differences in the effects of multiple causal factors occurring together and single causal factors on the final probability. This indicates that the relationships among factors are not simply independent and linear but rather dynamic and nonlinear.

Given the critical nature of FFH, it is imperative to establish a robust Bayesian Network (BN) model tailored to the specific causative factors of each project. This approach allows for timely input of relevant information, enabling proactive identification of potential hazards and implementation of appropriate remedial measures. By doing so, project managers can better comprehend the probability of accidents and take proactive actions to mitigate risks, ensuring the safety of construction personnel and protecting economic interests.

(2) Diagnostic reasoning of FFH

In this paper, the top event is set as the evidence node (i.e., the probability of FFH is 100 %), and the posterior probability distribution of each sub-node is derived using the fault diagnostic function of the BN model, as shown in Fig. 6.

As can be seen from the figure, the ranking of the probability of the bottom event when the top event occurs is P (14) > P (16) > P (10) > P (1) > P (19) = P (5) > P (17) > P (4) > P (21) > P (22) > P (15) = P (13) > P (23) > P (2) > P (18) = P (9) = P (3) > P (8) = P (6) > P (20) > P (7) > P (12) > P (11).

It can be seen that when the FFH occurs, D14 (Management's failure to supervise safety), D16(Lax site safety management), B10 (Inadequate safety protection measures), and A5 (Low-security awareness), indicating that it is very likely that these four factors lead to the occurrence of FFH, the results are consistent with the actual case situation. Henceforth, it behooves managers to leverage the newfound understanding of the causal mechanisms that lead to FFH. By exerting control over the source of cause and effect, managers can tailor bespoke prevention measures that mitigate risk from the get-go, thereby reducing the likelihood of FFH at the roots. This holistic approach ensures the safeguarding of the physical safety of construction personnel and the bottom line of businesses alike, making it an indispensable tool in the safety management arsenal.

### 5.4. Models comparison

To demonstrate the superiority and significance of this study, we conducted a comparative analysis with recent research models for FFH causation analysis. The literature information is shown in Table 5. In Literature 1, Wong et al. examined fall-from-height accidents' characteristics and root causes using frequency analysis, along with investigating cause associations through Fisher's exact test and latent class analysis (LCA). Literature 2, by Sajjad et al. employed DEMATEL-ANP to explore the interactions and importance of causal factors. Yahia et al. (Literature 3) utilized frequency analysis to identify fall accident trends, correlated accident factors with injury severity using actual data and ensured the objective validity of experimental results. Additionally, they established a predictive model for diagnosable fatal and non-fatal accidents using logistic regression analysis. In Literature 4, Aminu et al. developed an AHP hierarchical analysis model to determine the relative weights and priorities of fall accident factors.

The literature analysis reveals researchers' dedication to developing a superior causative model for fall-from-height accidents, which plays a crucial role in causative analysis. However, certain shortcomings remain. For instance, Literature 1 explored root causes

**Table 5**
Literature information.

| Serial No. | Literature name | Author | Year of publication | Research methodology |
|---|---|---|---|---|
| 1 | Association of root causes in fatal fall-from-height construction accidents in Hong Kong | L Wong | 2016 | HFACS、Fisher's exact test and latent class analysis (LCA) |
| 2 | An integrated DEMATEL–ANP approach for identification and prioritization of factors affecting fall from height accidents in the construction industry | Sajjad Rostamzadeh | 2023 | DEMATEL–ANP |
| 3 | Causal factors and risk assessment of fall accidents in the U.S. construction industry: A comprehensive data analysis (2000–2020) | Yahia Halabi | 2022 | Frequency analysis; logistic regression analysis |
| 4 | Analysis of the causes and preventive measures of fatal fall-related accidents in the construction industry | Aminu Darda'u Rafindadi | 2022 | AHP |

without delving deeper into causal relationships or quantifying their strength. Literature 2 explored deeper relationships but lacked quantitative assessment. Moreover, traditional DEMATEL's flaw lies in assigning overly deterministic values, rendering experiments highly subjective. Literature 3 focused on the correlation between factors and injury degree but overlooked internal relationships. Literature 4, using the AHP method, failed to analyze deeper inter-factor relationships and lacked quantitative investigations.

In summary, existing studies have analyzed numerous factors contributing to fall-from-height accidents. However, comprehensive qualitative and quantitative analyses of the complex causal relationships among contributing factors are lacking. To address this research gap, this study proposes the combined framework Grey-DEMATEL-ISM-BN, demonstrating its effectiveness in conducting complex causal relationship analysis and quantitative research on causal factors. This framework provides a comprehensive analysis method for safety management in building construction.

### *5.5. Policy or management implications and related observations*

Given the complexity and nonlinearity of fall-from-height (FFH) causal factors and the intricate feedback loops between these factors, the article elucidates the implications of the findings for management, policy, and targeted recommendations based on that impact:

Implications for management:

1. Optimizing safety training: According to the results of the Grey-DEMATEL-ISM-BN study, low safety awareness (A5), command violations, command errors (A2), and lack of safety operation skills and knowledge (A3) are the key factors in fall accidents in construction from heights. Managers can optimize safety training programs based on these results, focusing on developing employees' safety awareness, strengthening command and operation norms, and improving workers' safety operation skills and knowledge.
2. Enhancing accident prevention: Based on the results of BN causal reasoning, the probability of a fall from height accident is 57 %, emphasizing the high risk of system failure. Managers can identify potential risks in advance and strengthen the prevention of fall-from-height accidents in building construction through more detailed accident prevention measures, including maintenance of equipment and improvement of safety precautions.
3. Strengthening on-site supervision: Direct factors such as Violation of work rules, operating errors (A1), Insufficient safety of the support system (B8), and Inadequate safety protection measures (B10) were identified, which suggests that managers should strengthen on-site supervision to ensure that the construction operations comply with the specification requirements and that the support system and safety precautions are effectively implemented.
4. Improvement of the safety responsibility system: Basic or potential factors such as Inadequate safety production responsibility and management norms (D22) and Insufficient investment in production safety personnel and funds (D23) need to be brought to the attention of managers. Establishing a sound safety responsibility system, clarifying the responsibilities and obligations of all parties, and increasing the financial investment in production safety will help to improve the overall level of safety management.

Policy implications:

1. Enhancing enforcement: Policymakers can strengthen enforcement based on the Grey-DEMATEL-ISM-BN study's results, particularly for direct factors like a Violation of work rules, operating errors (A1), Insufficient safety of the support system (B8), and Inadequate safety protection measures (B10). Strict enforcement and penalties will create a strong deterrent effect, motivating relevant units and individuals to comply with safety norms and reduce accidents.
2. Reinforcing accountability: The BN results illustrate the dynamic and non-linear relationship between causal factors, enabling policymakers to strengthen the accountability mechanism for responsible parties. Establishing a comprehensive accountability system will incentivize all parties and departments to collaborate in maintaining construction safety.
3. Increasing safety investment: Based on the study's findings, policymakers should boost safety production investment to ensure adequate financial support for safety management. Especially for basic or potential factors like Inadequate safety production responsibility and management norms (D22) and Insufficient investment in production safety personnel and funds (D23), increased safety investment can significantly address these shortcomings.
4. Enhancement of safety standards and norms: The study's findings identify key factors contributing to fall accidents in construction from heights. Policymakers can utilize these results to develop more refined and improved safety standards and norms. These regulations will serve as a code of conduct for construction units and practitioners, enhancing overall construction safety.
5. Advancement of accident reporting and diagnostic mechanisms: Through BN's accident diagnostic reasoning and analysis, a comprehensive understanding of the probability ranking for each causative factor during a fall-from-height accident can be obtained. Policymakers can prioritize high-risk factors based on these rankings, establish a sound and complete accident reporting and diagnostic mechanism, obtain timely accident information, and guide the formulation and optimization of safety management policies more scientifically and effectively.

In summary, the Grey-DEMATEL-ISM-BN study's results have clear implications for both management and policy. Management measures like optimizing safety training, strengthening on-site supervision, and improving safety responsibility systems can effectively prevent and reduce fall accidents in construction from heights. Simultaneously, policymakers can bolster law enforcement, increase safety investments, and enhance safety standards and codes to continuously improve safety management in the construction industry.

## 6. Summary of results and contributions

In this study, we systematically analyzed the causal factors of fall-from-height accidents (FFH) by combining the Grey-DEMATEL, ISM, and BN methods and proposed a framework mechanism for quantifying the causal factors of FFH with non-linear interactions. The main results are as follows:

1. The article begins by identifying 23 factors that contribute to the occurrence of fall-from-height accidents through a literature review, analysis of accident investigation reports, and expert advice.
2. The in-depth relationship between causal factors was analyzed in depth through Grey-DEMATEL and key causal factors were elucidated. The results of the analyses show that: A5 (Low-security awareness), A2 (Command violation, command error), and A3 (Lack of safety operation skills and knowledge) are the key factors that cause falls from height accidents. Among them, A5 (Low-security awareness) is the main factor leading to the occurrence of falls from height accidents.
3. The article utilized ISM hierarchical analysis to classify the 23 causal factors into seven layers, further distinguishing them as direct, fundamental, and transitional factors. Among these, A1 (unauthorized command and operation errors), B8 (insufficient safety of the support system), B10 (inadequate safety protection measures), D21 (inadequate investigation of hidden dangers), and B7 (inadequate safety due to untimely maintenance and upkeep of equipment) are identified as direct factors. On the other hand, D22 (imperfect production safety responsibility system and management norms) and D23 (insufficient investment of personnel and funds in safety) are considered fundamental, or potential factors, while the remaining factors fall under the category of transitional factors.
4. To quantify the strength of the coupling relationship between the causal factors of fall-from-height accidents, the article is based on the data of 420 actual accident cases, and the ISM multilevel recursive hierarchical model is mapped to the BN model through GeNie2.0. The BN causal reasoning shows that the probability of a fall from height accident is 57%, indicating that the risk of system failure is high and that the prevention of construction accidents involving falls from height should be strengthened. In addition, there is not a simple independent linear relationship between the factors, but a dynamic non-linear relationship. Through the BN accident diagnosis reasoning analysis, when the probability of occurrence of fall from height accidents is 100 %, the ranking of the probability of occurrence of each causal factor is $P(14) > P(16) > P(10) > P(1) > P(19) = P(5) > P(17) > P(4) > P(21) > P(22) > P(15) = P(13) > P(23) > P(2) > P(18)) = P(9) = P(3) > P(8) = P(6) > P(20) > P(7) > P(12) > P(11)$.

Research contribution:

Theoretical Contribution: The Grey-DEMATEL-ISM-BN methodology integrates grey theory, decision laboratory methodology, explanatory structural modeling, and Bayesian networks to address complexity and uncertainty in analyzing factors causing fall-from-height accidents. Based on the findings, corresponding policy and management recommendations are proposed.

Methodological Contribution:

The Grey-DEMATEL-ISM-BN methodology provides a systematic framework for causal analysis, revealing critical and direct factors and enabling quantification of causal relationship coupling strength. This study bridges the gap in previous research and offers a comprehensive analytical approach for analyzing fall-from-height accidents.

Practical Application Contribution:

This study improves safety management at construction sites, providing a scientific basis for safety training and supervision to effectively prevent and reduce fall-from-height accidents. Additionally, applying the Grey-DEMATEL-ISM-BN method promotes integrated research methods in other fields and facilitates international cooperation and experience exchange.

Limitations of this study include the subjectivity despite the introduction of grey theory to reduce bias in the traditional DEMATEL method. Additionally, the static treatment of dynamic and complex causal factors hinders a comprehensive reflection of real-world scenarios. To enhance objectivity, future research will leverage text mining technology for factor extraction from accident investigation reports and employ association rule mining to determine correlations among causal factors. Moreover, dynamic Bayesian networks will be used to conduct a more scientific and effective analysis of the dynamic nature of these factors, thus improving safety management in construction at height.

### Ethics approval and consent to participate

Informed consent was obtained from all participants for this study.

### Data availability

Data will be made available on request.

### Additional information

No additional information is available for this paper.

## CRediT authorship contribution statement

**Jun long Peng:** Formal analysis, Funding acquisition. **Xiao Liu:** Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – original draft, Writing – review & editing. **Chao Peng:** Formal analysis. **Yu Shao:** Funding acquisition.

## Declaration of competing interest

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

## Appendix

**Exhibit 1**
Information Sheet on Causal Factors of Construction Fall Accidents

| Tier 1 Indicators | Secondary indicators | Tertiary indicators | Refine metrics | Frequency | Frequency | Related Literature |
|---|---|---|---|---|---|---|
| Causes of fall from height accidents in building construction | Human Factors | Unsafe Behavior | Violation of work rules and operating errors | 280 | 66.67 % | [5,37,38] |
| | | | Command violation, command error | 150 | 35.71 % | [5,37,38] |
| | | Unsafe habits or psychology | Lack of safety operation skills and knowledge | 130 | 30.95 % | [5,37,39] |
| | | | Improper use of protective equipment | 240 | 57.14 % | [5,37,39–44] |
| | | | Low security awareness | 260 | 61.90 % | [5,37,39,44,45] |
| | | | Mental or physical discomfort of workers | 90 | 21.43 % | [5,37,46,47] |
| | Material factors | Unsafe material state | Inadequate safety due to lack of timely maintenance and repair of equipment | 80 | 19.05 % | [5,38,39,44,47] |
| | | | Insufficient security of the support system | 100 | 23.81 % | [5,39,44] |
| | | | The quality of protective supplies and materials is not qualified | 140 | 33.33 % | [5,44] |
| | | | Inadequate safety protection measures | 270 | 64.29 % | [5,37,39,40,43,44,48] |
| | Environmental Factors | Unsafe environment | Poor hydrogeological environment | 20 | 4.76 % | [5,49] |
| | | | Sudden adverse weather effects | 50 | 11.90 % | [5,49] |
| | | | Poor on-site operating environment | 170 | 40.48 % | [5,44,50] |
| | Management Factors | Security Management Failures | Management's failure to supervise safety | 390 | 92.86 % | [5,39,44] |
| | | | Lacking a well-prepared construction plan or an organized expert demonstration | 160 | 38.10 % | [5] |
| | | | Lax site safety management | 380 | 90.48 % | [5,39] |
| | | | Safety technical briefing is not in place | 230 | 54.76 % | [5,39] |
| | | | Inadequate personnel qualification review | 130 | 30.95 % | [5] |
| | | | Inadequate safety training | 270 | 64.29 % | [5,38,39,44] |
| | | | Failure to provide safety gear to construction personnel | 70 | 16.67 % | [5,39,40] |
| | | | Hidden danger investigation has not been properly executed | 230 | 54.76 % | [5] |
| | | Lack of safety culture | Inadequate safety production responsibility and management norms | 170 | 40.48 % | [5] |
| | | | Insufficient investment in production safety personnel and funds | 160 | 38.10 % | [5] |

**Exhibit 2**
y number directly affects the matrix

| | A1 | A2 | A3 | A4 | A5 | A6 | B7 | B8 | B9 | B10 | C11 | C12 | C13 | D14 | D15 | D16 | D17 | D18 | D19 | D20 | D21 | D22 | D23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 0.0000 | 0.0295 | 0.0236 | 0.0705 | 0.0164 | 0.0722 | 0.0764 | 0.0647 | 0.0247 | 0.0825 | 0.0056 | 0.0028 | 0.0389 | 0.0090 | 0.0178 | 0.0325 | 0.0275 | 0.0139 | 0.0231 | 0.0079 | 0.0636 | 0.0225 | 0.0114 |
| A2 | 0.4167 | 0.0000 | 0.0115 | 0.3700 | 0.0447 | 0.0775 | 0.0403 | 0.0372 | 0.0118 | 0.4072 | 0.0000 | 0.0076 | 0.3328 | 0.0525 | 0.0164 | 0.0436 | 0.0601 | 0.0115 | 0.0219 | 0.3356 | 0.1064 | 0.0547 | 0.0097 |
| A3 | 0.3924 | 0.1214 | 0.0000 | 0.4033 | 0.1019 | 0.0181 | 0.3856 | 0.3844 | 0.0597 | 0.4120 | 0.0000 | 0.0000 | 0.0170 | 0.0842 | 0.0347 | 0.0653 | 0.3924 | 0.0222 | 0.0347 | 0.0719 | 0.4149 | 0.0481 | 0.0222 |
| A4 | 0.0403 | 0.0104 | 0.0014 | 0.0000 | 0.0670 | 0.0594 | 0.0080 | 0.0247 | 0.0021 | 0.4100 | 0.0000 | 0.0000 | 0.0204 | 0.0097 | 0.0097 | 0.0119 | 0.0128 | 0.0021 | 0.0060 | 0.0153 | 0.0125 | 0.0153 | 0.0087 |
| A5 | 0.4167 | 0.1147 | 0.1136 | 0.4172 | 0.0000 | 0.0203 | 0.4206 | 0.0933 | 0.0522 | 0.4120 | 0.0000 | 0.0000 | 0.3806 | 0.1131 | 0.0853 | 0.1003 | 0.3739 | 0.0897 | 0.0936 | 0.0747 | 0.3872 | 0.0836 | 0.0573 |
| A6 | 0.1119 | 0.0364 | 0.3572 | 0.0809 | 0.3606 | 0.0000 | 0.0163 | 0.0118 | 0.0007 | 0.0492 | 0.0000 | 0.0076 | 0.0292 | 0.0122 | 0.0014 | 0.0144 | 0.0101 | 0.0035 | 0.0347 | 0.0051 | 0.0410 | 0.0069 | 0.0021 |
| B7 | 0.0969 | 0.0394 | 0.0153 | 0.0205 | 0.0132 | 0.0646 | 0.0000 | 0.0431 | 0.0769 | 0.0697 | 0.0000 | 0.0046 | 0.0469 | 0.0021 | 0.0021 | 0.0192 | 0.0264 | 0.0214 | 0.0060 | 0.0051 | 0.0197 | 0.0158 | 0.0114 |
| B8 | 0.0508 | 0.0614 | 0.0212 | 0.0065 | 0.0333 | 0.0225 | 0.0153 | 0.0000 | 0.0181 | 0.0831 | 0.0014 | 0.0076 | 0.0769 | 0.0205 | 0.0051 | 0.0247 | 0.0212 | 0.0106 | 0.0156 | 0.0205 | 0.0229 | 0.0197 | 0.0212 |
| B9 | 0.0369 | 0.0465 | 0.0032 | 0.0386 | 0.0715 | 0.0797 | 0.0375 | 0.4106 | 0.0000 | 0.3559 | 0.0076 | 0.0076 | 0.0703 | 0.0021 | 0.0007 | 0.0007 | 0.0158 | 0.0035 | 0.0051 | 0.0247 | 0.0119 | 0.0056 | 0.0125 |
| B10 | 0.0786 | 0.0375 | 0.0114 | 0.0992 | 0.0462 | 0.0719 | 0.0697 | 0.0692 | 0.0146 | 0.0000 | 0.0000 | 0.0000 | 0.0712 | 0.0060 | 0.0035 | 0.0205 | 0.0292 | 0.0021 | 0.0147 | 0.0364 | 0.0564 | 0.0101 | 0.0163 |
| C11 | 0.3744 | 0.0564 | 0.0079 | 0.0128 | 0.0144 | 0.4172 | 0.0420 | 0.0392 | 0.0125 | 0.0622 | 0.0000 | 0.0214 | 0.4022 | 0.0134 | 0.0116 | 0.0125 | 0.0125 | 0.0079 | 0.0128 | 0.0021 | 0.0119 | 0.0035 | 0.0119 |
| C12 | 0.3461 | 0.0581 | 0.0045 | 0.0163 | 0.0186 | 0.3802 | 0.0656 | 0.0453 | 0.0142 | 0.0448 | 0.0219 | 0.0000 | 0.3789 | 0.0372 | 0.0170 | 0.0087 | 0.0156 | 0.0080 | 0.0156 | 0.0115 | 0.0413 | 0.0122 | 0.0052 |
| C13 | 0.3456 | 0.0508 | 0.0032 | 0.0192 | 0.0170 | 0.1169 | 0.0639 | 0.0397 | 0.0116 | 0.0514 | 0.0111 | 0.0014 | 0.0000 | 0.0455 | 0.0122 | 0.0440 | 0.0170 | 0.0097 | 0.0114 | 0.0060 | 0.0448 | 0.0128 | 0.0060 |
| D14 | 0.3728 | 0.3489 | 0.0669 | 0.0419 | 0.4111 | 0.0384 | 0.3906 | 0.0636 | 0.3611 | 0.3898 | 0.0046 | 0.0046 | 0.0608 | 0.0000 | 0.0636 | 0.3819 | 0.0719 | 0.3389 | 0.3689 | 0.0919 | 0.0914 | 0.0786 | 0.0381 |
| D15 | 0.3787 | 0.3839 | 0.0369 | 0.0191 | 0.0670 | 0.0094 | 0.0403 | 0.3844 | 0.0225 | 0.0851 | 0.0106 | 0.0106 | 0.0323 | 0.0781 | 0.0000 | 0.0851 | 0.0608 | 0.0073 | 0.0503 | 0.0108 | 0.0747 | 0.0836 | 0.0186 |
| D16 | 0.3917 | 0.3989 | 0.0686 | 0.3854 | 0.4149 | 0.0153 | 0.3628 | 0.0869 | 0.3511 | 0.3880 | 0.0000 | 0.0000 | 0.0514 | 0.0792 | 0.0219 | 0.0000 | 0.0486 | 0.3422 | 0.3611 | 0.3646 | 0.0914 | 0.0381 | 0.0164 |
| D17 | 0.3576 | 0.0847 | 0.0786 | 0.0419 | 0.1153 | 0.0144 | 0.3439 | 0.0809 | 0.0175 | 0.3644 | 0.0217 | 0.0076 | 0.0364 | 0.0698 | 0.0052 | 0.0531 | 0.0000 | 0.0087 | 0.0440 | 0.0492 | 0.0853 | 0.0177 | 0.0116 |
| D18 | 0.3628 | 0.0964 | 0.3928 | 0.0403 | 0.0853 | 0.0042 | 0.0369 | 0.0397 | 0.0253 | 0.0608 | 0.0000 | 0.0000 | 0.0253 | 0.0792 | 0.0413 | 0.0920 | 0.0358 | 0.0222 | 0.0490 | 0.0135 | 0.0503 | 0.0146 | 0.0042 |
| D19 | 0.3681 | 0.0981 | 0.4139 | 0.1119 | 0.4201 | 0.0212 | 0.0436 | 0.0647 | 0.0281 | 0.0947 | 0.0093 | 0.0046 | 0.0316 | 0.0758 | 0.0104 | 0.1003 | 0.0192 | 0.0101 | 0.0000 | 0.0603 | 0.0769 | 0.0153 | 0.0125 |
| D20 | 0.0653 | 0.0542 | 0.0394 | 0.4206 | 0.0947 | 0.0803 | 0.0101 | 0.0181 | 0.0205 | 0.4211 | 0.0000 | 0.0000 | 0.0547 | 0.0079 | 0.0042 | 0.0079 | 0.0106 | 0.0060 | 0.0060 | 0.0000 | 0.0158 | 0.0186 | 0.0021 |
| D21 | 0.1053 | 0.1075 | 0.0229 | 0.0553 | 0.0764 | 0.0492 | 0.0497 | 0.0774 | 0.0503 | 0.1269 | 0.0000 | 0.0000 | 0.0347 | 0.0347 | 0.0035 | 0.0258 | 0.0170 | 0.0205 | 0.0186 | 0.0364 | 0.0000 | 0.0079 | 0.0170 |
| D22 | 0.0986 | 0.0947 | 0.0903 | 0.0969 | 0.1236 | 0.0094 | 0.0358 | 0.0851 | 0.0316 | 0.0803 | 0.0000 | 0.0076 | 0.0353 | 0.4161 | 0.3178 | 0.3576 | 0.0353 | 0.0453 | 0.0714 | 0.0386 | 0.0686 | 0.0000 | 0.0392 |
| D23 | 0.0519 | 0.0608 | 0.0181 | 0.0247 | 0.0514 | 0.0094 | 0.0936 | 0.0559 | 0.3561 | 0.0719 | 0.0014 | 0.0014 | 0.0774 | 0.3567 | 0.3967 | 0.3306 | 0.0553 | 0.0156 | 0.0519 | 0.0253 | 0.0486 | 0.0286 | 0.0000 |

**Exhibit 3**
standardized direct impact matrix

| | A1 | A2 | A3 | A4 | A5 | A6 | B7 | B8 | B9 | B10 | C11 | C12 | C13 | D14 | D15 | D16 | D17 | D18 | D19 | D20 | D21 | D22 | D23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 0.0000 | 0.0056 | 0.0045 | 0.0134 | 0.0031 | 0.0137 | 0.0145 | 0.0123 | 0.0047 | 0.0157 | 0.0011 | 0.0005 | 0.0074 | 0.0017 | 0.0034 | 0.0062 | 0.0052 | 0.0026 | 0.0044 | 0.0015 | 0.0121 | 0.0043 | 0.0022 |
| A2 | 0.0792 | 0.0000 | 0.0022 | 0.0703 | 0.0085 | 0.0147 | 0.0077 | 0.0071 | 0.0022 | 0.0774 | 0.0000 | 0.0015 | 0.0633 | 0.0100 | 0.0031 | 0.0083 | 0.0114 | 0.0022 | 0.0042 | 0.0638 | 0.0202 | 0.0104 | 0.0018 |
| A3 | 0.0746 | 0.0231 | 0.0000 | 0.0767 | 0.0194 | 0.0034 | 0.0733 | 0.0731 | 0.0114 | 0.0783 | 0.0000 | 0.0000 | 0.0032 | 0.0160 | 0.0066 | 0.0124 | 0.0746 | 0.0042 | 0.0066 | 0.0137 | 0.0789 | 0.0091 | 0.0042 |
| A4 | 0.0077 | 0.0020 | 0.0003 | 0.0000 | 0.0127 | 0.0113 | 0.0015 | 0.0047 | 0.0004 | 0.0779 | 0.0000 | 0.0000 | 0.0039 | 0.0018 | 0.0018 | 0.0023 | 0.0024 | 0.0004 | 0.0011 | 0.0029 | 0.0024 | 0.0029 | 0.0017 |
| A5 | 0.0792 | 0.0218 | 0.0216 | 0.0793 | 0.0000 | 0.0039 | 0.0800 | 0.0177 | 0.0099 | 0.0783 | 0.0000 | 0.0000 | 0.0723 | 0.0215 | 0.0162 | 0.0191 | 0.0711 | 0.0171 | 0.0178 | 0.0142 | 0.0736 | 0.0159 | 0.0109 |
| A6 | 0.0213 | 0.0069 | 0.0679 | 0.0154 | 0.0685 | 0.0000 | 0.0031 | 0.0022 | 0.0001 | 0.0093 | 0.0000 | 0.0015 | 0.0055 | 0.0023 | 0.0003 | 0.0027 | 0.0019 | 0.0007 | 0.0066 | 0.0010 | 0.0078 | 0.0013 | 0.0004 |
| B7 | 0.0184 | 0.0075 | 0.0029 | 0.0039 | 0.0025 | 0.0123 | 0.0000 | 0.0082 | 0.0146 | 0.0133 | 0.0000 | 0.0009 | 0.0089 | 0.0004 | 0.0004 | 0.0036 | 0.0050 | 0.0041 | 0.0011 | 0.0010 | 0.0037 | 0.0030 | 0.0022 |
| B8 | 0.0097 | 0.0117 | 0.0040 | 0.0012 | 0.0063 | 0.0043 | 0.0029 | 0.0000 | 0.0034 | 0.0158 | 0.0003 | 0.0015 | 0.0146 | 0.0039 | 0.0010 | 0.0047 | 0.0040 | 0.0020 | 0.0030 | 0.0039 | 0.0044 | 0.0037 | 0.0040 |
| B9 | 0.0070 | 0.0088 | 0.0006 | 0.0073 | 0.0136 | 0.0152 | 0.0071 | 0.0780 | 0.0000 | 0.0677 | 0.0015 | 0.0015 | 0.0134 | 0.0004 | 0.0001 | 0.0001 | 0.0030 | 0.0007 | 0.0010 | 0.0047 | 0.0023 | 0.0011 | 0.0024 |
| B10 | 0.0149 | 0.0071 | 0.0022 | 0.0189 | 0.0088 | 0.0137 | 0.0133 | 0.0131 | 0.0028 | 0.0000 | 0.0000 | 0.0000 | 0.0135 | 0.0011 | 0.0007 | 0.0039 | 0.0055 | 0.0004 | 0.0028 | 0.0069 | 0.0107 | 0.0019 | 0.0031 |
| C11 | 0.0712 | 0.0107 | 0.0015 | 0.0024 | 0.0027 | 0.0793 | 0.0080 | 0.0074 | 0.0024 | 0.0118 | 0.0000 | 0.0041 | 0.0765 | 0.0026 | 0.0022 | 0.0024 | 0.0024 | 0.0015 | 0.0024 | 0.0004 | 0.0023 | 0.0007 | 0.0023 |
| C12 | 0.0658 | 0.0110 | 0.0009 | 0.0031 | 0.0035 | 0.0723 | 0.0125 | 0.0086 | 0.0027 | 0.0085 | 0.0042 | 0.0000 | 0.0720 | 0.0071 | 0.0032 | 0.0017 | 0.0030 | 0.0015 | 0.0030 | 0.0022 | 0.0079 | 0.0023 | 0.0010 |
| C13 | 0.0657 | 0.0097 | 0.0006 | 0.0036 | 0.0032 | 0.0222 | 0.0121 | 0.0076 | 0.0022 | 0.0098 | 0.0021 | 0.0003 | 0.0000 | 0.0086 | 0.0023 | 0.0084 | 0.0032 | 0.0018 | 0.0022 | 0.0011 | 0.0085 | 0.0024 | 0.0011 |
| D14 | 0.0709 | 0.0663 | 0.0127 | 0.0080 | 0.0782 | 0.0073 | 0.0742 | 0.0121 | 0.0687 | 0.0741 | 0.0009 | 0.0009 | 0.0116 | 0.0000 | 0.0121 | 0.0726 | 0.0137 | 0.0644 | 0.0701 | 0.0175 | 0.0174 | 0.0149 | 0.0072 |
| D15 | 0.0720 | 0.0730 | 0.0070 | 0.0036 | 0.0127 | 0.0018 | 0.0077 | 0.0731 | 0.0043 | 0.0162 | 0.0020 | 0.0020 | 0.0061 | 0.0149 | 0.0000 | 0.0162 | 0.0116 | 0.0014 | 0.0096 | 0.0020 | 0.0142 | 0.0159 | 0.0035 |
| D16 | 0.0745 | 0.0758 | 0.0130 | 0.0733 | 0.0789 | 0.0029 | 0.0690 | 0.0165 | 0.0667 | 0.0738 | 0.0000 | 0.0000 | 0.0098 | 0.0151 | 0.0042 | 0.0000 | 0.0092 | 0.0651 | 0.0687 | 0.0693 | 0.0174 | 0.0072 | 0.0031 |
| D17 | 0.0680 | 0.0161 | 0.0149 | 0.0080 | 0.0219 | 0.0027 | 0.0654 | 0.0154 | 0.0033 | 0.0693 | 0.0041 | 0.0015 | 0.0069 | 0.0133 | 0.0010 | 0.0101 | 0.0000 | 0.0017 | 0.0084 | 0.0093 | 0.0162 | 0.0034 | 0.0022 |
| D18 | 0.0690 | 0.0183 | 0.0747 | 0.0077 | 0.0162 | 0.0008 | 0.0070 | 0.0076 | 0.0048 | 0.0116 | 0.0000 | 0.0000 | 0.0048 | 0.0151 | 0.0079 | 0.0175 | 0.0068 | 0.0042 | 0.0093 | 0.0026 | 0.0096 | 0.0028 | 0.0008 |
| D19 | 0.0700 | 0.0186 | 0.0787 | 0.0213 | 0.0799 | 0.0040 | 0.0083 | 0.0123 | 0.0053 | 0.0180 | 0.0018 | 0.0009 | 0.0060 | 0.0144 | 0.0020 | 0.0191 | 0.0036 | 0.0019 | 0.0000 | 0.0115 | 0.0146 | 0.0029 | 0.0024 |
| D20 | 0.0124 | 0.0103 | 0.0075 | 0.0800 | 0.0180 | 0.0153 | 0.0019 | 0.0034 | 0.0039 | 0.0801 | 0.0000 | 0.0000 | 0.0104 | 0.0015 | 0.0008 | 0.0015 | 0.0020 | 0.0011 | 0.0011 | 0.0000 | 0.0030 | 0.0035 | 0.0004 |
| D21 | 0.0200 | 0.0204 | 0.0044 | 0.0105 | 0.0145 | 0.0093 | 0.0095 | 0.0147 | 0.0096 | 0.0241 | 0.0000 | 0.0000 | 0.0066 | 0.0066 | 0.0007 | 0.0049 | 0.0032 | 0.0039 | 0.0035 | 0.0069 | 0.0000 | 0.0015 | 0.0032 |
| D22 | 0.0187 | 0.0180 | 0.0172 | 0.0184 | 0.0235 | 0.0018 | 0.0068 | 0.0162 | 0.0060 | 0.0153 | 0.0000 | 0.0015 | 0.0067 | 0.0791 | 0.0604 | 0.0680 | 0.0067 | 0.0086 | 0.0136 | 0.0073 | 0.0130 | 0.0000 | 0.0074 |
| D23 | 0.0099 | 0.0116 | 0.0034 | 0.0047 | 0.0098 | 0.0018 | 0.0178 | 0.0106 | 0.0677 | 0.0137 | 0.0003 | 0.0003 | 0.0147 | 0.0678 | 0.0754 | 0.0628 | 0.0105 | 0.0030 | 0.0099 | 0.0048 | 0.0092 | 0.0054 | 0.0000 |

**Exhibit 4**
comprehensive impact matrix

| | A1 | A2 | A3 | A4 | A5 | A6 | B7 | B8 | B9 | B10 | C11 | C12 | C13 | D14 | D15 | D16 | D17 | D18 | D19 | D20 | D21 | D22 | D23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 0.0067 | 0.0087 | 0.0072 | 0.0175 | 0.0072 | 0.0156 | 0.0180 | 0.0153 | 0.0066 | 0.0225 | 0.0012 | 0.0007 | 0.0101 | 0.0035 | 0.0043 | 0.0081 | 0.0072 | 0.0039 | 0.0060 | 0.0035 | 0.0147 | 0.0051 | 0.0027 |
| A2 | 0.0957 | 0.0076 | 0.0074 | 0.0842 | 0.0182 | 0.0222 | 0.0173 | 0.0142 | 0.0066 | 0.0996 | 0.0004 | 0.0017 | 0.0697 | 0.0139 | 0.0056 | 0.0136 | 0.0158 | 0.0053 | 0.0083 | 0.0677 | 0.0270 | 0.0128 | 0.0034 |
| A3 | 0.1001 | 0.0354 | 0.0073 | 0.0922 | 0.0327 | 0.0119 | 0.0901 | 0.0844 | 0.0191 | 0.1105 | 0.0006 | 0.0005 | 0.0151 | 0.0221 | 0.0099 | 0.0203 | 0.0814 | 0.0093 | 0.0131 | 0.0217 | 0.0889 | 0.0129 | 0.0069 |
| A4 | 0.0132 | 0.0045 | 0.0024 | 0.0047 | 0.0159 | 0.0133 | 0.0055 | 0.0073 | 0.0018 | 0.0824 | 0.0001 | 0.0001 | 0.0071 | 0.0032 | 0.0028 | 0.0040 | 0.0047 | 0.0014 | 0.0026 | 0.0046 | 0.0055 | 0.0037 | 0.0023 |
| A5 | 0.1136 | 0.0372 | 0.0311 | 0.0975 | 0.0169 | 0.0143 | 0.0997 | 0.0329 | 0.0198 | 0.1139 | 0.0008 | 0.0006 | 0.0833 | 0.0298 | 0.0208 | 0.0296 | 0.0793 | 0.0233 | 0.0258 | 0.0234 | 0.0859 | 0.0202 | 0.0136 |
| A6 | 0.0395 | 0.0134 | 0.0718 | 0.0307 | 0.0741 | 0.0032 | 0.0180 | 0.0117 | 0.0038 | 0.0290 | 0.0002 | 0.0016 | 0.0139 | 0.0067 | 0.0028 | 0.0073 | 0.0137 | 0.0036 | 0.0102 | 0.0054 | 0.0211 | 0.0041 | 0.0021 |
| B7 | 0.0235 | 0.0096 | 0.0051 | 0.0074 | 0.0055 | 0.0139 | 0.0029 | 0.0112 | 0.0158 | 0.0188 | 0.0001 | 0.0010 | 0.0112 | 0.0018 | 0.0012 | 0.0051 | 0.0065 | 0.0049 | 0.0023 | 0.0026 | 0.0060 | 0.0037 | 0.0026 |
| B8 | 0.0163 | 0.0142 | 0.0059 | 0.0057 | 0.0094 | 0.0061 | 0.0066 | 0.0026 | 0.0052 | 0.0218 | 0.0004 | 0.0015 | 0.0174 | 0.0056 | 0.0021 | 0.0067 | 0.0060 | 0.0033 | 0.0046 | 0.0061 | 0.0071 | 0.0046 | 0.0045 |
| B9 | 0.0151 | 0.0122 | 0.0035 | 0.0130 | 0.0176 | 0.0182 | 0.0116 | 0.0809 | 0.0017 | 0.0751 | 0.0016 | 0.0017 | 0.0185 | 0.0023 | 0.0012 | 0.0024 | 0.0059 | 0.0017 | 0.0026 | 0.0071 | 0.0062 | 0.0023 | 0.0034 |
| B10 | 0.0214 | 0.0098 | 0.0046 | 0.0232 | 0.0124 | 0.0156 | 0.0168 | 0.0156 | 0.0045 | 0.0077 | 0.0001 | 0.0001 | 0.0164 | 0.0028 | 0.0017 | 0.0057 | 0.0076 | 0.0015 | 0.0043 | 0.0088 | 0.0135 | 0.0028 | 0.0037 |
| C11 | 0.0843 | 0.0150 | 0.0090 | 0.0093 | 0.0115 | 0.0838 | 0.0139 | 0.0118 | 0.0046 | 0.0207 | 0.0003 | 0.0043 | 0.0807 | 0.0050 | 0.0035 | 0.0055 | 0.0055 | 0.0031 | 0.0049 | 0.0029 | 0.0074 | 0.0022 | 0.0031 |
| C12 | 0.0793 | 0.0158 | 0.0081 | 0.0101 | 0.0123 | 0.0768 | 0.0186 | 0.0132 | 0.0053 | 0.0182 | 0.0045 | 0.0003 | 0.0765 | 0.0096 | 0.0046 | 0.0051 | 0.0061 | 0.0034 | 0.0057 | 0.0048 | 0.0129 | 0.0039 | 0.0019 |
| C13 | 0.0726 | 0.0134 | 0.0042 | 0.0089 | 0.0084 | 0.0248 | 0.0169 | 0.0109 | 0.0048 | 0.0174 | 0.0023 | 0.0004 | 0.0035 | 0.0102 | 0.0034 | 0.0109 | 0.0054 | 0.0039 | 0.0047 | 0.0037 | 0.0119 | 0.0036 | 0.0018 |
| D14 | 0.1189 | 0.0868 | 0.0324 | 0.0425 | 0.1024 | 0.0182 | 0.1007 | 0.0337 | 0.0816 | 0.1204 | 0.0015 | 0.0016 | 0.0331 | 0.0115 | 0.0184 | 0.0845 | 0.0292 | 0.0747 | 0.0822 | 0.0347 | 0.0380 | 0.0211 | 0.0110 |
| D15 | 0.0914 | 0.0809 | 0.0120 | 0.0181 | 0.0218 | 0.0073 | 0.0181 | 0.0798 | 0.0097 | 0.0369 | 0.0023 | 0.0024 | 0.0171 | 0.0200 | 0.0032 | 0.0226 | 0.0171 | 0.0057 | 0.0148 | 0.0111 | 0.0222 | 0.0189 | 0.0053 |
| D16 | 0.1166 | 0.0908 | 0.0309 | 0.1057 | 0.0987 | 0.0147 | 0.0905 | 0.0357 | 0.0752 | 0.1227 | 0.0006 | 0.0006 | 0.0309 | 0.0243 | 0.0095 | 0.0117 | 0.0239 | 0.0712 | 0.0763 | 0.0818 | 0.0364 | 0.0131 | 0.0066 |
| D17 | 0.0832 | 0.0231 | 0.0193 | 0.0198 | 0.0293 | 0.0084 | 0.0752 | 0.0227 | 0.0086 | 0.0849 | 0.0043 | 0.0017 | 0.0149 | 0.0165 | 0.0031 | 0.0149 | 0.0060 | 0.0052 | 0.0125 | 0.0143 | 0.0240 | 0.0058 | 0.0038 |
| D18 | 0.0885 | 0.0272 | 0.0791 | 0.0232 | 0.0253 | 0.0050 | 0.0218 | 0.0190 | 0.0105 | 0.0327 | 0.0003 | 0.0002 | 0.0116 | 0.0194 | 0.0103 | 0.0230 | 0.0166 | 0.0085 | 0.0145 | 0.0088 | 0.0216 | 0.0057 | 0.0024 |
| D19 | 0.0966 | 0.0299 | 0.0846 | 0.0442 | 0.0901 | 0.0099 | 0.0297 | 0.0260 | 0.0125 | 0.0486 | 0.0021 | 0.0012 | 0.0186 | 0.0207 | 0.0059 | 0.0264 | 0.0189 | 0.0078 | 0.0070 | 0.0194 | 0.0324 | 0.0072 | 0.0049 |
| D20 | 0.0217 | 0.0137 | 0.0105 | 0.0869 | 0.0232 | 0.0189 | 0.0078 | 0.0079 | 0.0056 | 0.0934 | 0.0001 | 0.0001 | 0.0154 | 0.0036 | 0.0021 | 0.0041 | 0.0058 | 0.0024 | 0.0031 | 0.0029 | 0.0081 | 0.0050 | 0.0014 |
| D21 | 0.0290 | 0.0240 | 0.0073 | 0.0175 | 0.0190 | 0.0119 | 0.0148 | 0.0186 | 0.0120 | 0.0343 | 0.0001 | 0.0002 | 0.0114 | 0.0086 | 0.0020 | 0.0076 | 0.0064 | 0.0057 | 0.0058 | 0.0102 | 0.0042 | 0.0029 | 0.0040 |
| D22 | 0.0531 | 0.0399 | 0.0263 | 0.0385 | 0.0443 | 0.0075 | 0.0289 | 0.0311 | 0.0207 | 0.0479 | 0.0005 | 0.0019 | 0.0180 | 0.0858 | 0.0645 | 0.0800 | 0.0165 | 0.0212 | 0.0281 | 0.0197 | 0.0259 | 0.0053 | 0.0101 |
| D23 | 0.0407 | 0.0326 | 0.0111 | 0.0211 | 0.0288 | 0.0078 | 0.0363 | 0.0292 | 0.0802 | 0.0442 | 0.0008 | 0.0008 | 0.0246 | 0.0736 | 0.0786 | 0.0732 | 0.0179 | 0.0140 | 0.0227 | 0.0156 | 0.0193 | 0.0102 | 0.0024 |

**Exhibit 5**
the overall impact matrix

| | A1 | A2 | A3 | A4 | A5 | A6 | B7 | B8 | B9 | B10 | C11 | C12 | C13 | D14 | D15 | D16 | D17 | D18 | D19 | D20 | D21 | D22 | D23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 1.0067 | 0.0087 | 0.0072 | 0.0175 | 0.0072 | 0.0156 | 0.0180 | 0.0153 | 0.0066 | 0.0225 | 0.0012 | 0.0007 | 0.0101 | 0.0035 | 0.0043 | 0.0081 | 0.0072 | 0.0039 | 0.0060 | 0.0035 | 0.0147 | 0.0051 | 0.0027 |
| A2 | 0.0957 | 1.0076 | 0.0074 | 0.0842 | 0.0182 | 0.0222 | 0.0173 | 0.0142 | 0.0066 | 0.0996 | 0.0004 | 0.0017 | 0.0697 | 0.0139 | 0.0056 | 0.0136 | 0.0158 | 0.0053 | 0.0083 | 0.0677 | 0.0270 | 0.0128 | 0.0034 |
| A3 | 0.1001 | 0.0354 | 1.0073 | 0.0922 | 0.0327 | 0.0119 | 0.0901 | 0.0844 | 0.0191 | 0.1105 | 0.0006 | 0.0005 | 0.0151 | 0.0221 | 0.0099 | 0.0203 | 0.0814 | 0.0093 | 0.0131 | 0.0217 | 0.0889 | 0.0129 | 0.0069 |
| A4 | 0.0132 | 0.0045 | 0.0024 | 1.0047 | 0.0159 | 0.0133 | 0.0055 | 0.0073 | 0.0018 | 0.0824 | 0.0001 | 0.0001 | 0.0071 | 0.0032 | 0.0028 | 0.0040 | 0.0047 | 0.0014 | 0.0026 | 0.0046 | 0.0055 | 0.0037 | 0.0023 |
| A5 | 0.1136 | 0.0372 | 0.0311 | 0.0975 | 1.0169 | 0.0143 | 0.0997 | 0.0329 | 0.0198 | 0.1139 | 0.0008 | 0.0006 | 0.0833 | 0.0298 | 0.0208 | 0.0296 | 0.0793 | 0.0233 | 0.0258 | 0.0234 | 0.0859 | 0.0202 | 0.0136 |
| A6 | 0.0395 | 0.0134 | 0.0718 | 0.0307 | 0.0741 | 1.0032 | 0.0180 | 0.0117 | 0.0038 | 0.0290 | 0.0002 | 0.0016 | 0.0139 | 0.0067 | 0.0028 | 0.0073 | 0.0137 | 0.0036 | 0.0102 | 0.0054 | 0.0211 | 0.0041 | 0.0021 |
| B7 | 0.0235 | 0.0096 | 0.0051 | 0.0074 | 0.0055 | 0.0139 | 1.0029 | 0.0112 | 0.0158 | 0.0188 | 0.0001 | 0.0010 | 0.0112 | 0.0018 | 0.0012 | 0.0051 | 0.0065 | 0.0049 | 0.0023 | 0.0026 | 0.0060 | 0.0037 | 0.0026 |
| B8 | 0.0163 | 0.0142 | 0.0059 | 0.0057 | 0.0094 | 0.0061 | 0.0066 | 1.0026 | 0.0052 | 0.0218 | 0.0004 | 0.0015 | 0.0174 | 0.0056 | 0.0021 | 0.0067 | 0.0060 | 0.0033 | 0.0046 | 0.0061 | 0.0071 | 0.0046 | 0.0045 |
| B9 | 0.0151 | 0.0122 | 0.0035 | 0.0130 | 0.0176 | 0.0182 | 0.0116 | 0.0809 | 1.0017 | 0.0751 | 0.0016 | 0.0017 | 0.0185 | 0.0023 | 0.0012 | 0.0024 | 0.0059 | 0.0017 | 0.0026 | 0.0071 | 0.0062 | 0.0023 | 0.0034 |
| B10 | 0.0214 | 0.0098 | 0.0046 | 0.0232 | 0.0124 | 0.0156 | 0.0168 | 0.0156 | 0.0045 | 1.0077 | 0.0001 | 0.0001 | 0.0164 | 0.0028 | 0.0017 | 0.0057 | 0.0076 | 0.0015 | 0.0043 | 0.0088 | 0.0135 | 0.0028 | 0.0037 |
| C11 | 0.0843 | 0.0150 | 0.0090 | 0.0093 | 0.0115 | 0.0838 | 0.0139 | 0.0118 | 0.0046 | 0.0207 | 1.0003 | 0.0043 | 0.0807 | 0.0050 | 0.0035 | 0.0055 | 0.0055 | 0.0031 | 0.0049 | 0.0029 | 0.0074 | 0.0022 | 0.0031 |
| C12 | 0.0793 | 0.0158 | 0.0081 | 0.0101 | 0.0123 | 0.0768 | 0.0186 | 0.0132 | 0.0053 | 0.0182 | 0.0045 | 1.0003 | 0.0765 | 0.0096 | 0.0046 | 0.0051 | 0.0061 | 0.0034 | 0.0057 | 0.0048 | 0.0129 | 0.0039 | 0.0019 |
| C13 | 0.0726 | 0.0134 | 0.0042 | 0.0089 | 0.0084 | 0.0248 | 0.0169 | 0.0109 | 0.0048 | 0.0174 | 0.0023 | 0.0004 | 1.0035 | 0.0102 | 0.0034 | 0.0109 | 0.0054 | 0.0039 | 0.0047 | 0.0037 | 0.0119 | 0.0036 | 0.0018 |
| D14 | 0.1189 | 0.0868 | 0.0324 | 0.0425 | 0.1024 | 0.0182 | 0.1007 | 0.0337 | 0.0816 | 0.1204 | 0.0015 | 0.0016 | 0.0331 | 1.0115 | 0.0184 | 0.0845 | 0.0292 | 0.0747 | 0.0822 | 0.0347 | 0.0380 | 0.0211 | 0.0110 |
| D15 | 0.0914 | 0.0809 | 0.0120 | 0.0181 | 0.0218 | 0.0073 | 0.0181 | 0.0798 | 0.0097 | 0.0369 | 0.0023 | 0.0024 | 0.0171 | 0.0200 | 1.0032 | 0.0226 | 0.0171 | 0.0057 | 0.0148 | 0.0111 | 0.0222 | 0.0189 | 0.0053 |
| D16 | 0.1166 | 0.0908 | 0.0309 | 0.1057 | 0.0987 | 0.0147 | 0.0905 | 0.0357 | 0.0752 | 0.1227 | 0.0006 | 0.0006 | 0.0309 | 0.0243 | 0.0095 | 1.0117 | 0.0239 | 0.0712 | 0.0763 | 0.0818 | 0.0364 | 0.0131 | 0.0066 |
| D17 | 0.0832 | 0.0231 | 0.0193 | 0.0198 | 0.0293 | 0.0084 | 0.0752 | 0.0227 | 0.0086 | 0.0849 | 0.0043 | 0.0017 | 0.0149 | 0.0165 | 0.0031 | 0.0149 | 1.0060 | 0.0052 | 0.0125 | 0.0143 | 0.0240 | 0.0058 | 0.0038 |
| D18 | 0.0885 | 0.0272 | 0.0791 | 0.0232 | 0.0253 | 0.0050 | 0.0218 | 0.0190 | 0.0105 | 0.0327 | 0.0003 | 0.0002 | 0.0116 | 0.0194 | 0.0103 | 0.0230 | 0.0166 | 1.0085 | 0.0145 | 0.0088 | 0.0216 | 0.0057 | 0.0024 |
| D19 | 0.0966 | 0.0299 | 0.0846 | 0.0442 | 0.0901 | 0.0099 | 0.0297 | 0.0260 | 0.0125 | 0.0486 | 0.0021 | 0.0012 | 0.0186 | 0.0207 | 0.0059 | 0.0264 | 0.0189 | 0.0078 | 1.0070 | 0.0194 | 0.0324 | 0.0072 | 0.0049 |
| D20 | 0.0217 | 0.0137 | 0.0105 | 0.0869 | 0.0232 | 0.0189 | 0.0078 | 0.0079 | 0.0056 | 0.0934 | 0.0001 | 0.0001 | 0.0154 | 0.0036 | 0.0021 | 0.0041 | 0.0058 | 0.0024 | 0.0031 | 1.0029 | 0.0081 | 0.0050 | 0.0014 |
| D21 | 0.0290 | 0.0240 | 0.0073 | 0.0175 | 0.0190 | 0.0119 | 0.0148 | 0.0186 | 0.0120 | 0.0343 | 0.0001 | 0.0002 | 0.0114 | 0.0086 | 0.0020 | 0.0076 | 0.0064 | 0.0057 | 0.0058 | 0.0102 | 1.0042 | 0.0029 | 0.0040 |
| D22 | 0.0531 | 0.0399 | 0.0263 | 0.0385 | 0.0443 | 0.0075 | 0.0289 | 0.0311 | 0.0207 | 0.0479 | 0.0005 | 0.0019 | 0.0180 | 0.0858 | 0.0645 | 0.0800 | 0.0165 | 0.0212 | 0.0281 | 0.0197 | 0.0259 | 1.0053 | 0.0101 |
| D23 | 0.0407 | 0.0326 | 0.0111 | 0.0211 | 0.0288 | 0.0078 | 0.0363 | 0.0292 | 0.0802 | 0.0442 | 0.0008 | 0.0008 | 0.0246 | 0.0736 | 0.0786 | 0.0732 | 0.0179 | 0.0140 | 0.0227 | 0.0156 | 0.0193 | 0.0102 | 1.0024 |

**Exhibit 6**
the reachable matrix

| | A1 | A2 | A3 | A4 | A5 | A6 | B7 | B8 | B9 | B10 | C11 | C12 | C13 | D14 | D15 | D16 | D17 | D18 | D19 | D20 | D21 | D22 | D23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| A2 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| A3 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| A4 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| A5 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| A6 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| B7 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C11 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| C12 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| C13 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D14 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| D15 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| D16 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| D17 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| D18 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| D19 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 |
| D20 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| D21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| D22 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| D23 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e22167.

## References


[1] C.-F. Chi, T.-C. Chang, H.-I. Ting, Accident patterns and prevention measures for fatal occupational falls in the construction industry, Appl. Ergon. 36 (4) (2005) 391–400.
[2] F.A.S. Sánchez, G.I.C. Peláez, J.C. Alís, Occupational safety and health in construction: a review of applications and trends, Ind. Health 55 (3) (2017) 210–218.
[3] G. Ofori, Nature of the construction industry, its needs and its development: a review of four decades of research, J. Constr. Dev. Ctries. (JCDC) 20 (2) (2015) 115.
[4] Z. Zhou, Y.M. Goh, Q. Shi, H. Qi, S. Liu, Data-driven determination of collapse accident patterns for the mitigation of safety risks at metro construction sites, Tunn. Undergr. Space Technol. 127 (2022), 104616.
[5] A.D.u. Rafindadi, et al., Analysis of the causes and preventive measures of fatal fall-related accidents in the construction industry, Ain Shams Eng. J. 13 (4) (2022), 101712.
[6] Y. Halabi, et al., Causal factors and risk assessment of fall accidents in the US construction industry: a comprehensive data analysis (2000–2020), Saf. Sci. 146 (2022), 105537.
[7] A. Zermane, M.Z.M. Tohir, H. Zermane, M.R. Baharudin, H.M. Yusoff, Predicting fatal fall from heights accidents using random forest classification machine learning model, Saf. Sci. 159 (2023), 106023.
[8] S. Shi, M. Jiang, Y. Liu, R. Li, Risk assessment on falling from height based on AHP-fuzzy, Procedia Eng. 45 (2012) 112–118.
[9] A. Zermane, M.Z.M. Tohir, M.R. Baharudin, H.M. Yusoff, Risk assessment of fatal accidents due to work at heights activities using fault tree analysis: case study in Malaysia, Saf. Sci. 151 (2022), 105724.
[10] W. Huang, Y. Zhang, X. Kou, D. Yin, R. Mi, L. Li, Railway dangerous goods transportation system risk analysis: an Interpretive Structural Modeling and Bayesian Network combining approach, Reliab. Eng. Syst. Saf. 204 (2020), 107220.
[11] F. Li, W. Wang, S. Dubljevic, F. Khan, J. Xu, J. Yi, Analysis on accident-causing factors of urban buried gas pipeline network by combining DEMATEL, ISM and BN methods, J. Loss Prev. Process. Ind. 61 (2019) 49–57.
[12] G. Sun, J. Sun, F. Li, Influencing factors of early termination for PPP projects based on multicase Grounded theory, J. Construct. Eng. Manag. 148 (11) (2022), 04022120.
[13] V. Stelzenmüller, et al., A risk-based approach to cumulative effect assessments for marine management, Sci. Total Environ. 612 (2018) 1132–1140.
[14] H. Shakeri, M. Khalilzadeh, Analysis of factors affecting project communications with a hybrid DEMATEL-ISM approach (A case study in Iran), Heliyon 6 (8) (2020), e04430.
[15] J. Peng, C. Peng, M. Wang, K. Hu, D. Wu, Research on the factors of extremely short construction period under the sufficient resources based on Grey-DEMATEL-ISM, PLoS One 17 (3) (2022), e0265087.
[16] H. Chen, et al., Influencing factors of novice pilot SA based on DEMATEL-AISM method: from pilots? view, English), Heliyon 9 (2) (Feb 2023) 14, https://doi.org/10.1016/j.heliyon.2023.e13425. Art no. e13425.
[17] L. Wang, Q. Cao, L. Zhou, Research on the influencing factors in coal mine production safety based on the combination of DEMATEL and ISM, Saf. Sci. 103 (2018) 51–61.
[18] B. Fernández-Muñiz, J.M. Montes-Peón, C.J. Vázquez-Ordás, The role of safety leadership and working conditions in safety performance in process industries, J. Loss Prev. Process. Ind. 50 (2017) 403–415.
[19] S. Bathrinath, R.A. Koshy, R. Bhalaji, K. Koppiahraj, Identification of the critical activity in heat treatment process using TISM, Mater. Today: Proc. 39 (2021) 60–65.
[20] A. Suraji, A.R. Duff, S.J. Peckitt, Development of causal model of construction accident causation, J. Construct. Eng. Manag. 127 (4) (2001) 337–344.
[21] Z. Ismail, S. Doostdar, Z. Harun, Factors influencing the implementation of a safety management system for construction sites, Saf. Sci. 50 (3) (2012) 418–423.

[22] S. Winge, E. Albrechtsen, Accident types and barrier failures in the construction industry, Saf. Sci. 105 (2018) 158–166.
[23] Y.-H. Chiang, F.K.-W. Wong, S. Liang, Fatal construction accidents in Hong Kong, J. Construct. Eng. Manag. 144 (3) (2018), 04017121.
[24] A. Hoła, B. Hoła, M. Szóstak, Analysis of the causes and consequences of falls from scaffolding using the Polish construction industry as an example, 1, in: IOP Conference Series: Materials Science and Engineering, vol. 251, IOP Publishing, 2017, 012050.
[25] C.-F. Chi, S.-Z. Lin, R.S. Dewi, Graphical fault tree analysis for fatal falls in the construction industry, Accid. Anal. Prev. 72 (2014) 359–369.
[26] M. Xing, X. Luo, Y. Zan, L. Yang, H. Jin, J. Luo, Identification of factors affecting hoisting quality of large offshore structures and analysis of their coupling relationship based on grey-DEMATEL-ISM-MICMAC, Ocean Eng. 280 (2023), 114805.
[27] L. Li, The analysis on influencing factor of cost control of EPC project based on the DEMATEL-ISM, Stavební obzor-Civil Engineering Journal 31 (1) (2022) 66–84.
[28] X. Luo, Q. Liu, Z. Qiu, A correlation analysis of construction site fall accidents based on text mining, Frontiers in Built Environment 7 (2021), 690071.
[29] D. Guo, Z. Song, T. Xu, Y. Zhang, L. Ding, Coupling analysis of tunnel construction risk in complex geology and construction factors, J. Construct. Eng. Manag. 148 (9) (2022), 04022097.
[30] T. Xu, Z. Song, D. Guo, Y. Song, A cloud model-based risk assessment methodology for tunneling-induced damage to existing tunnel, Adv. Civ. Eng. 2020 (2020) 1–11.
[31] S. Bathrinath, S. Mohan, K. Koppiahraj, R. Bhalaji, B. Santhi, Analysis of factors affecting sustainable performance in construction sites using fuzzy AHP-WASPAS methods, Mater. Today: Proc. 62 (2022) 3118–3121.
[32] S. Rostamzadeh, A. Abouhossein, M.H. Chalak, S. Vosoughi, R. Norouzi, An integrated DEMATEL–ANP approach for identification and prioritization of factors affecting fall from height accidents in the construction industry, Int. J. Occup. Saf. Ergon. (2022) 1–10.
[33] B. Tunçer, F. Benita, Data-driven thinking for measuring the human experience in the built environment, Int. J. Architect. Comput. 20 (2) (2022) 316–333.
[34] X.A. Wang, X.F. Hu, Quantitative risk assessment of college campus considering risk interactions, English), Heliyon 9 (2) (Feb 2023) 16, https://doi.org/10.1016/j.heliyon.2023.e13674. Art no. e13674.
[35] C. Vishnu, R. Sridharan, P. Ram Kumar, V. Regi Kumar, Analysis of the operational risk factors in public hospitals in an indian state: a hybrid DEMATEL–ISM–PROMETHEE approach, Int. J. Health Care Qual. Assur. 33 (1) (2020) 67–88.
[36] S. Yadav, S. Luthra, D. Garg, Internet of things (IoT) based coordination system in Agri-food supply chain: development of an efficient framework using DEMATEL-ISM, Operations management research (2020) 1–27.
[37] X. Huang, J. Hinze, Analysis of construction worker fall accidents, J. Construct. Eng. Manag. 129 (3) (2003) 262–271.
[38] F.K. Wong, et al., Findings from a research study of construction safety in Hong Kong: accidents related to fall of person from height, J. Eng. Des. Technol. 7 (2) (2009) 130–142.
[39] T. Nowobilski, B. Hoła, Methodology based on causes of accidents for forcasting the effects of falls from scaffoldings using the construction industry in Poland as an example, Saf. Sci. 157 (2023), 105945.
[40] M.T. Newaz, M. Ershadi, L. Carothers, M. Jefferies, P. Davis, A review and assessment of technologies for addressing the risk of falling from height on construction sites, Saf. Sci. 147 (2022), 105618.
[41] M.Z. Shanti, C.-S. Cho, B.G. de Soto, Y.-J. Byon, C.Y. Yeun, T.Y. Kim, Real-time monitoring of work-at-height safety hazards in construction sites using drones and deep learning, J. Saf. Res. 83 (2022) 364–370.
[42] S. Chen, K. Demachi, Towards on-site hazards identification of improper use of personal protective equipment using deep learning-based geometric relationships and hierarchical scene graph, Autom. ConStruct. 125 (2021), 103619.
[43] R. Sehsah, A.-H. El-Gilany, A.M. Ibrahim, Personal protective equipment (PPE) use and its relation to accidents among construction workers, Med. Lavoro 111 (4) (2020) 285.
[44] N. Mohammad Hanapi, M.M. Mohd Kamal, M.I. Ismail, I.A. Putera Abdullah, Identifying root causes and mitigation measures of construction fall accidents, Gading Journal for the Social Sciences 17 (1) (2013) 65–79.
[45] Z.E. Zhou, L.L. Meier, P.E. Spector, The role of personality and job stressors in predicting counterproductive work behavior: a three-way interaction, Int. J. Sel. Assess. 22 (3) (2014) 286–296.
[46] G.C. Homans, Social behavior as exchange, Am. J. Sociol. 63 (6) (1958) 597–606.
[47] Y. Yang, Y. Wang, S.M. Easa, X. Yan, Risk Factors Influencing Tunnel Construction Safety: Structural Equation Model Approach, Heliyon, 2023, e12924.
[48] S. Antomarioni, M.M. Bellinello, M. Bevilacqua, F.E. Ciarapica, R.F. da Silva, G.F.M. de Souza, A data-driven approach to extend failure analysis: a framework development and a case study on a hydroelectric power plant, Energies 13 (23) (2020) 6400.
[49] F. Lin, P. Wu, Y. Xu, Investigation of factors influencing the construction safety of high-speed railway stations based on DEMATEL and ISM, Adv. Civ. Eng. 2021 (2021) 1–12.
[50] Z.F. Olcay, A.E. Sakalli, S. Temur, A. Yazici, A study of the shift in fatal construction work-related accidents during 2012–2019 in Turkey, Int. J. Occup. Saf. Ergon. 28 (3) (2022) 1522–1532.