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Fine-Kinney fuzzy-based occupational health risk assessment for Workers in different construction trades

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ABSTRACT

This paper aims to enhance occupational health risk assessment for construction workers by introducing and validating two innovative models: the Occupational Health Risk Assessment Hierarchy Model (OHRAHM) and the Occupational Health Hazard Factor Risk Assessment Model (OHHFRAM). Utilizing the Fine-Kinney method (FKM), fuzzy sets, and the fuzzy inference system (FIS), these models provide a nuanced understanding of health risks in various construction trades. The models are demonstrated and validated in a specific region of China, including applying the FKM to different construction work types and evaluating occupational health across multiple trades. The principal results show the potential of OHRAHM and OHHFRAM in assessing risk magnitudes for various health factors, offering valuable insights for risk classification and proposing effective control measures. This paper addresses the need for improved health risk assessment models in the construction industry.

1. Introduction

The Chinese construction industry has been plagued with labor shortages due to decreases in the labor force participation rate [1]. This phenomenon is a global crisis [2], which also reflects the dilemma faced by the construction industry in both developed (UK, U.S., New Zealand, etc.) and developing countries (India, Ghana, Sri Lanka etc.) simultaneously [3]. Featured as a labor-intensive industry, construction productivity enhancement is constrained by labor shortages [2].

To counter this, it is an urgent task for both the government and practitioners to increase the participation rate of construction workers (CWs) (Ho et al., 2016) and prolong their working lives [4]. However, potential new employees tend to be discouraged from entering the industry due to its unpleasant, dirty, and dangerous working conditions (Ho et al., 2016), which have posed serious risks (e.g., musculoskeletal disorders and pneumoconiosis) to the occupational health and safety (OHS) of CWs [4,5,6]. Moreover, CWs are reluctant to continue to work until retirement age [4] and can even be forced into early retirement [7]. Therefore, improving the OHS of CWs could enhance the attractiveness of the construction industry to prospective employees (Ho et al., 2016).

These issues have triggered a body of research into risk assessment [8], which can guide practitioners to adopt appropriate preventive measures in advance and a more targeted manner [9]. However, while the importance of OHS risk assessment is well recognized in the construction industry [8], most studies in this field do not distinguish between occupational safety and health. According to Liu et al. [10], occupational health is a long-term process involving chronic health concerns that take time to manifest, such as musculoskeletal problems and pneumoconiosis. In contrast, occupational safety entails instantaneous impacts like an electrical shock or falling from a height.

In response, therefore, this study aims to identify and assess the risk occupational health hazards of CWs in different trades based on the CWs' judgments to provide them with a better understanding of the nature of OHS and to help practitioners carry out OHS management in a more targeted manner to improve the industry's poor image and health status. The developed occupational health hazard factor risk assessment model (OHHFRAM) employs the Fine-Kinney method (FKM), fuzzy sets, and the fuzzy inference system (FIS) to acquire the risk magnitude of each hazard factor for use as input in the model to obtain the overall risk magnitudes of different construction trades. The risks are classified into

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three categories based on these two indicators, and risk control measures are proposed based on CWs and construction managers (CMs).

2. Literature review

2.1. Risk identification

The initial step of any risk assessment approach begins with identifying the potential risks (e.g., [11]). Most studies on the risk identification of OHS have reviewed the literature concerning related papers, reports, articles, OHS information (e.g., [12]), and the Delphi method (e.g., [13]). Ilbahar et al. [13] identified 32 OHS risks in a construction yard, but only one involved noise's chronic occupational health hazards. Khan et al. [12] enumerated 15 OHS construction industry risks, but none focused on occupational health. Similarly, Ding et al.'s [14] summary of metro construction's safety risks and risk factors also fails to address OHS. Although Mohandes and Zhang [8] recognized 18 risks of OHCW, including such health factors as chemical substances, hot temperature, and poisonous gas, they did not distinguish between safety and health and the lack of a comprehensive health factors system.

China has introduced a regulation named Classification of Occupational Hazards, which lists 459 hazard factors that cause occupational diseases in detail and divides them into six categories: dust, chemical, physical, radioactive, biological, and 'other factors' [15]. In addition, another regulation called Occupation Disease Classification and Catalogue clearly defines the occupational diseases that affect the life and health of workers [16]. Zhu [17] conducted a study of the corresponding relationship between hazards and diseases in these two regulations, pointing out that most occupational hazards mentioned in the regulations lack methods for their detection and require more risk assessment methods to evaluate them. Therefore, while China's regulations in occupational health provide a foundation for risk identification, there is little guidance for risk assessment.

2.2. Risk assessment

Risk assessment, in general, is regarded as the most effective way to evaluate and reduce risks in advance [9,18]; it involves a three-step process of identification, assessment, and control [19]. For occupational health risks, their assessment refers to comprehensively and systematically identifying and analyzing workplace risk factors and protective measures, qualitatively or quantitatively evaluating occupational health risk levels, and thus taking corresponding control measures [20].

For many years, governments worldwide have been increasingly pursuing the development of occupational health risk assessment by promulgating standards or laws. The Ministry of Labor and Social Protection Department of Romania [21], for instance, has assessed the probability and severity of the occurrence of this risk factor based on an established checklist. The Environmental Protection Agency of the United States [22] has carried out inhalation risk assessment through the assessment of duration, exposure pattern, concentration, etc. The Ministry of Manpower of Singapore [23] has established a 5*5 risk matrix for health and safety risk assessment in the workplace by a risk assessment team that evaluates the severity and likelihood of the hazards involved. Although these are different in evaluation standards and methods, there is a consensus that most use such parameters as frequency, severity, and possibility to assess the risk exposure of workers. The assessment of the parameters is limited to on-site testing data or the subjective judgment of experts, which is more concerned with temporary risks than long-term risks to the workers.

In recent years, there has been increasing literature on risk assessment. The methods are often divided into qualitative and quantitative [24]. Qualitative methods include fault tree analysis, cause-consequence analysis, risk tree analysis, dynamic event tree analysis, and bow-tie risk analysis [25]. Although these are relatively user-friendly, they cannot directly reflect the risk situation – a feature that quantitative methods can overcome. Most studies investigating quantitative methods utilize Multiple Criteria Decision Making (MCDM), Monte Carlo Simulation, the Fine-Kinney method (FKM) [26], Failure Modes and Effects Analysis (FMEA), the Alternative Queuing Method (AQM) [27], and Bayesian networks [28]. Firstly, the most commonly used MCDM techniques include the analytic hierarchy process (AHP) (e.g., [29,13,30]), analytic network process [31,32], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [33], VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [34], CFD models [35] Best-Worst Method (BWM) and Measurement of Alternatives and Ranking to Compromise Solution (MARCOS) [36]. Although MCDM techniques help decision-makers prioritize risks [37], they do not fit the current study aiming at acquiring crisp risk magnitudes (rather than risk ranking) to compare risks between different CW trades. Secondly, Monte Carlo Simulation considers the impact of uncertainty on risk in various forecasting models [38], which requires a large dataset [39]. However, data for OHCW are difficult to obtain since most countries prefer to remain silent about the high mortality rate involved [40]. Moreover, compared with the classical risk assessment model, which contains only two parameters of probability and severity, FKM and FMEA consider one more parameter of frequency and detectability to obtain more comprehensive risk assessment outcomes [41]. Considering the time value of risk, frequency is a more practical parameter in risk treatment [33]. Moreover, occupational health risks are not detectable due to the chronic effect of hazard factors.

FKM has been favored by researchers in different fields based on the judgment of the three parameters of experts but is limited to research into certain projects or places. For example, Kokangül et al. [42] applied FKM to evaluate risks in a large manufacturing company, Ilbahar et al. [13] used FKM to assess the hazards involved in an excavation process, and Karasan et al. [43] incorporated the FKM and FMEA to create a novel approach to assess the hazards in an excavation process. Moreover, FKM has deficiencies due to its proportional formula for obtaining the risk magnitude. For example, suppose a hazard's severity, frequency, and probability levels are 9, 5, and 5, respectively. In that case, the risk magnitude is 955 = 225, but if they are 7, 7, and 5, respectively, then the risk magnitude is 245, making the risk of the former appear greater from the CMs' perspective [44]. In addition, because different people have different degrees of risk acceptance, it is difficult to accurately express the numbers according to the relevant evaluation standards [44]. Therefore, FKM needs further improvement to minimize the sensitivity and uncertainty in decision-makers judgments.

Fuzzy sets and the FIS are commonly used to ameliorate these limitations. Lin et al. [45], for example, applied fuzzy sets to assess construction project risks, allowing experts to provide a precise numerical value, range of numerical values, linguistic term, or fuzzy number; Abou [46] introduces a new interpretation of intuitionistic fuzzy sets in the Dempster-Shafer theory of evidence for monitoring safety-critical systems' performance to address the practical problem of formal ship safety assessment; Abdelgawad and Fayek [44] used fuzzy logic and fuzzy AHP to address the limitations of FMEA; while Samantra et al. [40] developed an improved method using fuzzy sets to convert linguistic data into numeric risk ratings. Ilbahar et al. [13] considered the three methods of FKM, Pythagorean fuzzy AHP, and FIS, proposing a Pythagorean fuzzy proportional risk assessment model. After obtaining the weight of each hazard factor, rather than directly multiplying the result in the classical approach, they used FIS instead to determine the risk magnitude through the degree of membership. Therefore, FIS can reduce a problem of high sensitivity due to scalar multiplication, and fuzzy sets can give evaluators greater judgment freedom.

2.3. Risk control

Risk control means that risks are classified in terms of risk magnitude so that control measures are proposed [47]. Oz et al. [33] conduct risk classification according to the ranking of risk magnitude to identify the 10 most serious hazards, while Isaac and Edrei [48] use a statistical model utilizing real-time tracking data to control the exposure of construction workers to safety risks. In addition, risks can be classified within the range of their maximum and minimum magnitudes according to the different outcomes they can achieve under the evaluation criteria [49,40]. Based on the risk classification, such risk control measures are proposed as corrective action, mitigating action, or neglect [50,49,40]. Although risks have been classified into four [49] or five [47] groups, their classification criteria are biased toward the CMs' perspective: CMs care about the overall status of all CWs, while CWs pay more attention to themselves. Moreover, the two above classification methods do not fully consider the extreme differences in risk magnitude and the objective existence of risk.

2.4. Conclusion

This section critically examines risk assessments in OHCWs, examining a variety of methodologies and identifying gaps in addressing chronic occupational health hazards. It critiques the FKM and emphasizes the importance of fuzzy sets and the FIS for mitigating limitations in existing risk assessment practices. The review also identifies risks based on magnitude and proposes control measures, highlighting biases in current methods. This lays the groundwork for the study's research objectives, aiming to bridge identified gaps through a holistic risk assessment model incorporating government regulations, worker perspectives, and inclusive risk classification and control strategies involving both CWs and CMs.

3. Development of the models

3.1. The occupational health risk assessment hierarchy model (OHRAHM)

Combining the superiority chart method (SCM) and specialist reliability analysis method (SRAM), OHRAHM aims to retrieve the importance weightings of hazard factors in the hierarchy model based on risk identification. The SCM is based on Li et al. [51] with some modifications by SRAM to assign the evaluators' weightings objectively. SCM is a method that establishes a matrix between factors and compares them pairwise to determine the factor weightings [51]: it avoids the situation where the consistency ratio is not passed due to a logical error of the evaluators in the AHP. SRAM constructs a new formula for the reliability coefficient based on the reliability definition [52]. The OHRSHM comprises six steps as follows.

Step 1: Divide the factors that need to be compared horizontally and vertically to form an n*n matrix.

Step 2: Compare the factors in pairs and add the results to the corresponding squares.

Step 3: Calculate the factor weightings based on

$$R_i = R_{i1} + R_{i2} + \ldots R_{in} \tag{1}$$

$$W_{ci} = R_i / \sum_{i=0}^{n} R_i \tag{2}$$

Step 4: Calculate the reliability coefficient of each decision-maker based on.

$$RC = \frac{\sum_{j}\sum_{j'} l_{jj'}}{\sum_{j}\sum_{j'} q_{jj'}} = \frac{\sum_{j}\sum_{j'} l_{jj'}}{\sum_{j}\sum_{j'} \frac{(l_{jj} + l_{j'j'})}{2}} \left(j' > \mathrm{j}\right) \tag{3}$$

where n denotes the number of evaluation objects, $i = 1, 2, \ldots, n$; m evaluators, and $j = 1, 2 \ldots, m$; the evaluation result of each evaluator on n factors is $X_{ij} (i = 1, 2, \ldots, n)$; l_{jj} and $l_{jj'}$ (are)

$$l_{jj} = \sum \left(X_j - \overline{X}_i\right)^2 = \sum X_j^{\,2} - \frac{\left(\sum X_j\right)^2}{n} \tag{4}$$

$$l_{jj'} = \sum \left(X_j - \overline{X}_i\right)\left(X_{j'} - \overline{X}_i\right) = \sum X_j X_{j'} - \frac{\sum X_j \sum X_{j'}}{n} \tag{5}$$

Step 5: Calculate the evaluators' weightings. Based on the reliability coefficient, the weightings of the jth evaluator can be obtained from

$$W_j = \frac{RC_j}{RC_1 + RC_2 + RC_3 + \ldots + RC_m} \tag{6}$$

Step 6: Obtain the final weightings of each factor based on W_{ci} and W_j, (with)

$$W_i' = \sum_{j=1}^{m} W_j * W_{ci} \ (i = 1, 2, \ldots, n) \tag{7}$$

3.2. The occupational health hazard factor risk assessment model (OHHFRAM)

The OHHFRAM combines FKM, fuzzy sets, and FIS to estimate the risk magnitude of the hazard factors (HFRM). FKM adopts three parameters – likelihood, frequency, and severity – to assess risk quantitatively, the product of which expresses the risk magnitude of the hazard [53]. Based on the three parameters, a revised version of FKM was proposed through fuzzy sets and FIS in the OHHFRAM. A fuzzy set A in X is characterized by a fuzzy membership function $\mu_A(x)$, which is associated with each point in X and a real number in the interval $[0, 1]$ [54]. According to Zeng et al. [55] and a pilot test, the 5-level triangle and 4-level trapezoid fuzzy membership functions were set for the risk assessment, as shown in Fig. 1 and Table 1. Moreover, FIS was applied to obtain a crisp risk magnitude Karamustafa and Cebi [56].[1]

The main steps of OHHFRAM are:

Step 1: Evaluate the parameters' likelihood, frequency, and severity based on the 5-level linguistic variables Table 1.

Step 2: Determine the trade involved according to questionnaire data.

Step 3: Convert the linguistic variables of different types of work into corresponding fuzzy numbers using the scale in Table 1.

Step 4: Sum the triangular fuzzy numbers of each parameter of the different trades according to its operation rules – $A_1 \oplus A_2 = (a_1 + a_2, b_1 + b_2, c_1 + c_2)$ – and take the average of the fuzzy numbers to obtain the aggregate fuzzy number.

Step 5: Transform the aggregate triangular fuzzy numbers into matching fuzzy sets favorable to the FIS by considering the intersections between the aggregate triangular fuzzy numbers and the membership functions of the corresponding parameter. The aggregate triangular fuzzy number can then be converted into the form $\mu_l = \{(VL\ ,\ \mu_1), (L\ ,\ \mu_2), (M\ ,\ \mu_3)\}$.

Step 6: Use the membership degree μ of likelihood, frequency, and severity of a hazard found in step 5 as input to FIS. To achieve this, take the minimum membership degree of likelihood, frequency, and severity of a hazard to find the X_{lfs} values, where l, f, and s represent likelihood, frequency, and severity, respectively, as in

$$X_{lfs} = min\left(\mu_l, \mu_f, \mu_s\right) \tag{8}$$

where μ_l, μ_f, and μ_s represent the membership degree of the likelihood, frequency, and severity of a hazard found in step 5.

Step 7: Using Table 2, determine the class of a hazard as negligible (N), minor (Mi), major (Ma), or critical (C). The same rules given in Table 2 are used by Ilbahar et al. [13] for the evaluation of occupational

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[1] Refer to Guan et al. [47], Ilbahar et al. [13], Karasan et al. [43], and Zeng et al. [55] for more information concerning fuzzy sets and FIS.

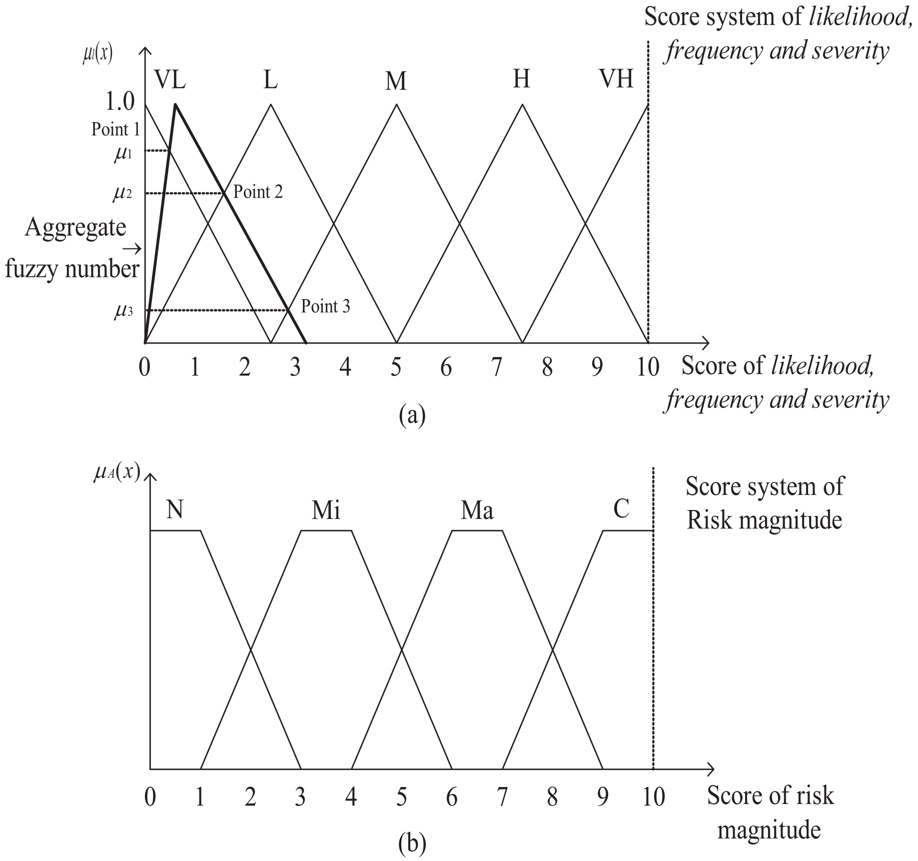

Fig. 1. Fuzzy membership function. A-for likelihood, frequency, and severity; b-for risk magnitude [55].

Table 1
Descriptions of likelihood, frequency, and severity.

Description of *likelihood*	General interpretation	Fuzzy number
Very low (VL)	Impossible to happen	(*0.0* , *0.0* , *2.5*)
Low (L)	Occurrence is conceivable but very unlikely	(*0.0* , *2.5* , *5.0*)
Medium (M)	Only remotely possible to occur	(*2.5* , *5.0* , *7.5*)
High (H)	Unusual, but possible to occur	(*5.0* , *7.5* , *10.0*)
Very high (VH)	Occurrence might well be expected	(*7.5* , *10.0* , *10.0*)
Description of *frequency*	General interpretation	Fuzzy number
Very low (VL)	Very rare contact at work	(*0.0* , *0.0* , *2.5*)
Low (L)	Unusual contact at work	(*0.0* , *2.5* , *5.0*)
Medium (M)	Occasional contact at work	(*2.5* , *5.0* , *7.5*)
High (H)	Frequent contact at work	(*5.0* , *7.5* , *10.0*)
Very high (VH)	Continue contact at work	(*7.5* , *10.0* , *10.0*)
Description of *severity*	General interpretation	Fuzzy number
Very low (VL)	Basically, no harm to health	(*0.0* , *0.0* , *2.5*)
Low (L)	The harm to health can be cured	(*0.0* , *2.5* , *5.0*)
Medium (M)	The harm to health cannot be cured	(*2.5* , *5.0* , *7.5*)
High (H)	Endanger life health	(*5.0* , *7.5* , *10.0*)
Very high (VH)	Cause death	(*7.5* , *10.0* , *10.0*)

Table 2
Fuzzy inference system rule.

Frequency	Severity	Likelihood				
		VL	L	M	H	VH
VL	VL	N	N	N	N	Mi
	L	N	N	N	Mi	Mi
	M	N	N	Mi	Mi	Mi
	H	Mi	Mi	Mi	Mi	Mi
	VH	Mi	Mi	Mi	Ma	Ma
L	VL	N	N	N	Mi	Mi
	L	N	N	N	Mi	Ma
	M	N	Mi	Mi	Ma	Ma
	H	Mi	Mi	Ma	Ma	Ma
	VH	Mi	Mi	Ma	C	C
M	VL	N	N	Mi	Mi	Ma
	L	N	Mi	Mi	Ma	Ma
	M	Mi	Mi	Ma	Ma	Ma
	H	Mi	Ma	Ma	Ma	C
	VH	Mi	Ma	Ma	C	C
H	VL	N	N	Mi	Ma	Ma
	L	N	Mi	Mi	Ma	Ma
	M	Mi	Mi	Ma	Ma	C
	H	Mi	Ma	Ma	C	C
	VH	Ma	Ma	C	C	C
VH	VL	N	N	Mi	Ma	Ma
	L	N	Mi	Ma	Ma	C
	M	Mi	Ma	Ma	C	C
	H	Ma	Ma	C	C	C
	VH	Ma	C	C	C	C

construction site risks.

Step 8: Take the maximum of the $Xijk$values that belong to the same class to determine the N, Mi, Ma, and C values for the defuzzification procedure from

$$N = max(\mu_N)\forall\mu_N \in N \tag{9}$$

$$Mi = max(\mu_{Mi})\forall\mu_{Mi} \in Mi \tag{10}$$

$$Ma = max(\mu_{Ma}) \forall \mu_{Ma} \in Ma \tag{11}$$

$$C = max(\mu_C) \forall \mu_C \in C \tag{12}$$

Step 9: Defuzzify the N, Mi, Ma, and C values to obtain the hazard factor risk magnitude [55].

$$HFRM = \frac{1 \times N + 4 \times Mi + 7 \times Ma + 10 \times C}{N + Mi + Ma + C} \tag{13}$$

Step 10: Substitute HFRM into OHRAHM to obtain the different trades' overall risk magnitude (ORM).

3.3. Comparison-based risk classification method

A comparative study is conducted within and between the trades to obtain the risk classification from the perspective of CWs and CMs. The risks can be managed by dividing them into three categories from the current research. Zhou and Deng [57] used the quartile method to grade the importance of quality characteristics into three categories. This inspired us to divide the relative numerical interval using 0.75 and 0.5 as the cut-off points. The steps for the comparative study within trades are:

Step 1: Set the maximum HFRM in each work trade to 1 and divide the other HFRM in the trade by the maximum HFRM to convert them into comparable data.

Step 2: Divide the interval according to the comparative data obtained in Step 1 into three areas [57]:

- Area 1: Interval $[0, 0.5]$ is the core area.
- Area 2: Interval $[0.5, 0.75]$ is the base area.
- Area 3: Interval $[0.75, 1]$ is the gap area.

Step 3: Based on the comparison of the HFRM of certain trades with the HFRM of all workers, the risks are grouped into three categories according to steps 2 and 3:

- Category 1: Other situations except categories 2 and 3.
- Category 2: The factor is in area 2, and its HFRM is greater than the level of the corresponding hazard factor for all workers, or the factor is in area 3, and its HFRM is less than the level of the corresponding hazard factor for all workers.
- Category 3: The factor is in area 3, and its HFRM is greater than the level of the corresponding hazard factor of all workers.

Step 4: Risk control measures are proposed to solve the corresponding risks [50,49].

- Category 1: No action is required.
- Category 2: Develop and maintain preventive control and supervision plans and reassess these risks appropriately.
- Category 3: Take immediate action to improve.

Comparative study between the trades of work is slightly different from the method mentioned above, which is mainly reflected in step 1. Step 1 in the comparative study between work types needs to set the maximum HFRM of each hazard factor (or ORM of each work trade) to 1 and divide the HFRM of each hazard factor (or ORM) of each trade by the maximum HFRM (or ORM) to convert them into comparable data. Then, steps 2 to 4 are approximately the same as the above method.

3.4. Discussion

One potential problem with the presented models lies in the complexity and intricacy of the methodology, particularly in the OHRAHM. The multi-step process involving SCM, SRAM, and various mathematical formulations may pose challenges in practical implementation and interpretation for users not well-versed in these specific methodologies. This complexity might hinder the model's accessibility and applicability in real-world scenarios. Moreover, the OHHFRAM introduces fuzzy sets and the FIS, which may add another layer of complexity. The practical implications and ease of implementation of fuzzy logic-based systems need careful consideration, especially in industries where simplicity and user-friendly tools are crucial.

Another point to consider is the need for comprehensive validation of the proposed models. While they are theoretically constructed based on existing methods and modifications, some empirical validation is needed to strengthen the confidence in their effectiveness. This and the concern over their practical application are addressed in a real-world demonstration and validation study in the following section.

4. Demonstration and validation

The Pearl River Delta region (PRD) in China is used to demonstrate and validate the developed models. This involves the OHRAHM, OHHFRAM, comparison-based risk classification method, and data collection by a questionnaire survey of the occupational health risk assessment of workers in different construction trades.

4.1. Data collection

Two questionnaire surveys were used to acquire data. These were conducted online because of the Covid-19 epidemic. The OHRAHM questionnaire's purpose was to assign weightings to the importance of the hazard factors in the established hierarchical model. The first surveyed a sample of CMs in the form of site safety officers, as CW occupational health management is mainly carried out on the platform of occupational safety. This comprised personal background information and three judgment matrices based on the hierarchical model and SCM. Seventeen questionnaires were distributed in March 2020, and 13 valid responses were obtained. However, a relatively small sample comprises experienced officers who have worked in the PRD for at least three years, with three over 15 years. Moreover, as all play the same role in the specialist area of the construction site, their responses would be significantly well-informed and homogenous to be representative of megaprojects of this nature.

The second survey was of a sample of CWs from various trades. Before undertaking this, a pilot study was carried out in November 2019 with five CWs. This led to some changes to the original version of the questionnaire, e.g., combining the detailed dust factors into a single dust factor. In addition, the final version of the questionnaire was revised by experts from academia and CMs. This questionnaire consisted of four parts. The first involved personal information of the CWs, the second involved the frequency of exposure to hazardous factors, the third involved the possibility of occupational diseases caused by the hazardous factors, and the last involved the severity of occupational diseases. The 5-level linguistic variables comprised 'very low', 'low', 'medium', 'high', and 'very high'. The main survey was conducted from March to April 2020. It resulted in the return of 53 valid responses from 13 trades of workers: namely, survey leveler, steel fixer, carpenter, tower crane operator, construction elevator operator, door and window worker, plasterer, electrician, concrete worker, bricklayer, painter, rig worker, and miscellaneous worker.

4.2. Risk identification

Nineteen hazard factors were identified, and the corresponding hazard consequences were obtained according to the Classification of Occupational Hazards and Occupation Disease Classification and Catalogue relationship. As Table 3 shows, the factors cause occupational health hazards, of which the first seven are dust factors, which have similar mechanisms and effects. The hazards to human health were mainly caused by inhalation of the respiratory tract to cause corresponding pneumoconiosis, although they were named differently

Table 3
Hazard identification and classification.

Top layer	Middle layer	Bottom layer		Description	Corresponding consequence
Occupational Health Risk Assessment Hierarchy Model (OHRAHM) (A_1)	Dust factor (B_1)	Dust (C_1)	Silica dust	Exists in environments where stones, soil, or sand is used for work	Silicosis
			Asbestos dust	Exists in the environment where asbestos products are installed, transported, and removed	Asbestosis, mesothelioma, and lung cancer caused by asbestos.
			Cement dust	Exists in the environment of cement handling, mixing, and concrete grinding	Cement pneumoconiosis
			Welding fume	Exists in the working environment of electric welding	Welder pneumoconiosis
			Wood dust	Exists in the wood processing environment	Without corresponding occupational diseases, but there are exposure restrictions.
			Gypsum dust	Exists in indoor plastering or other environments with high concentrations of gypsum dust	Without corresponding occupational diseases, but there are exposure restrictions.
			Metal dust	Exists in the environment of steel and aluminum alloy cutting	Metal and its compound pneumoconiosis
	Physical factor (B_2)	Noise (C_2)		Exist in a noisy environment	Noise deafness, explosive deafness
		High temperature (C_3)		Exist in an environment with hot weather or high temperature	Heatstroke
		Vibration (C_4)		This occurs using vibrating tools, such as electric drills, vibrators, etc.	Arm vibration disease
		Ultraviolet rays (C_5)		Exist in the environment where the sun is directly irradiated or electric welding is performed.	Electric ophthalmia, dermatitis, or cataracts
	Chemical Factor (B_3)	Metal and its compound (C_6)		Lead, mercury, manganese, cadmium, etc. Exists in environments such as electric welding, paint, and anti-corrosion operations	Poisoning of metal and its compound
		Nitrogen oxide (C_7)		This exists in an environment with exhaust emissions from vehicles or diesel machines.	Nitrogen oxide poisoning
		Toxic gas produced by underground operation (C_8)		Carbon monoxide, hydrogen sulfide, ozone, etc. Exists in the basement operation	Toxic gas poisoning
		Inhalable paint, gas, or vapor (C_9)		Exist in painting and anti-corrosion operation	Poisoning, leukemia, or chemical eye burns
		Formaldehyde (C_{10})		Exists in the environment of indoor decoration	Formaldehyde poisoning, chemical eye burns, contact dermatitis, or asthma
		Coal tar (C_{11})		Exists in the process of thermal decomposition of coal	Skin cancer, light contact dermatitis, or melanosis
		Epoxy resin (C_{12})		This exists in plastic gloves, paint, and glue	Contact dermatitis, allergic dermatitis
		Asphalt fume (C_{13})		Exist in the environment where asphalt is heated	Skin cancer, lung cancer, gastric cancer, or esophageal cancer

because of the different harmful substances involved. Different trades are exposed to different types of dust due to their trade work. For example, concrete workers are exposed to cement dust, and steel fixers are exposed to welding fumes. The first seven types of dust factors were summarized as general dust to obtain an occupational health hazard factor system applicable to all trades. According to the six categories of related hazards in the Classification of Occupational Hazards, the hazards were identified and classified to establish the hierarchical model shown in Table 3.

4.3. Risk assessment

For risk assessment, OHHFRAM was used to calculate the HFRM and then as input to OHRAHM to obtain the ORM of each trade. Based on the establishment of the hierarchical model, OHRAHM was used to assign weightings to the factors in the hierarchical model after data collection from the CMs in the first survey. Next, the specialist reliability analysis method was applied to carry out the objective weightings of each evaluator to improve the shortcomings of directly taking the arithmetic average of each sample. Based on Eq. (7), the final OHRAHM was:

$$\begin{aligned} A_1 &= 0.46669{*}B_1 + 0.19243{*}B_2 + 0.34088{*}B_3 \\ &= 0.46669{*}C_1 + 0.04931{*}C_2 + 0.05531{*}C_3 + 0.03461{*}C_4 + \\ &\quad 0.05320{*}C_5 + 0.04630{*}C_6 + 0.04183{*}C_7 + 0.04903{*}C_8 + \\ &\quad 0.05086{*}C_9 + 0.03764{*}C_{10} + 0.03458{*}C_{11} + 0.03350{*}C_{12} + \\ &\quad 0.04714{*}C_{13} \end{aligned} \tag{14}$$

In distinguishing between different trades in the risk assessment process, a group was regarded as comprising at least two respondents for the same trade. Cronbach's alpha was first calculated from each trade group's last three sections of the OHHFRAM questionnaire data. Thus, seven types of work were considered for carrying out occupational health risk assessment. Additionally, the total worker group was considered to obtain an average level for the different trades. Then, the membership degrees of likelihood, frequency, and severity were obtained by transforming the linguistic variables and the aggregate fuzzy number. After calculating the N, Mi, Ma, and C by Eqs. (9)–(12), these were inputs for FIS defuzzification performed by Eq. (13) to obtain the HFRM. Next, the HFRM of each work trade was entered into Eq. (14) to obtain the overall risk magnitude of different worker trades. Table 4 shows the results.

4.4. Risk control

According to the ORM of each work trade, tower crane operator, survey leveler, construction elevator operator, and door and window worker were grouped into Category 1. Steel fixers, carpenters, and plasterers were in Category 3, with none in Category 2.

Table 5 shows the risk category *based on CWs* according to the comparison-based risk classification within work types, and the risk category *based on CMs* is provided based on comparison-based risk classification between work types in Table 5. The circles represent Category 1, squares represent Category 2, and triangles represent Category 3.

Table 4
Hazard factor risk magnitude.

Trade of work Hazard Factor	Tower crane operator	Survey leveler	Steel fixer	Carpenter	Construction elevator operator	Door and window worker	Plasterer	All CWs
C_1	2.2150	2.4488	6.4246	4.4386	2.4000	3.1875	5.5536	3.6531
C_2	2.7769	2.2981	4.0160	4.5561	1.7500	2.0909	6.0541	3.4863
C_3	3.4732	2.5000	6.6112	5.4450	2.6000	3.1875	5.0161	3.9402
C_4	2.5000	1.9593	3.5962	4.4347	1.7500	2.6364	5.2564	3.1649
C_5	2.9894	2.6639	5.1558	5.1838	2.2000	3.1875	4.7241	3.7194
C_6	2.4423	2.0714	5.0125	3.9493	2.0370	3.2500	4.9900	3.1915
C_7	2.5991	2.0714	3.5161	3.2986	1.2658	2.5789	5.0161	3.1215
C_8	2.7368	1.7595	3.4779	4.6285	1.3000	3.1429	4.4397	3.0255
C_9	2.8919	2.2623	3.4533	4.0588	2.0000	3.4356	5.6047	3.1405
C_{10}	2.1053	2.3333	3.3333	5.0183	2.0000	3.2917	4.5235	3.1784
C_{11}	2.1507	2.0714	2.9483	4.0977	1.2658	3.4356	4.2177	3.0124
C_{12}	2.8025	2.2623	3.1615	3.4878	1.5455	3.2212	4.5122	3.0782
C_{13}	2.5390	2.2623	2.9894	4.9555	1.7500	3.4356	4.6657	3.1084
ORM	2.4790	2.3302	5.1616	4.4627	2.0943	3.1282	5.2330	3.4627

Table 5
Risk category.

		Tower crane operator		Survey leveler		Steel fixer		Carpenter		Construction elevator operator		Door and window worker		Plasterer	
		CW	CE	CW	CE	CW	CE	CW	CE	CW	CE	CW	CE	CW	CE
Dust Factor	Dust	○	○	□	○	△	△	△	□	□	○	□	○	△	△
	Noise	□	○	□	○	□	□	△	△	○	○	○	○	△	△
Physical Factor	High temperature	□	○	□	○	△	△	△	△	□	○	□	○	△	△
	Vibration	○	○	○	○	□	□	△	△	○	○	□	○	△	△
	Ultraviolet ray	□	○	□	○	△	△	△	△	□	○	□	○	△	△
Chemical Factor	Metal and its compound	○	○	□	○	△	△	□	△	□	○	△	□	△	△
	Nitrogen oxide	○	○	□	○	□	□	□	□	○	○	□	○	△	△
	Toxic gas	□	○	○	○	□	△	△	△	○	○	△	□	□	△
	Inhalable paint, gas, or vapor	□	○	□	○	□	□	□	□	□	○	△	□	△	△
	Formaldehyde	○	○	□	○	□	□	△	△	□	○	△	□	□	△
	Coal tar	○	○	□	○	○	○	△	△	○	○	△	△	□	△
	Epoxy resin	□	○	□	○	○	□	□	△	○	○	△	□	□	△
	Asphalt fume	○	○	□	○	○	○	△	△	○	○	△	□	△	△
	CW: Risk category based on CW										Category 1: ○				
	CM: Risk category based on CM										Category 2: □				
											Category 3: △				

4.5. *Validation and discussion*

The main results from this demonstration are shown in Tables 4 and 5. Firstly, the ORM of plasterers was the highest, followed by steel fixers, carpenters, door and window workers, tower crane operators, survey levelers, and construction elevator operators. This generally agrees with Okoye [58] in Nigeria's OHS risk assessment of CWs. Remarkably, though, the occupational safety risk of plasterers is at the *lowest* level of the trades researched in Hong Kong, according to Fung et al. [59]. The work content of plasterers is to apply coats of plaster and render walls and ceilings to produce finished surfaces, screed floors, staircases, and roofs [60], which makes plasterers seldom exposed to such safety hazards as electricity, fire, and height. However, plasterers' working environment can be indoors and outdoors [61], which exposes them to more health hazards, leading to a higher health risk.

Secondly, as Table 4 shows, the HFRMs (except for high temperature) of door and window workers are higher than survey levelers, ranging from 19.66 % to 78.62 %. Moreover, the ORM of the door and window workers (mainly indoors) is 34.25 % higher than survey levelers (mainly outdoors). This result extends that of Jung et al. [61], confirming that indoor CWs are exposed to a broader range of physicochemical factors and are at a higher health risk than outdoor CWs. A similar situation applies to tower crane operators, generally regarded as a trade with a high occupational safety risk [62]. There was also an expected relatively low occupational health risk due to working in a closed and fixed environment.

That both high temperature and ultraviolet rays are classified into categories 2 or 3 agree with the findings of such other studies as Li et al. [63], who found that the working environment temperature of steel fixers, especially in the afternoon, exceeded China's 37.05 % national exposure limit; and Lindelöf et al.'s [64] observation that the intensity of ultraviolet rays of CWs is higher than other occupations.

That dust also creates greater occupational health risks to CWs, which is reflected in the higher incidence of pneumoconiosis among CWs [65]. However, Chen et al. [9] have shown that wearing masks can reduce the risk of dust inhalation; few CWs wear them because this reduces work efficiency [66]. Similarly, the highest risk chemical factors are metal and its compound, inhalable paint, gas or vapor, and epoxy resins. They mainly affect CWs by cutting lead-containing metals and inhaling them [67]. Few studies have been conducted on inhalable paint, gas, or vapor, but the factor is classified into Categories 2 or 3, presumably due to the stacking of site materials. A report in New Zealand [68] stated that there were six cases of contact dermatitis in the construction industry within five years caused by exposure to epoxy resin, two of which were plasterers – an additional reason for the prominence of plasterers.

Applying the models also highlights their potential usefulness in identifying trends and prioritizing potential interventions. As seen from Fig. 2, for instance, none of the risk factors are in grids I and IX, and 52.75 % of the factors are in the grids on the diagonal, indicating no

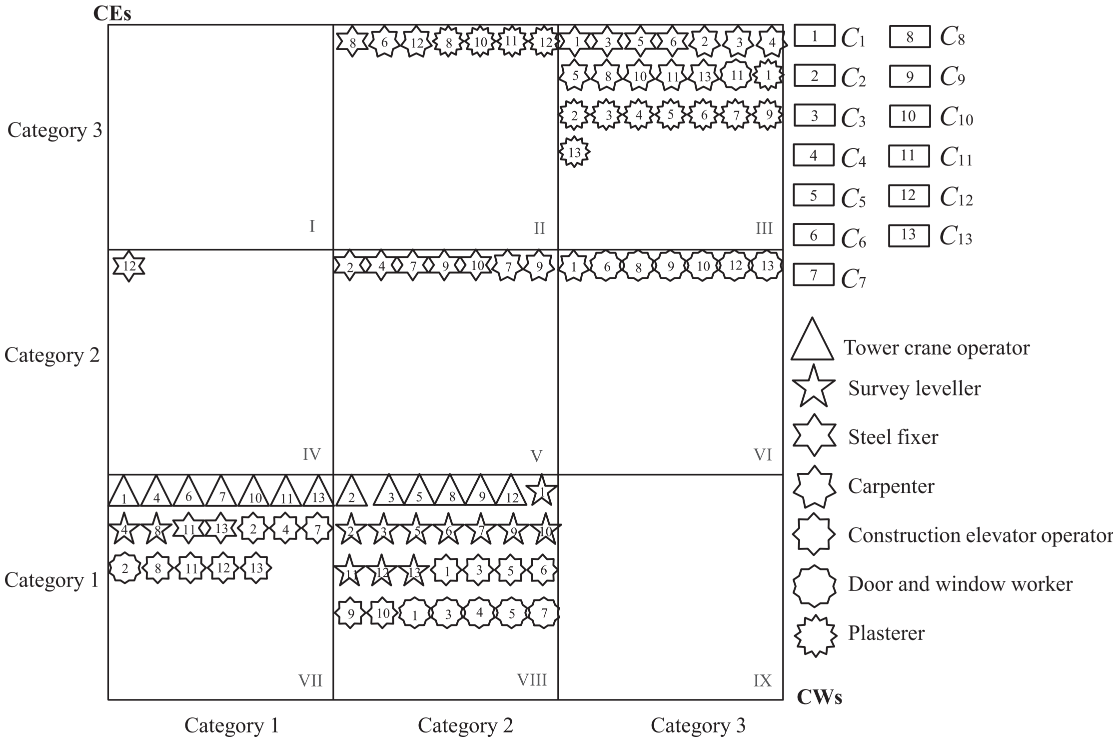

Fig. 2. Risk category matrix.

difference between CWs and CMs in risk classification. This points toward accepting a joint responsibility of CWs and CMs in OHS management [69]. While this is to be expected from the perspective of CMs, as their role in OHS management is supervision and their goal is to reduce the probability of risks [70] – thus focusing on key trades and key hazard factors – CWs being similarly focused is encouraging for the potential for a future, more collaborative approach to occupational health management and improvement.

Another identified feature is the eight factors in grids II and IV and 35 in grids VI and VII, suggesting that CWs need to pay more attention than CMs to *control risks*. On the other hand, the trades and factors located in grids II and IV are steel fixers, carpenters, plasterers, and chemical factors, suggesting that CMs need to pay more attention to the trades with greater risks and factors with urgent characteristics. In contrast, CWs are much more responsible for protecting and organizing their workplace [71]. The trades located in grids VI and VIII mainly include tower crane operators, survey levelers, construction elevator operators, and door and window workers. Although physical and dust factors account for 38.46 % of the identified factors, they account for 42.86 % of the total factors in these two grids, suggesting that CWs focus on *trades* feature as lowest risk and *factors* feature as chronic factors that can be reduced through effective personal protective equipment (PPE).

5. Conclusion

This paper introduces two occupational health risk assessment models tailored for construction workers (CWs) in various trades. The first model, the Occupational Health Risk Assessment Hierarchy Model (OHRAHM), integrates the FKM, fuzzy sets, and a fuzzy inference system (FIS) to calculate the risk magnitude of each hazard factor. The second model, the Occupational Health Hazard Factor Risk Assessment Model (OHHFRAM), serves as input for OHRAHM to derive the overall risk magnitude across different trades. These models were validated through a demonstration in China's PRD region, yielding detailed risk magnitudes for each hazard and comprehensive risk profiles for different trades. This allowed for effective risk classification and the proposal of control measures from both CW and construction manager (CM) perspectives.

The paper makes significant contributions in several areas. Firstly, it pioneers the application of the FKM in occupational health risk assessment across diverse construction work types, broadening the method's applicability. Secondly, the models facilitate a thorough evaluation of the occupational health status of CWs across various trades, pinpointing the risk magnitudes of different health factors. Thirdly, the occupational health risk data and control measures derived from this study highlight the models' potential to distinguish between occupational health and safety risks and to differentiate the health management needs of CWs and CMs.

In practical terms, the study offers several key implications. The OHRAHM and OHHFRAM models provide a robust framework for assessing and managing occupational health risks in the construction industry. They enable the identification of specific health hazards, allowing for targeted interventions and control measures tailored to different trades. By focusing on occupational health rather than safety alone, the models address a critical gap in current risk assessment practices, ensuring a more comprehensive approach to worker well-being. This can lead to improved health outcomes for CWs, reduced work-related illnesses, and enhanced overall safety in construction environments.

Moreover, the study underscores the importance of a holistic approach to occupational health management, highlighting the need to consider both immediate safety and long-term health risks. The findings suggest that integrating these models into standard practice can help organizations better protect their workers, comply with regulatory requirements, and foster a healthier, more productive workforce.

The validation study's limitations, such as a small sample size and regional focus, suggest a need for broader research to enhance the models' generalizability. Future studies should include diverse participants from various trades and regions to capture a wider range of practices, regulatory contexts, and worker demographics. Expanding the application of these risk assessment frameworks across different work types and industries will help identify commonalities and distinctions in occupational health risks, facilitating the development of universally applicable guidelines. Additionally, validating these models on a larger scale is crucial to address potential selection biases and to ensure their robustness and reliability in diverse settings. Further research should also delve deeper into the nuances of occupational health versus safety, providing a richer understanding of the distinct perspectives of CWs and CMs.

In conclusion, this study presents innovative and practical methodologies for assessing and managing occupational health risks in the construction industry. The OHRAHM and OHHFRAM models offer a comprehensive framework that addresses current gaps in risk assessment practices, providing valuable insights for both CWs and CMs. The research highlights the need for a holistic approach to occupational health and emphasizes the importance of targeted, trade-specific interventions. By addressing the study's limitations and expanding future research, these models can contribute significantly to advancing occupational health management in the construction sector.

CRediT authorship contribution statement

Hongyang Li: Supervision, Project administration, Methodology, Funding acquisition. **Yousong Wang:** Writing – original draft, Investigation. **Dan Chong:** Writing – original draft, Investigation. **Darmicka Rajendra:** Writing – review & editing. **Martin Skitmore:** Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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References

[1] S.S. Ho, J. Looi, A.S. Chuah, A.D. Leong, N. Pang, I can live with nuclear energy if…": exploring public perceptions of nuclear energy in Singapore, Energy Policy 120 (2018) 436–447.

[2] W. Zhan, W. Pan, Formulating systemic construction productivity enhancement strategies, J. Constr. Eng. Manag. 146 (8) (2020) 05020008, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001886.

[3] B. Brucker Juricic, M. Galic, S. Marenjak, Review of the construction labour demand and shortages in the EU, Buildings 11 (1) (2021) 17, https://doi.org/10.3390/buildings11010017.

[4] K.M. Oude Hengel, B.M. Blatter, C.I. Joling, A.J. van der Beek, P.M. Bongers, Effectiveness of an intervention at construction worksites on work engagement, social support, physical workload and the need for recovery: results from a cluster randomized controlled trial, BMC Public Health 12 (2012), https://doi.org/10.1186/1471-2458-12-1008.

[5] D. Snashall, Occupational health in the construction industry, Scand. J. Work Environ. Health 31 (2005) 5–10. http://www.jstor.org/stable/40967457.

[6] S.J. Stocks, S. Turner, R. McNamee, M. Carder, L. Hussey, R.M. Agius, Occupation and work-related ill-health in UK construction workers, Occup. Med. 61 (6) (2011) 407–415, https://doi.org/10.1093/occmed/kqr075.

[7] H. Lingard, M. Turner, Improving the health of male, blue collar construction workers a social ecological perspective, Constr. Manag. Econ. 33 (1) (2015) 18–34, https://doi.org/10.1080/01446193.2014.997259.

[8] S.R. Mohandes, X. Zhang, Towards the development of a comprehensive hybrid fuzzy-based occupational risk assessment model for construction workers, Saf. Sci. 115 (2019) 294–309, https://doi.org/10.1016/j.ssci.2019.02.018.

[9] X. Chen, C. Guo, J. Song, X. Wang, J. Cheng, Occupational health risk assessment based on actual dust exposure in a tunnel construction adopting roadheader in Chongqing, China, Build. Environ. 165 (2019) 106415, https://doi.org/10.1016/j.buildenv.2019.106415.

[10] S. Liu, E.N.K. Nkrumah, L.S. Akoto, E. Gyabeng, E. Nkrumah, The state of occupational health and safety management frameworks (OHSMF) and occupational injuries and accidents in the Ghanaian oil and gas industry: assessing the mediating role of safety knowledge, Biomed. Res. Int. 2020 (2020), https://doi.org/10.1155/2020/6354895.

[11] J. Oehmen, A. Ziegenbein, R. Alard, P. Schönsleben, System-oriented supply chain risk management, Prod. Plan. Control 20 (4) (2009) 343–361, https://doi.org/10.1080/09537280902843789.

[12] M.W. Khan, Y. Ali, F. De Felice, A. Petrillo, Occupational health and safety in construction industry in Pakistan using modified-SIRA method, Saf. Sci. 118 (2019) 109–118, https://doi.org/10.1016/j.ssci.2019.05.001.

[13] E. Ilbahar, A. Karaşan, S. Cebi, C. Kahraman, A novel approach to risk assessment for occupational health and safety using Pythagorean fuzzy AHP and fuzzy inference system, Saf. Sci. 103 (2018) 124–136, https://doi.org/10.1016/j.ssci.2017.10.025.

[14] L.Y. Ding, H.L. Yu, H. Li, C. Zhou, X.G. Wu, M.H. Yu, Safety risk identification system for metro construction on the basis of construction drawings, Autom. Constr. 27 (2012) 120–137, https://doi.org/10.1016/j.autcon.2012.05.010.

[15] Z. Zhou, Updated information on administrative regulation on occupational health in China since, 2018, Saf. Health Work (2022) S202, https://doi.org/10.1539/joh.17-0229-RA.

[16] National Health Commission of the People''s Republic of China (NHCPRC), Occupation Disease Classification and Catalogue. http://www.nhc.gov.cn/cms-search/xxgk/getManuscriptXxgk.htm?id=3abbd667050849d19b3bf6439a48b775, 2013.

[17] Z. Zhu, The corresponding relationship between the new classification catalogue of occupational hazards and the catalogue of occupational diseases, Pract. Prevent. Med. 23 (01) (2016) 1–6, https://doi.org/10.3969/j.issn.1006-3110.2016.01.001.

[18] R. Cigolini, T. Rossi, Managing operational risks along the oil supply chain, Prod. Plan. Control 21 (5) (2010) 452–467, https://doi.org/10.1080/09537280903453695.

[19] M. Leddy, HSE Corporate Safety Statement, 2022, p. 2022. https://assets.hse.ie/media/documents/ncr/HSP00709_HSE_Corporate_Safety_Statement.pdf.

[20] National Health Commission of the People''s Republic of China (NCHPRC), Guidelines for Occupational Health Risk Assessment of Chemicals in the Workplace. GBZ/T, 2017, pp. 298–2017. http://www.nhc.gov.cn/ewebeditor/uploadfile/2017/10/20171026154012835.pdf.

[21] Ministry of Labor and Social Protection Department of Romania, Risk Assessment Method for Occupational Accidents and Diseases. http://protectiamuncii.ro/pdfs/risk_assessment_method.pdf, 1998.

[22] Environmental Protection Agency of the United States, Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment). https://www.epa.gov/sites/production/files/2015-09/documents/partf_200901_final.pdf, 2009.

[23] Ministry of Manpower of Singapore, Code of Practice on Workplace Safety and Health (WSH) Risk Assessment. https://wshc.sg/files/wshc/upload/cms/file/CodeOfPractice_RiskManagement_SecondRevision.pdf, 2011.

[24] X. Wang, P. Tiwari, X. Chen, Communicating supply chain risks and mitigation strategies: a comprehensive framework, Prod. Plan. Control 28 (13) (2017) 1023–1036, https://doi.org/10.1080/09537287.2017.1329562.

[25] A. Sharafat, K. Latif, J. Seo, Risk analysis of TBM tunneling projects based on generic bow-tie risk analysis approach in difficult ground conditions, Tunn. Undergr. Space Technol. 111 (2021) 103860, https://doi.org/10.1016/j.tust.2021.103860.

[26] M. Gul, S. Mete, F. Serin, E. Celik, Fine–Kinney-Based Fuzzy Multi-Criteria Occupational Risk Assessment, Springer, Springer Nature Cham, Switzerland, 2021, https://doi.org/10.1007/978-3-030-52148-6.

[27] R. Liu, Z. Liu, H.C. Liu, H. Shi, An improved alternative queuing method for occupational health and safety risk assessment and its application to construction excavation, Autom. Constr. 126 (2021) 103672, https://doi.org/10.1016/j.autcon.2021.103672.

[28] S.S. Leu, C.M. Chang, Bayesian-network-based safety risk assessment for steel construction projects, Accid. Anal. Prev. 54 (2013) 122–133, https://doi.org/10.1016/j.aap.2013.02.019.

[29] R. Bhagwat, M.K. Sharma, Performance measurement of supply chain management using the analytical hierarchy process, Prod. Plan. Control 18 (8) (2007) 666–680, https://doi.org/10.1080/09537280701614407.

[30] A. Siekelova, I. Podhorska, J.J. Imppola, Analytic hierarchy process in multiple–criteria decision–making: A model example, in: SHS Web of Conferences vol. 90, EDP Sciences, 2021, https://doi.org/10.1051/shsconf/20219001019, p. 01019.

[31] B. Salman, O. Salem, S. He, Project-level sustainable asphalt roadway treatment selection framework featuring a flowchart and analytic network process, J. Transport. Eng. Part B: Pavem. 146 (3) (2020) 04020041, https://doi.org/10.1061/JPEODX.0000202.

[32] C. Wu, D. Barnes, D. Rosenberg, X. Luo, An analytic network process-mixed integer multi-objective programming model for partner selection in agile supply chains, Prod. Plan. Control 20 (3) (2009) 254–275, https://doi.org/10.1080/09537280902856047.

[33] N.E. Oz, S. Mete, F. Serin, M. Gul, Risk assessment for clearing and grading process of a natural gas pipeline project: An extended TOPSIS model with Pythagorean

fuzzy sets for prioritizing hazards, Hum. Ecol. Risk Assess. Int. J. 25 (6) (2019) 1615–1632, https://doi.org/10.1080/10807039.2018.1495057.

[34] M. Gul, B. Guven, A.F. Guneri, A new fine-Kinney-based risk assessment framework using FAHP-FVIKOR incorporation, J. Loss Prev. Process Ind. 53 (2018) 3–16, https://doi.org/10.1016/j.jlp.2017.08.014.

[35] P. Vidmar, Novel approach in tunnel safety assessment, in: Accident Analysis and Prevention, IntechOpen, London, UK, 2020, https://doi.org/10.5772/intechopen.90494.

[36] E. Celik, M. Gul, Hazard identification, risk assessment and control for dam construction safety using an integrated BWM and MARCOS approach under interval type-2 fuzzy sets environment, Autom. Constr. 127 (2021) 103699, https://doi.org/10.1016/j.autcon.2021.103699.

[37] M. Gul, A review of occupational health and safety risk assessment approaches based on multi-criteria decision-making methods and their fuzzy versions, Hum. Ecol. Risk Assess. Int. J. 24 (7) (2018) 1723–1760, https://doi.org/10.1080/10807039.2018.1424531.

[38] A. Mahdiyar, M. Hasanipanah, D.J. Armaghani, B. Gordan, A. Abdullah, H. Arab, M.Z. Abd Majid, A Monte Carlo technique in safety assessment of slope under seismic condition, Eng. Comput. 33 (4) (2017) 807–817, https://doi.org/10.1007/s00366-016-0499-1.

[39] H. Sadeghi, S.R. Mohandes, M.R. Hosseini, S. Banihashemi, A. Mahdiyar, A. Abdullah, Developing an ensemble predictive safety risk assessment model: case of Malaysian construction projects, Int. J. Environ. Res. Public Health 17 (22) (2020) 8395, https://doi.org/10.3390/ijerph17228395.

[40] C. Samantra, S. Datta, S.S. Mahapatra, Analysis of occupational health hazards and associated risks in fuzzy environment: a case research in an Indian underground coal mine, Int. J. Inj. Control Saf. Promot. 24 (3) (2017) 311–327, https://doi.org/10.1080/17457300.2016.1178298.

[41] M. Gunduz, H. Laitinen, Construction safety risk assessment with introduced control levels, J. Civ. Eng. Manag. 24 (1) (2018) 11–18, https://doi.org/10.3846/jcem.2018.284.

[42] A. Kokangül, U. Polat, C. Dağsuyu, A new approximation for risk assessment using the AHP and fine Kinney methodologies, Saf. Sci. 91 (2017) 24–32, https://doi.org/10.1016/j.ssci.2016.07.015.

[43] A. Karasan, E. Ilbahar, S. Cebi, C. Kahraman, A new risk assessment approach: Safety and Critical Effect Analysis (SCEA) and its extension with Pythagorean fuzzy sets, Saf. Sci. 108 (2018) 173–187, https://doi.org/10.1016/j.ssci.2018.04.031.

[44] M. Abdelgawad, A.R. Fayek, Risk management in the construction industry using combined fuzzy FMEA and fuzzy AHP, J. Constr. Eng. Manag. 136 (9) (2010) 1028–1036, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000210.

[45] S.S. Lin, S.L. Shen, A. Zhou, Y.S. Xu, Risk assessment and management of excavation system based on fuzzy set theory and machine learning methods, Autom. Constr. 122 (2021) 103490, https://doi.org/10.1016/j.autcon.2020.103490.

[46] S.C. Abou, Fuzzy-logic-based network for complex systems risk assessment: application to ship performance analysis, Accid. Anal. Prev. 45 (2010) 305–316, https://doi.org/10.1016/j.aap.2011.07.017.

[47] L. Guan, Q. Liu, A. Abbasi, M.J. Ryan, Developing a comprehensive risk assessment model based on fuzzy Bayesian belief network (FBBN), J. Civ. Eng. Manag. 26 (7) (2020) 614–634, https://doi.org/10.3846/jcem.2020.12322.

[48] S. Isaac, T. Edrei, A statistical model for dynamic safety risk control on construction sites, Autom. Constr. 63 (2016) 66–78, https://doi.org/10.1016/j.autcon.2015.12.006.

[49] S.R. Mohandes, H. Sadeghi, A. Mahdiyar, S. Durdyev, A. Banaitis, K. Yahya, S. Ismail, Assessing construction labours' safety level: a fuzzy MCDM approach, J. Civ. Eng. Manag. 26 (2) (2020) 175–188, https://doi.org/10.3846/jcem.2020.11926.

[50] M. Gul, M.F. Ak, A comparative outline for quantifying risk ratings in occupational health and safety risk assessment, J. Clean. Prod. 196 (2018) 653–664, https://doi.org/10.1016/j.jclepro.2018.06.106.

[51] H. Li, S.T. Ng, M. Skitmore, Stakeholder impact analysis during post-occupancy evaluation of green buildings – a Chinese context, Build. Environ. 128 (2018) 89–95, https://doi.org/10.1016/j.buildenv.2017.11.014.

[52] Z. Huang, Reliability analysis for specialists judging, Chin. J. Health Statist. 03 (2010) 27–29. https://kns.cnki.net/kcms/detail/detail.aspx?FileName=ZGWT200003010andDbName=CJFQ2000.

[53] G.F. Kinney, A.D. Wiruth, Practical Risk Analysis for Safety Management, Tech Rep, Naval Weapons Center, China Lake, CA, 1976. https://apps.dtic.mil/dtic/tr/fulltext/u2/a027189.pdf.

[54] L.A. Zadeh, Fuzzy sets, Inf. Control. 8 (3) (1965) 338–353, https://doi.org/10.1016/S0019-9958(65)90241-X.

[55] J. Zeng, M. An, N.J. Smith, Application of a fuzzy based decision making methodology to construction project risk assessment, Int. J. Proj. Manag. 25 (6) (2007) 589–600, https://doi.org/10.1016/j.ijproman.2007.02.006.

[56] M. Karamustafa, S. Cebi, Extension of safety and critical effect analysis to neutrosophic sets for the evaluation of occupational risks, Appl. Soft Comput. 110 (2021) 107719, https://doi.org/10.1016/j.asoc.2021.107719.

[57] C. Zhou, F. Deng, Solution method of multivariate process capability indices based on rough set and quartile method, Ind. Eng. J. 14 (04) (2011) 78–81. https://kns.cnki.net/kcms/detail/detail.aspx?FileName=GDJX201104013andDbName=CJFQ2011.

[58] P.U. Okoye, Occupational health and safety risk levels of building construction trades in Nigeria, Construct. Economi. Build. 18 (2) (2018) 92–109, https://doi.org/10.5130/AJCEB.v18i2.5882.

[59] I.W. Fung, V.W. Tam, T.Y. Lo, L.L. Lu, Developing a risk assessment model for construction safety, Int. J. Proj. Manag. 28 (6) (2010) 593–600, https://doi.org/10.1016/j.ijproman.2009.09.006.

[60] I.W. Fung, T.Y. Lo, K.C. Tung, Towards a better reliability of risk assessment: development of a qualitative and quantitative risk evaluation model (Q2REM) for different trades of construction works in Hong Kong, Accid. Anal. Prev. 48 (2012) 167–184, https://doi.org/10.1016/j.aap.2011.05.011.

[61] S.W. Jung, J.H. Lee, K.J. Lee, H.R. Kim, Association between occupational physicochemical exposures and headache/eyestrain symptoms among Korean indoor/outdoor construction workers, Saf. Health Work 10 (4) (2019) 437–444, https://doi.org/10.1016/j.shaw.2019.09.004.

[62] H. Borgheipour, G. Tehrani, S. Madadi, I. Mohammadfam, Identification and assessment of human errors among tower crane operators using SHERPA and CREAM techniques, J Health Safety Work 10 (1) (2020) 5–8. https://jhsw.tums.ac.ir/files/site1/user_files_0ab0c0/eng/sayeh-A-10-74-35-10802ed.pdf.

[63] X. Li, K.H. Chow, Y. Zhu, Y. Lin, Evaluating the impacts of high-temperature outdoor working environments on construction labor productivity in China: a case study of rebar workers, Build. Environ. 95 (2016) 42–52, https://doi.org/10.1016/j.buildenv.2015.09.005.

[64] B. Lindelöf, J. Lapins, H. Dal, Shift in occupational risk for basal cell carcinoma from outdoor to indoor workers: a large population-based case-control register study from Sweden, Acta Derm. Venereol. 97 (6–7) (2017) 830–833, https://doi.org/10.2340/00015555-2660.

[65] G.A. Andaque, M. de Las Nieves González-García, J.C. Branco, E. Nunes, J. C. Guedes, J.S. Baptista, Prevalence of pneumoconiosis in the construction industry: a systematic review, in: Occupational and Environmental Safety and Health IV, 647-660, 2022, https://doi.org/10.1007/978-3-031-12547-8_51.

[66] H. Martin, N. Mohan, L. Ellis, S. Dunne, Exploring the role of PPE knowledge, attitude, and correct practices in safety outcomes on construction sites, J. Archit. Eng. 27 (4) (2021), https://doi.org/10.1061/(ASCE)AE.1943-5568.0000501, 05021011.

[67] P.E. Marino, A. Franzblau, R. Lilis, P.J. Landrigan, Acute lead poisoning in construction workers: the failure of current protective standards, Arch. Environment. Health: Int. J. 44 (3) (1989) 140–145, https://doi.org/10.1080/00039896.1989.9935877.

[68] M. Rademaker, Occupational epoxy resin allergic contact dermatitis, Australas. J. Dermatol. 41 (4) (2000) 222–224, https://doi.org/10.1046/j.1440-0960.2000.00441.x.

[69] R. Grytnes, D.E. Tutt, L.P.S. Andersen, Developing safety cooperation in construction: between facilitating independence and tightening the grip, Constr. Manag. Econ. 38 (11) (2020) 977–992, https://doi.org/10.1080/01446193.2020.1726978.

[70] S.X. Zeng, V.W. Tam, C.M. Tam, Towards occupational health and safety systems in the construction industry of China, Saf. Sci. 46 (8) (2008) 1155–1168, https://doi.org/10.1016/j.ssci.2007.08.005.

[71] A. Pinto, I.L. Nunes, R.A. Ribeiro, Occupational risk assessment in construction industry–overview and reflection, Saf. Sci. 49 (5) (2011) 616–624, https://doi.org/10.1016/j.ssci.2011.01.003.