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Evaluation of Ergonomic Risks for Construction Workers Based on Multicriteria Decision Framework with the Integration of Spherical Fuzzy Set and Alternative Queuing Method

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Abstract: Ergonomic risks critically impact workers' occupational health, safety, and productivity, and thereby the sustainability of a workforce. In the construction industry, the physical demands and dynamic environment exposes workers to various ergonomic hazards. While previous research has mainly focused on postural risks, there is a need to broaden the scope to include more relevant factors and assess them systematically. This study introduces a multi-criteria decision framework integrating the Spherical Fuzzy Sets (SFSs) and Alternative Queuing Method (AQM) to evaluate and prioritize ergonomic hazards. First, SFSs are employed to quantify the linguistic expressions of experts, addressing the inherent vagueness and uncertainty. Then, an entropy-based objective weighting method is adopted to determine the criteria weights. Finally, AQM is utilized to generate the risk priority. The proposed method has been implemented in a real-life construction project, where "overexertion due to unreasonable task organization", "hypertension and heart diseases", and "existing WMSD record" are identified as the top three ergonomic hazards. Then, a thorough discussion of intervention strategies regarding different risk categories is presented to facilitate ergonomic interventions. This proposed decision support system can promote effective ergonomic risk management, benefiting workers' health and well-being and contributing to the sustainable workforce development of the construction industry.

Keywords: ergonomic risk; construction workers; multi-criteria decision making (MCDM); Spherical Fuzzy Set; risk prioritization; sustainable workforce development; occupational health and safety; decision support systems

Citation: Tao, Y.; Hu, H.; Xue, J.; Zhang, Z.; Xu, F. Evaluation of Ergonomic Risks for Construction Workers Based on Multicriteria Decision Framework with the Integration of Spherical Fuzzy Set and Alternative Queuing Method. *Sustainability* **2024**, *16*, 3950. https://doi.org/10.3390/su16103950

Academic Editor: Tin-Chih Toly Chen

Received: 8 April 2024
Revised: 28 April 2024
Accepted: 30 April 2024
Published: 8 May 2024

1. Introduction

Ergonomic risks extensively exist among workers in labor-intensive and physically demanding industries, posing a substantial threat to their occupational health and safety (OHS) and negatively affecting the sustainable workforce development. Especially in the construction industry, the execution of daily tasks often requires prolonged working time, fast working pace, awkward working posture (e.g., bending, stooping, kneeling, etc.), and working in crowded spaces and uncomfortable environments [1–3]. Thus, construction workers are more prone to work-related injuries and safety accidents compared with other industries, and work-related musculoskeletal disorders (WMSDs) are the primary cause of non-fatal injuries with very high prevalence [4–6]. Instances of WMSD prevalence include 76% (12-month prevalence) in Malaysia [7], 41% (3-month prevalence) in Hong Kong [8], and 36% (12-month prevalence) in Ethiopia [9]. Notably, the figures likely underrepresent the actual incidence, as highlighted by Pransky et al. [10]. Poor ergonomics in the workplace can lead to a range of detrimental outcomes. These include, but are not limited to, physical discomfort, diminished productivity, absenteeism, unexpected project disruptions, delays, safety accidents, and, in severe cases, human casualties. Specifically, physical fatigue or

WMSDs increase the susceptibility to mistakes and have become important root causes of accidents [11,12]. From a cost perspective, ergonomic risks are responsible for 30% of construction delays [13]. They also contribute to escalating indirect costs, including higher insurance premiums, training, and turnover expenses, adversely affecting project delivery and, potentially, the company's market competitiveness [14]. Therefore, given the widespread prevalence and significant impact of ergonomic risks, effective management of these risks is crucial for enhancing both worker occupational health and safety and effective project management. As the field of ergonomics remains a relatively new topic in the construction industry [15], comprehensive risk identification and assessment can form a critical foundation for advancing effective risk management, benefiting workers' well-being and safety, as well as overall project management efficiency.

Significant research progress has been made in ergonomic risk assessment, focusing on physical-related factors such as awkward posture, vibration, and lifting heavy objects [6]. Moreover, the rapid development of digital technologies, including computers and wearable sensors, has enabled the automated extraction of postural or behavioral information. The integration of different technologies and advanced algorithms has been extensively studied in recent years [2,16–18]. Unlike the significant progress of postural risk analysis, a variety of non-postural factors, from demographic characteristics to work and health habits, and environmental conditions, are also influential. Though various factors have been identified and discussed in interdisciplinary studies [19–21], there is still a lack of sufficient investigation in the construction sector with high risk exposure [22]. Recently, individual and environmental factors have been integrated with the postural evaluation to establish a comprehensive ergonomic risk assessment for construction workers and projects, while an in-depth analysis of risk factors is still insufficient [23]. In addition, considering the interdisciplinary nature and complexity of OHS risk analysis, risk ranking or prioritization can be a primary and critical step to understand the various risk factors [24–26]. Specific attention to ergonomic risks remains limited in existing research. On the other hand, OHS considerations in the construction industry of developing countries like Pakistan often receive insufficient attention due to the additional costs associated with personal protective equipment, safety training, and related activities, and a deeper understanding of the different risk factors becomes even more crucial in such contexts. Moreover, though the research progress has accelerated ergonomic risk management in construction, most studies focusing on the identification and evaluation of ergonomic risk factors have been conducted in a controlled laboratory environment, thereby lacking practicability to some extent [15]. Thus, involving practitioners could be beneficial to take the research a step further. Given the complexity and uncertainty of ergonomic risk assessment, the evaluation process is often fuzzy and imprecise in the context of real-life construction projects, and thus a scientific decision-support system is necessary.

In this context, a research gap has been identified regarding comprehensive ergonomic risk analysis and prioritization. Thus, this study aims to establish a holistic ergonomic hazard ranking system that considers a variety of risk factors and multiple risk criteria. To achieve this, an integration of Spherical Fuzzy Sets (SFS) and Alternative Queuing Method (AQM) under the Multi-Criteria Decision-Making (MCDM) framework has been proposed. The recently developed SFS is powerful and effective in dealing with significant obstacles of expert evaluation systems, including uncertainty, fuzziness, and randomness. Then, AQM is employed to determine the risk priority. AQM excels in simplifying the computation process and enhancing result intuitiveness through the use of a 0–1 precedence relationship matrix and directed graphs, thereby making it a robust tool for the MCDM method. The novelty of the approach lies in developing a customized MCDM integrated with the appropriate techniques, tailored specifically to address the complexities of construction environments. The proposed framework is expected to be implemented in a realistic case study to demonstrate its practical applicability. Compared with the existing ergonomic risk analysis in the construction sector, which predominantly focused on postural risks [17,18], the proposed approach provides a comprehensive examination of risk factors from individual, work, and environmental perspectives. In addition, by integrating SFS and AQM, the framework effectively incorporates the knowledge and judgments of practitioners, thereby enhancing its practical significance. This complements the current instrument-based methods, which are somewhat limited in practicability [2]. Furthermore, this study aims to not only assist in decision-making regarding risk assessment and prioritization, but also to offer guidance for controlling ergonomic risks. This, in turn, is expected to enhance the health, safety, and overall well-being of construction workers.

2. Related Work

2.1. Ergonomics Risk Analysis for Construction Workers

2.1.1. Postural Ergonomic Assessment

Ergonomic risk assessment has received increasing research focus in construction management. In particular, physical factors have received the most attention, especially due to the prevalence of poor working postures in construction tasks, such as bending, squatting, and other strenuous activities [2,17,18].

In the field of ergonomics, a variety of evaluation methods have been established to assess working posture, such as the rapid upper limb assessment (RULA) [27], the Ovako working posture analysis system (OWAS) [28], and the rapid entire body assessment (REBA) [29]. The ergonomic standard and task-specific predefined awkward postures have also been adopted as the criteria of ergonomic assessment [2,30]. The integration of ergonomic rules and digital technologies has been extensively investigated (summarized in Table 1). In recent years, the feasibility of posture detection for construction activities has been significantly enhanced by the increased availability of vision-based and sensor-based technologies. Specifically, inertial measurement units (IMUs) are the most widely used wearable sensor systems that are attached to construction workers' key joints to extract the real-time working posture based on the location and acceleration of the key points [31]. Considering the complexity of construction operations and environments, the wearable insole pressure system was developed to predict predefined awkward working postures to reduce the intrusiveness of construction workers [2]. Given the inevitable impact of the attached sensors on workers' work, vision-based methods have higher applicability and enjoy higher popularity in recent studies. For example, Yu, Yang, Li, Luo, Guo and Fang [16] developed a joint-level ergonomic assessment tool by integrating vision-based 3D pose estimation algorithms and REBA rules for different trades, including bricklayer, concreter, pipelayer, bar fixer, scaffolder, and formwork erector. Also, based on REBA and convolutional pose machine algorithm, Wang, Chen, Zhu and Sun [18] proposed an ergonomic risk assessment system with modules including a posture detector, risk evaluator, and task risk predictor. Palikhe et al. [32] examined awkward postures for the formwork process based on the ergonomic simulation tool, software-JACK. Wang et al. [33] adopted a 3D visualization method and ergonomic tools (REBA and RULA) to quantify the ergonomic risks of continuous motions and to achieve proactive workplace design. The research progress reviewed above has provided an applicable ergonomic assessment scheme and generated valuable insights into the ergonomic characteristics of construction tasks, thereby enriching both academic research and practical application. However, it is important to note that most existing studies do not sufficiently consider non-postural factors, especially the characteristics of the construction workforce and the dynamic construction environment. This limitation can affect the accuracy of risk assessments and the effectiveness of interventions. Additionally, many instrument-based methods have primarily been tested in a controlled laboratory or field settings, limiting their practical application in real-world construction sites. These gaps highlight the need for more comprehensive research that includes a wider range of risk factors and develops methods suitable for actual workplace environments.

Table 1. Selected publications on postural ergonomic risk assessment in construction.

Digital Applications	Ergonomic Assessment Methods	References
IMUs and personalized warning thresholds algorithm	Trunk inclination angle and Maximum holding time (MHT) in ISO 11226:2000 [34]	Yan, Li, Zhang and Rose [30]
IMU and deep neural networks	OWAS	Zhao and Obonyo [35]
Wearable insole pressure system and deep learning networks	Predefined awkward working postures	Antwi-Afari, Qarout, Herzallah, Anwer, Umer, Zhang and Manu [2]
Vision-based 3D pose estimation algorithms	REBA	Yu, Yang, Li, Luo, Guo and Fang [16]
Convolutional pose machine algorithm and probabilistic neural network	REBA	Wang, Chen, Zhu and Sun [18]
Ergonomic simulation tool, JACK	RULA, OWAS, and Energy Expenditure Rate (EER)	Palikhe, Lee, Kim, Yirong and Lee [32]
3D human model simulation system	REBA and RULA	Wang, Li, Han and Al-Hussein [33]

2.1.2. Non-Postural Ergonomic Factors

Notably, non-postural factors, such as individual factors and environmental hazards, also contribute to the WMSDs [22,23], while they have not been extensively investigated among construction workers. Various non-postural ergonomic risk factors have been identified and examined within or beyond the context of construction. For example, researchers in the manufacturing industry emphasized the importance of individual factor considerations [36], especially human body characteristics such as height, weight, and age, and have incorporated related factors into the ergonomic assessment and feedback systems [37]. According to the review across various industries, in addition to demographic characteristics, health-related factors, such as sedentary lifestyle, high BMI, comorbidities, and smoking, were also identified as key ergonomic risk factors from individual perspectives [19]. Regarding construction workers, age has been recognized as a significant influential factor, given that physical fatigue accumulates over time, making middle-aged and older workers more susceptible to ergonomic hazards [38]. Other health-related factors, including heart diseases, elevated blood pressure and sugar levels, and unhealthy habits, have also been identified as relevant factors in ergonomic analysis for construction workers [39]. In particular, the relationship between psychosocial or mental stressors and WMSDs has been supported by existing studies [40,41]. Recently, the measurement of mental fatigue based on electroencephalogram (EEG) signals has been explored through experimental studies and opened up new possibilities [42,43], while the current limitation on the practicability of EEG in real construction environment may hinder the consideration of psychosocial factors to some extent. In addition, as construction workers often perform tasks in a dynamic outdoor environment, environmental factors can result in increased WMSD risks or aggravated symptoms, such as extreme temperature and poor weather [33,44].

Building on this, Tao, Hu, Xu and Zhang [23] recently established an ergonomic risk assessment framework tailored for construction workers considering risk factors from task, individual, and environment perspectives, which extends the current ergonomics assessment methods focusing on posture-based analysis. However, the importance or priority of the risk factors has not been investigated in a systematic way. Wang et al. [22] highlighted the inadequacies in existing research regarding the investigation of non-postural factors and the necessity for further investigation in their review study. The potential reasons may include but are not limited to, less developed risk measurement techniques compared to those for postural ergonomic evaluation and the limited data availability in the dynamic construction environment. To be more specific, although various non-postural risk factors have been examined to different extents in the abovementioned studies, there remains a lack of a holistic view that comparatively assesses the importance of these risks focusing on construction projects. This comprehensive perspective is crucial for effective ergonomic risk management, particularly in such complex environments. Given the varying occurrence, severity, and impacts of these risk factors on individual workers and project management, evaluating and prioritizing them based on practical criteria becomes crucial. Such an investigation will deepen the understanding of ergonomic risks in real-world projects, which is beneficial to guide the proper design of ergonomic intervention strategy.

2.2. Applicability of MCDM and Fuzzy Set Theory in Risk Assessment

2.2.1. MCDM Methods in Risk Assessment

Multi-criteria decision-making (MCDM) methods provide a structured decision-making framework addressing various criteria. The general steps of MCDM include problem definition, objectives and criteria setting, alternatives design, criteria weighting, alternatives performance quantification, weights and performance integration, and final decision [45]. MCDM has been widely applied in the area of safety risk management to support well-informed priority decisions across different industries, mainly including the prioritization of risk factors [46–48] and risk mitigation strategies [49,50]. With a specific focus on OHS-related risk analysis, MCDM has been successfully adopted to provide risk ranking or priority, as OHS management involves multidisciplinary activity. For example, Liu and Tsai [51] proposed the risk assessment approach to assess the occupational hazard in the construction industry with the integration of Quality Function Deployment (QFD), fuzzy Analytic Network Process (ANP) method, and Failure Modes and Effect Analysis (FMEA). Khan et al. [52] developed a fuzzy-TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) MCDM model to identify and prioritize the critical OHS hazards of the construction industry. Liu et al. [53] adopted the TODIM method under a linguistic fuzzy environment to provide an OHS risk ranking of medical staff in a hospital. Liu, Liu, Liu and Shi [24] developed a novel risk assessment model by combining the picture fuzzy sets and AQM, focusing on occupational hazards in the construction industry. Similarly, Mohandes and Zhang [25] developed a holistic risk assessment to identify and analyze OHS risks for construction projects by integrating logarithmic fuzzy ANP, interval-valued Pythagorean fuzzy TOPSIS, and grey relational analysis. Though the risk prioritization of general OHS factors in construction projects has been extensively studied, the specific focus on ergonomic factors is still necessary for effectively designing and implementing targeted preventive strategies in the future [15]. The applicability and effectiveness of MCDM methods have been proven by the existing literature, indicating their suitability to address the research problem in this study. In particular, the AQM surpasses traditional methods like TOPSIS [25,52] and TODIM [53] by employing a simplified computational process using a 0–1 precedence relationship matrix and providing intuitive results through directed graphs, making it especially effective in uncertain and fuzzy decision environments [24,54]. This approach reduces complexity and enhances the clarity and efficiency of decision-making, distinguishing it from other MCDM tools. Moreover, based on the recent application [53], more advanced fuzzy techniques could be considered to better represent the experts' judgment.

2.2.2. Fuzzy Set Theory in Risk Assessment

Fuzzy set theory (FST), introduced by Zadeh [55], aims to deal with the uncertainty inherent in multidisciplinary OHS risk assessment due to imprecision and vagueness [56,57]. The MCDM methods combined with FST have significantly contributed to risk analysis [46,58], particularly in construction projects where expert knowledge often compensates for the lack of precise information, sufficient data, and complete knowledge [59,60]. The FST can be employed to represent diverse expert judgments in a quantitative and scientific way [61], and a variety of fuzzy sets can reflect varying risk preferences or attitudes of experts [62]. Specifically, Triangular Fuzzy Sets (TFS) have three parameters, including lower boundary, upper boundary, and possible maximum value, and have been widely adopted in risk analysis with the advantage of simplicity and intuitiveness [47,63]. Then, in an Intuitionistic Fuzzy Set (IFS), the sum of the membership degree and non-membership degree should range from 0 to 1, with the indeterminacy or degree of hesitancy derived by subtracting this sum from 1 [64]. This feature renders IFS more precise than both type-1 and type-2 fuzzy sets, leading to its significant use in engineering applications. Pythagorean fuzzy sets (PFS) extend the space of IFS and allow the sum of the degrees of membership and non-membership to exceed 1, while ensuring that the sum of their squares remains less than or equal to 1. This expansion permits a broader range of non-standard membership grades compared to IFS [65]. In Spherical Fuzzy Sets (SFS), the sum of the degree of membership, non-membership degree, and indeterminacy/degree of hesitancy can exceed one, while the square sum of these three parameters is constrained to fall between 0 and 1, consequently making it nonlinear [66]. Compared with IFS and PFS, SFS offers enhanced capabilities for defining decision-making criteria with more comprehensive information and increased flexibility. This provides a significant advantage when integrated into the MCDM framework for ergonomic risk analysis. As one of the most recent advancements in fuzzy set theory, SFSs can deliver superior intelligence and accuracy in the MCDM process [67,68]. Recently, the applications of SFS in the MCDM process have varied from optimal construction method evaluation [59] and safety performance quantification [69] to OHS risk ranking [24,53]. Therefore, the combination of SFS and AQM presents a promising and novel approach for assessing ergonomic risks in construction, leveraging the strengths of both methods to achieve more precise and effective outcomes.

3. Materials and Methods

3.1. Proposed MCDM Framework

As illustrated in Figure 1, the framework is proposed based on a typical MCDM process, which integrates SFSs, entropy measure, and AQM to evaluate and prioritize ergonomic hazards. In the first stage, ergonomic hazards and criteria are predefined with careful consideration of the existing literature and engineering practices. As discussed in the literature review, it can be derived that both postural and non-postural factors need to be considered. Therefore, this study adopted the framework proposed by Tao, Hu, Xu and Zhang [23] to collect the alternatives of ergonomic risks from individual, work-related, and environment aspects, as listed in Table 2. To be specific, individual risks include previous WMSDs, hypertension, unhealthy personal habits such as excessive alcohol consumption and insufficient sleep, and obesity, all of which are prevalent among construction workers and can compromise a worker’s physical ability and resilience. Work-related factors encompass psychosocial stress from demanding deadlines and tasks, repetitive or prolonged awkward postures during tasks such as rebar tying or brick laying, exposure to vibrations from heavy machinery, heavy lifting, and overexertion due to poorly organized tasks, which are common in dynamic construction environments. Environmental risks involve working under extreme temperatures or adverse weather conditions that can exacerbate physical strain and affect performance.

To evaluate the ergonomic hazard comprehensively, six risk criteria were considered, including occurrence (C_1), severity (C_2), impact on workers’ productivity (C_3), impact on workers’ occupational health (C_4), impact on labor costs (C_5), impact on project schedule (C_6). Notably, the C_1 and C_2 are classic and widely-used criteria in OHS-related risk assessments [24,25,53], while the C_3 to C_6 are specifically designed for construction projects, taking into account both individual and project management perspectives, which have been initiated by the authors in the previous study [23].

In the risk ranking stage, the practitioners involved in the construction projects are selected to be the expert panel. In order to ensure both scientific accuracy and practical relevance, both construction management experience and professional understanding of ergonomic risks are required. Also, experts should ideally possess a higher education level (at least a B.Sc.) and extensive work experience (more than three years). The diversity in the experts’ roles within the project is also crucial to provide a comprehensive range of perspectives. Regarding the proper number of experts, Clemen and Winkler [70] noted the diminishing marginal returns with larger groups. Their findings, supported by Ferrell [71], suggested a panel of three to five experts, and therefore, five experts will be involved in this study. Then, SFSs are employed to express the fuzzy risk evaluation according to linguistic terms provided by experts, and then the performance of alternatives can be quantified and aggregated. On this basis, the weights of risk criteria can be obtained using the objective method based on an entropy measure for SFSs. Finally, the risk ranking of ergonomic hazards can be determined by integrating weights and performance using the AQM.

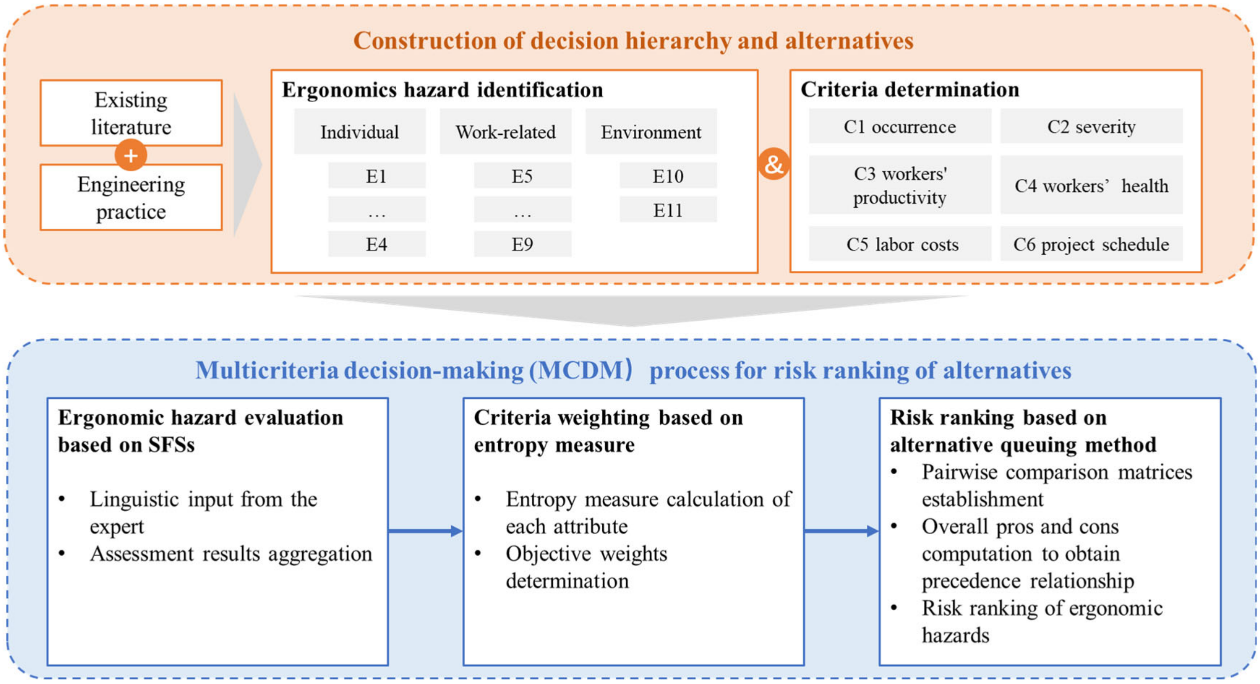

Figure 1. The framework of the proposed ergonomic risk ranking method.

Table 2. Identified ergonomic hazards.

Type	No.	Ergonomic Hazards	Reference
Individual	E1	Existing WMSD record	[20,23]
	E2	Hypertension and heart diseases	[25]
	E3	Unhealthy habits outside of work time (e.g., alcohol consumption, lack of sleep, etc.)	[19]
	E4	Overweight (BMI > 24)	[19,23]
Work-related	E5	Perceived psychosocial stress caused by time or task pressure	[22,72]
	E6	Repetitive or prolonged awkward postures	[2,6]
	E7	Vibration	[6,17]
	E8	Heavy load lifting	[73]
	E9	Overexertion due to unreasonable task organization	[33,74]
Environment	E10	Extreme cold or hot temperature	[23,25]
	E11	Poor weather	[23,44]

3.2. Ergonomic Hazard Evaluation Based on SFS

SFS is one of the latest developments in the area of MCDM with fuzzy logic [75]. Specifically, decision makers' hesitancy can be represented extensively to better deal with the uncertainty and vagueness of experts' opinions. In addition, integrating linguistic term sets and Spherical Fuzzy Sets can externalize the ambiguity of human cognition and the complex uncertain environment [53]. The basic concept of linguistic SFS is defined as follows.

Definition 1. *When X is a universe of discourse, SFSs S is defined by Equation (1)*

$$S = \{x, \alpha_S(x), \beta_S(x), \gamma_S(x) | x \in X\} \tag{1}$$

where $\alpha_S(x), \beta_S(x), \gamma_S(x) \ \in [0,1]$ *represent the linguistic membership degree, linguistic abstinence degree, and linguistic nonmembership degree, respectively, satisfying the following formula.*

$$0 \le \alpha_S(x)^2 + \beta_S(x)^2 + \gamma_S(x)^2 \le 1 \tag{2}$$

The numerical operations can be defined accordingly; the detailed functions are depicted in previous studies [76]. On this basis, the step-by-step procedures can be presented as follows.

Step 0: Linguistic input from the expert. l decision makers $DM_k(k = 1, 2, \ldots l)$ are involved in providing a linguistic evaluation of m predetermined ergonomic hazards $E_i(i = 1, 2, \ldots m)$ respecting n criteria $C_j(j = 1, 2, \ldots n)$. The weight of expert DM_k can be denoted as λ_k. The weight can be determined using various methods in existing studies or assigned by a moderator directly. The raw evaluation matrix of each expert can be established accordingly, denoted as $\widetilde{S}_k = \left[\widetilde{s}_{ij}^{k}\right]$,where $\widetilde{s}_{ij}^{k} = \left(\alpha_{ij}^k, \beta_{ij}^k, \gamma_{ij}^k\right)$.

Step 1: Assessment results aggregation. Evaluation results of different experts can be aggregated using the Spherical Weighted Arithmetic Mean (SWAM) operator [76] to obtain collective SFS ergonomic risk assessment matrix $S = \left[\widetilde{s}_{ij}\right]$. The aggragation rules are as follows.

$$\widetilde{S} = \mathrm{SWAM}\left(\widetilde{s}_{ij}^{1}, \widetilde{s}_{ij}^{2}, \ldots \widetilde{s}_{ij}^{l}\right) = < \alpha_{ij}, \beta_{ij}, \gamma_{ij} > \tag{3}$$

$$\alpha_{ij} = \left[1 - \prod_{k=1}^{l}\left(1 - \left(\alpha_{ij}^k\right)^2\right)^{\lambda_k}\right]^{\frac{1}{2}} \tag{4}$$

$$\beta_{ij} = \prod_{k=1}^{l}\left(\beta_{ij}^k\right)^{\lambda_k} \tag{5}$$

$$\gamma_{ij} = \left[\prod_{k=1}^{l}\left(1 - \left(\alpha_{ij}^k\right)^2\right)^{\lambda_k} - \prod_{k=1}^{l}\left(1 - \left(\alpha_{ij}^k\right)^2 - \left(\gamma_{ij}^k\right)^2\right)^{\lambda_k}\right]^{\frac{1}{2}} \tag{6}$$

3.3. Criteria Weighting Based on Entropy Measure

The objective weighting method extracted the information only from alternative scores, which can avoid the drawbacks of subjective weighting. In particular, entropy has been widely recognized as an efficient mathematical tool to obtain objective weighting by quantifying uncertain information. The basic logic behind this is that the greater dispersion in the evaluation results of specific criteria indicates the higher importance of these criteria. This study adopted the concept of entropy measure of SFS proposed by [76] as presented below, and detailed proof can be found in the original research.

$$E\left(\widetilde{S}\right) = \frac{1}{n}\sum_{i=1}^{n}\left(1 - \frac{4}{5}\left[\left|\alpha_{\widetilde{S}}^2(x_i) - \beta_{\widetilde{S}}^2(x_i)\right| + \left|\gamma_{\widetilde{S}}^2(x_i) - 0.25\right|\right]\right) \tag{7}$$

On this basis, the criteria weights can be computed as described in the following step.

Step 2: Objective weight determination of risk criteria. The entropy measure of criteria j can be calculated using Equation (8). Then, the weight of each criterion can be obtained accordingly in Equation (9), as the intrinsic information of criteria reflected by the divergence $1 - E_j$.

$$E_j = \frac{1}{n}\sum_{i=1}^{n}\left(1 - \frac{4}{5}\left[\left|\alpha_j^2 - \beta_j^2\right| + \left|\gamma_{\widetilde{S}}^2 - 0.25\right|\right]\right) \tag{8}$$

$$w_j = \frac{1 - E_j}{\sum_{j=1}^{m} (1 - E_j)} \tag{9}$$

3.4. Risk Ranking Based on AQM

As a new and powerful tool for MCDM problems, AQM was initiated by Gou, Xu and Liao [54] to create the ranking results by using the information of the 0–1 precedence relationship. AQM has been successfully adopted in OHS hazard evaluation problems and could provide credible and reasonable ranking results [24]. This study employed the AQM based on the linguistic evaluation under a fuzzy environment expressed by SFS. The step-by-step procedure is introduced below.

Step 3: Precedence relationship matrix construction. For each risk criterion, a 0–1 precedence relationship matrix $\Delta_j = \left[\delta_{ti}^j\right]_{m \times m}$ can be obtained based on the collective SFS assessment matrix according to the following rules.

$$\delta_{ti}^j = \begin{cases} if\ s_{ij} > s_{tj},\ then\ \delta_{it}^j = 1\ \delta_{ti}^j = 0\ and\ E_i > E_t,\ E_t < E_i \\ if\ s_{ij} < s_{tj},\ then\ \delta_{it}^j = 0\ \delta_{ti}^j = 1\ and\ E_i < E_t,\ E_t > E_i \\ if\ s_{ij} = s_{tj},\ then\ \delta_{it}^j = \delta_{ti}^j = 1\ and\ E_t \approx E_i \end{cases} \tag{10}$$

Step 4: Integrated weights calculation for each pair of ergonomic hazards. The overall score of all criteria with different weights can be calculated according to the following rules based on the weight of each criterion obtained in the previous section.

$$w = \begin{cases} w(E_i > E_t) = \sum_{j \in (E_i > E_t)_j} w_j \\ w(E_i < E_t) = \sum_{j \in (E_i < E_t)_j} w_j \\ w(E_i \approx E_t) = \sum_{j \in (E_i \approx E_t)_j} w_j \end{cases} \tag{11}$$

Step 5: Overall pros and cons indicated value calculations for each pair of ergonomic hazards. For ergonomic hazard pairs, the overall pros and cons indicated values H can be computed as below.

$$H(E_i, E_t) = \frac{w(E_i > E_t) + \rho \cdot w(E_i \approx E_t)}{w(E_i < E_t) + \rho \cdot w(E_i \approx E_t)} \tag{12}$$

where $\rho \in [0, 1]$ indicates the importance level of $w(E_i \approx E_t)$. For the case that $w(E_i < E_t) = 0$ and $w(E_i \approx E_t) = 0$, $H(E_i, E_t) = +\infty$.

Step 6: Precedence relationship establishment among ergonomic hazards. Based on the overall pros and cons indicated values for each pair of ergonomic hazards, the comparative relationship can be determined by the following rules.

$$\begin{cases} E_i > E_t,\ H(E_i, E_t) \geq \theta \\ E_i \approx\ E_t,\ \frac{1}{\theta} < H(E_i, E_t) \leq \theta \\ E_i > E_t,\ 0 < H(E_i, E_t) \leq \frac{1}{\theta} \end{cases} \tag{13}$$

Then, the final precedence relationship can be obtained accordingly, and the final precedence relationship matrix $U = [u_{it\ m \times m}]$ can be obtained.

$$u_{it} = \begin{cases} if E_i > E_t,\ then\ u_{it} = 1,\ u_{ti} = 0 \\ if E_i \approx\ E_t,\ then\ u_{it} = u_{ti} = 1 \\ if\ E_i < E_t,\ then\ u_{it} = 1,\ u_{ti} = 0 \end{cases} \tag{14}$$

Step 7: Risk ranking of ergonomic hazards. The final risk ranking of ergonomic hazards can be determined based on the precedence relationship matrix U

$$R_i = p_i - q_i \tag{15}$$

where $p_i = \sum_t u_{it}$ and $q_i = \sum_i u_{it}$ indicate the overall arcs outgoing from and incoming to the directed graph representing the precedence relationship matrix U. A smaller R_i means higher importance of the risk ranking.

4. Case Study

4.1. Implementation and Results

To testify the proposed ergonomic framework for the transportation infrastructure construction process, a real case of prefab construction systems for part of a viaduct in Shanghai currently under construction has been selected as a case study. There are two box girder production lines, a bent cap production line, and a column production line on the selected construction sites. Different trades of workers, such as rebar workers, formwork workers, concrete workers, and component decorators, are involved in the construction process. They execute demanding manual tasks and are exposed to ergonomic risks. Ergonomic hazards listed in Table 2 are the alternatives for further analysis.

A panel of five experts, including the project manager, site superintendent, safety engineer, quality engineer, and administration manager, were invited to conduct the assessment. All of the experts have expertise in the construction management of transportation infrastructure, with more than three years of professional experience. The importance weights are assigned based on their knowledge and profession related to ergonomic risk management, i.e., λ = (0.30, 0.25, 0.25, 0.10, 0.10). The seven-grade linguistic spherical fuzzy assessments were employed in this study, which have also been adopted in the recent OHS-related study [53], and corresponding spherical fuzzy numbers are shown in Table 3.

Table 3. Seven-grade linguistic terms and spherical fuzzy numbers.

Linguistic Term	Abb.	α [1]	β [2]	γ [3]
Very low importance	VLI	0.1	0.1	0.9
Low importance	LI	0.25	0.25	0.75
Moderately low importance	MLI	0.4	0.4	0.6
Fair	F	0.5	0.5	0.5
Moderately high importance	MHI	0.6	0.4	0.4
High importance	HI	0.75	0.25	0.25
Very high importance	VHI	0.9	0.1	0.1

[1] Linguistic membership degree; [2] linguistic abstinence degree; and [3] linguistic nonmembership degree.

Step 0: Assessment of 11 ergonomic hazards from the five experts was collected, and the results of the expert one are shown in Table 4 as an example, given the limitation of space. Then, the linguistic terms were converted to SFNs.

Table 4. Linguistic assessment result provided by Expert 1.

	C1	C2	C3	C4	C5	C6
E1	MHI	VLI	VLI	LI	LI	LI
E2	MLI	LI	LI	MLI	LI	F
E3	VLI	LI	MLI	F	MLI	LI
E4	MLI	LI	MLI	LI	MLI	LI
E5	MLI	LI	F	VLI	VLI	LI
E6	LI	MLI	HI	LI	LI	MLI
E7	LI	LI	F	LI	LI	LI
E8	F	LI	MLI	LI	MLI	MLI
E9	F	LI	F	F	LI	MLI
E10	MLI	LI	LI	MLI	VLI	VLI
E11	MLI	LI	LI	VLI	VLI	VLI

Step 1: To fuse the evaluation results of five experts, the SWAM operator (i.e., Equations (3)–(6)) was employed for the evaluation results of each attribute. The aggrega-

tion results of membership, nonmembership, and hesitancy degrees are given in Table 5, where $\widetilde{s}_{ij} = (\alpha_{ij}, \beta_{ij}, \gamma_{ij})$ represents the aggregated evaluation of ergonomic hazard E_i with respect to the criteria C_j.

Table 5. Aggregated evaluation results.

	C1	C2	C3	C4	C5	C6
E1	(0.59, 0.40, 0.41)	(0.50, 0.49, 0.43)	(0.53, 0.47, 0.45)	(0.49, 0.50, 0.47)	(0.30, 0.70, 0.31)	(0.37, 0.62, 0.38)
E2	(0.30, 0.70, 0.31)	(0.67, 0.33, 0.34)	(0.62, 0.38, 0.39)	(0.66, 0.33, 0.33)	(0.38, 0.61, 0.39)	(0.37, 0.62, 0.38)
E3	(0.29, 0.73, 0.31)	(0.26, 0.76, 0.27)	(0.27, 0.74, 0.29)	(0.38, 0.62, 0.40)	(0.27, 0.76, 0.30)	(0.20, 0.83, 0.22)
E4	(0.60, 0.40, 0.40)	(0.32, 0.69, 0.33)	(0.30, 0.70, 0.31)	(0.46, 0.53, 0.46)	(0.23, 0.79, 0.24)	(0.17, 0.84, 0.18)
E5	(0.44, 0.55, 0.45)	(0.34, 0.66, 0.35)	(0.38, 0.62, 0.40)	(0.49, 0.50, 0.44)	(0.30, 0.74, 0.28)	(0.26, 0.77, 0.27)
E6	(0.68, 0.32, 0.33)	(0.34, 0.66, 0.35)	(0.45, 0.54, 0.45)	(0.51, 0.48, 0.45)	(0.36, 0.63, 0.37)	(0.26, 0.75, 0.26)
E7	(0.46, 0.53, 0.47)	(0.32, 0.67, 0.33)	(0.42, 0.58, 0.43)	(0.33, 0.67, 0.35)	(0.29, 0.70, 0.30)	(0.27, 0.73, 0.28)
E8	(0.55, 0.44, 0.45)	(0.37, 0.64, 0.38)	(0.48, 0.51, 0.43)	(0.41, 0.60, 0.34)	(0.30, 0.70, 0.30)	(0.40, 0.59, 0.41)
E9	(0.62, 0.38, 0.39)	(0.41, 0.59, 0.43)	(0.62, 0.38, 0.39)	(0.60, 0.39, 0.41)	(0.36, 0.64, 0.36)	(0.47, 0.52, 0.47)
E10	(0.48, 0.51, 0.43)	(0.33, 0.67, 0.34)	(0.33, 0.67, 0.34)	(0.45, 0.54, 0.45)	(0.19, 0.82, 0.19)	(0.18, 0.82, 0.18)
E11	(0.4, 0.6, 0.4)	(0.22, 0.78, 0.22)	(0.19, 0.81, 0.19)	(0.19, 0.82, 0.19)	(0.15, 0.85, 0.15)	(0.14, 0.86, 0.14)

Step 2: With the input of aggregated results, the criteria weights were then calculated using the aforementioned objective entropy-based method. Specifically, the entropy measure of each criterion was calculated using Equation (8). Then, the objective weights were obtained using Equation (9). The calculated entropy measure E_j and final weight w_j were exhibited in Table 6.

Table 6. Results of entropy-based criteria weighting.

	C1	C2	C3	C4	C5	C6
Weight (w)	0.097	0.176	0.131	0.090	0.252	0.254
Entropy measure (E)	0.835	0.700	0.777	0.848	0.570	0.567

Step 3: Based on the hazard evaluation results by criteria, the 0–1 precedence relationship can be obtained based on the pairwise comparison rule presented in Equation (10). For example, the matrix for C1 is presented below.

$$\Delta_1 = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Step 4: By adopting the calculated weights, the overall score of each hazard pair can be obtained via Equation (11). The pros scores $w(E_i > E_t)$ are shown in Table 7 as an example. The overall cons scores $w(E_i < E_t)$ and the overall indifference scores $w(E_i \approx E_t)$ were calculated similarly.

Table 7. Overall pros score of each hazard pair.

$w(E_i>E_t)$	t = 1	t = 2	t = 3	t = 4	t = 5	t = 6	t = 7	t = 8	t = 9	t = 10	t = 11
i = 1	0.00	0.10	1.00	0.90	0.91	0.56	1.00	0.75	0.18	1.00	1.00
i = 2	0.65	0.00	1.00	0.90	0.90	0.90	0.90	0.65	0.52	0.90	0.90
i = 3	0.00	0.00	0.00	0.51	0.00	0.00	0.09	0.00	0.00	0.51	0.90
i = 4	0.10	0.10	0.49	0.00	0.10	0.00	0.19	0.19	0.00	0.44	1.00
i = 5	0.09	0.10	1.00	0.90	0.00	0.25	0.52	0.34	0.00	0.90	1.00
i = 6	0.44	0.10	1.00	1.00	0.57	0.00	0.75	0.44	0.35	1.00	1.00
i = 7	0.00	0.10	0.91	0.81	0.48	0.25	0.00	0.00	0.00	0.64	1.00
i = 8	0.25	0.35	1.00	0.81	0.66	0.56	1.00	0.00	0.00	0.91	1.00
i = 9	0.82	0.48	1.00	1.00	1.00	0.65	1.00	1.00	0.00	1.00	1.00
i = 10	0.00	0.10	0.49	0.56	0.10	0.00	0.36	0.09	0.00	0.00	1.00
i = 11	0.00	0.10	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Step 5: By applying $\rho = 0.5$, the overall pros and cons indicated values were computed, as provided in Table 8.

Table 8. Overall pros and cons indicated values of each hazard pair.

$H(E_i>E_t)$	t = 1	t = 2	t = 3	t = 4	t = 5	t = 6	t = 7	t = 8	t = 9	t = 10	t = 11
i = 1	0.66	0.43	3.96	2.59	2.66	3.01	3.96	1.47	0.31	3.96	3.96
i = 2	1.63	1.00	3.96	2.59	2.59	9.31	2.59	1.07	1.07	2.59	2.59
i = 3	0.00	0.00	0.66	0.68	0.00	0.00	0.10	0.00	0.00	0.68	2.59
i = 4	0.11	0.15	0.97	0.66	0.11	0.00	0.23	0.23	0.00	0.54	3.96
i = 5	0.10	0.15	3.96	2.59	0.66	0.84	0.70	0.38	0.00	2.59	3.96
i = 6	0.54	0.15	3.96	3.96	1.11	1.00	1.47	0.54	0.54	3.96	3.96
i = 7	0.00	0.15	2.66	1.85	0.93	0.52	0.66	0.00	0.00	1.04	3.96
i = 8	0.34	0.89	3.96	1.85	1.93	3.01	3.96	0.66	0.00	2.66	3.96
i = 9	1.92	1.82	3.96	3.96	3.96	6.71	3.96	3.96	1.00	3.96	3.96
i = 10	0.00	0.15	0.97	1.28	0.11	0.00	0.57	0.10	0.00	0.66	3.96
i = 11	0.00	0.15	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.66

Step 6: Based on the results of the overall pros and cons indicated values, the final comparative relationship can be determined using Equation (13) with the threshold value $\theta = 1.5$ [24]. Then, the final precedence relationship matrix U was obtained accordingly through Equation (14), as presented below.

$$U = \begin{bmatrix} 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Step 7: With the final precedence relationship matrix, the ranking results can be obtained via Equation (15). Table 9 outlines the calculated parameters and final risk ranking. Thus, the ergonomic hazard with a higher ranking indicates higher prioritization and a greater need for preventative measures. It was found that E9 (overexertion due to unreasonable task organization) ranked highest primarily due to the tight schedule demands of this transportation infrastructure project. E2 (hypertension and heart diseases) and E1 (existing WMSD record) also reflect significant concerns, mainly indicative of the characteristics of the workforce involved, suggesting a higher risk profile. Moreover, while other work-related factors did not rank as highly, this can be attributed to the high degree of industrialization at the prefabrication plant used in this project, which replaces some of the strenuous manual tasks in traditional construction settings. Additionally, the project's mix of indoor and outdoor work, combined with the absence of extreme weather conditions due to its geographical and temporal context, means that environmental factors were less critical, ranking at 9.5 on average. These findings highlight the need for more attention on workload and schedule management to effectively mitigate work-related ergonomic risks and prevent adverse outcomes. A more detailed discussion regarding ergonomic intervention is presented in the following section.

Table 9. Final ranking results based on AQM.

Hazards	Ranking	R_i	p_i	q_i
E1	3	6	8	2
E2	2	8	11	3
E3	9	−6	3	9
E4	10	−7	2	9
E5	6	0	6	6
E6	5	1	7	6
E7	7	−1	5	6
E8	4	5	8	3
E9	1	9	11	2
E10	8	−5	3	8
E11	11	−10	0	10

4.2. Sensitivity Analysis

The selection and weighting of risk criteria significantly influences the perception of risk, necessitating an exploration of ranking results under varying criteria. Figure 2 illustrates the results of different scenarios: Case 0 is the original weighting setup obtained in the case study; Case j represents considering the j^{th} evaluation criterion separately, i.e., $w_j = 1,\ w_t = 0\ (for\ all\ t \neq j)$. The sensitivity analysis indicates that the relative weights of risk criteria substantially affect the final risk ranking results of ergonomic hazards. It can be found that E_9 has the highest risk priority in four out of the six cases, implying the importance of proper task organization to avoid this ergonomic hazard. E_2 ranks first in two of the five cases, while its ranking for Case 1 is significantly low. That is because E_2 has a significant impact on both individual workers and construction projects, while the occurrence rate is relatively low under the current situation. The risk priority of this ergonomic hazard has the potential to increase, facing the workforce with an aging population and a declining health status, indicating the need for attention in the long run. In general, Cases 1 and 2 align with the widely applied criteria of occurrence and severity in previous studies [24,25]. Criteria 2–6, as emphasized in the author's previous work [23], are tailored for construction projects to better reflect the project-specific requirement. In practice, subjective weighting methods reflecting specific preferences in project management are also worth conducting for comparison to obtain a more comprehensive ergonomic risk perception. The scientific and practical determination of risk criteria weights for risk prioritization can benefit the development of intervention strategies. The results of sensitivity analysis can also serve as a risk dashboard, offering decision makers a comprehensive view of risk perceptions for each criterion, as a complement to risk ranking results. Future studies are encouraged to explore diverse combinations and methods for criteria setting, backed by objective evidence, to further refine our understanding of ergonomic risk assessment in construction projects.

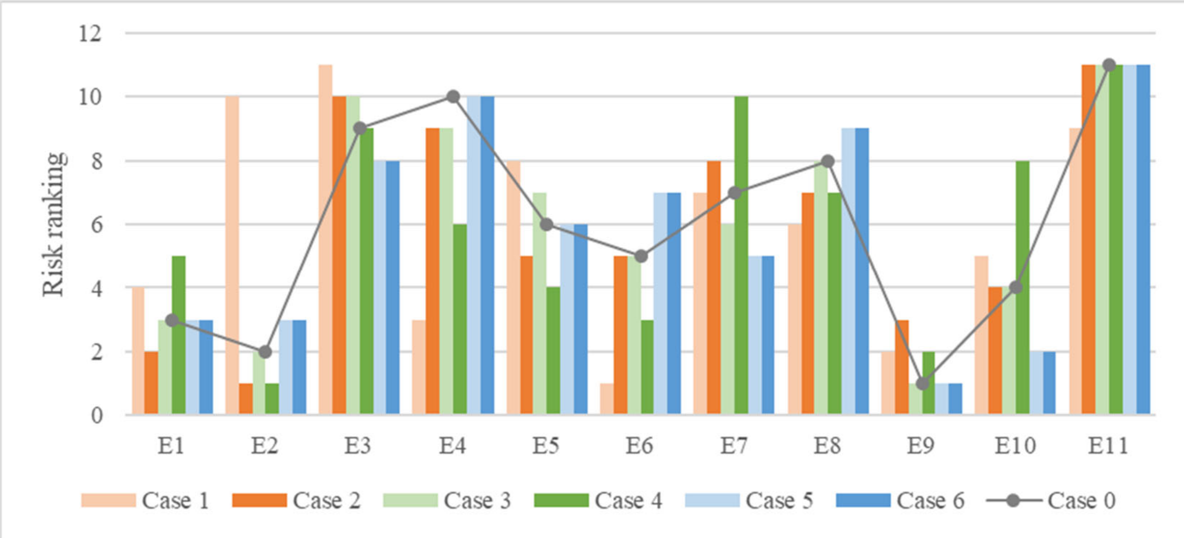

Figure 2. Risk ranking results of different scenarios.

5. Discussion

Systematic identification and prioritization of risks can enhance the understanding of ergonomic hazards and promote effective risk interventions, which are vital for the long-term sustainability of construction workforces. Ergonomic interventions can be generally categorized into engineering control and managerial control [3], which are vital for the long-term sustainability of construction workforces. Each category has specific applications and adaptability, making the selection and implementation of the proper strategy for a particular construction project crucial and requiring careful risk prioritization to ensure effectiveness. As highlighted by Chan, et al. [77] in their review study, effective ergonomic interventions should be based on previously identified risk factors and underlying mechanisms. The strategies should align with the specific needs of construction workers and adapt to construction site dynamics to ensure immediate and sustained reductions in ergonomic risks.

Specifically, the higher risk priority in individual factors indicates the need for personalized ergonomic monitoring and management, and personalization has also been increasingly emphasized in the OHS area in recent years [3,78,79]. Although existing systems have achieved high accuracies, personalized models are needed to provide instructive indicators such as exposure level, strength capacity, and injury risk indices for risk prevention. On this basis, personalized training programs can be developed with content including risk awareness of ergonomics and fatigue, safety culture education, healthy habits development, and more [80], and virtual reality technologies can be utilized to improve training effectiveness and efficiency [81]. In addition, the rapid development of real-time personalized mobile health systems and Personal Protective Equipment (PPE) have enabled the self-management of ergonomic hazards [30]. Due to the additional costs associated with equipment and systems, the consideration of risk prioritization is necessary under the resource constraints. Implementing personalized management for relatively vulnerable workers can effectively mitigate safety hazards and injury risks [23]. In addition, the identified individual ergonomic risks, such as increasing WMSD records, aging trends, and deteriorating health conditions, can provide instructions on recruitment and retention strategies to benefit long-term workforce development. Going forward, with a deeper understanding of personalized risk factors and advancements in objective risk measurement, human-centric personalized health management is expected to promote workers' safety, health, and well-being significantly.

As to the work-related ergonomic risks, higher risk ranking indicates potential issues with unreasonable workload management or task organization, which extensively occurs in construction tasks [18]. Removing or replacing overly demanding tasks is acknowledged as the most effective way to mitigate such risks [80]. Furthermore, solutions tailored to specific trades that lessen physical strain and discomfort should be broadly adopted, especially when they are cost-efficient and simple to implement. For example, Umer, et al. [82] developed a squatting stool to reduce the ergonomic risks of rebar-tying tasks. Moreover, human-robot collaboration has been widely recognized in the literature as a promising method to boost ergonomics and productivity [83]. For instance, exoskeleton systems have been developed to reduce the risks of back disorders of concrete work [84] and manual repetitive handling tasks [85], while the high cost can be one of the primary concerns for large-scale adoption. Another category of inexpensive solutions is managerial or administrative interventions [3,80]. In particular, the work–rest schedule can be optimized considering the workload and workers' fatigue to avoid overexertion and mitigate ergonomic risks [74,86]. The schedule optimization with ergonomic factors has been extensively explored in the field of manufacturing that also faces the aging workforce problem, and strategies included job rotation [87], rest allowance optimization [88], and ergonomic risks leveling [36], given the higher level of standardization of assembly lines. Going forward, with the trend of construction industrialization, strategies from the manufacturing industry are worth learning to promote managerial ergonomic risk control for the construction industry.

Although specific strategies targeting environmental risk factors are limited, they can be integrated into the aforementioned interventions based on their priority. For example, minimizing the exposure of high-risk workers to harsh weather conditions may reduce the risks of injuries or accidents, which may result in more severe consequences in harsh environments. In summary, with the increasing data availability and digital penetration, the integrated analysis of individual, work-related, and environmental risk would be more accurate and feasible, and can therefore support the decision process of intervention selection and implementation.

The often insufficient attention paid to OHS is typically linked to the need for cost control and profit margin improvement [52], which is also the case for ergonomic risk management. Given the constrained resources of construction projects, a proper understanding of project-specific ergonomic risk exposure may aid in prioritizing alternative risk control measures, thereby yielding feasible and cost-effective intervention plans. Thus, a deeper understanding of various risk factors can facilitate the integration and advancement of different ergonomic intervention strategies. Moreover, it is important to emphasize the long-term economic benefits of addressing ergonomic risks in the construction industry. By reducing health-related costs and absences due to injuries, decreasing compensation claims, and enhancing both productivity and employee retention, these measures can substantially contribute to the economic sustainability of the construction sector. Further in-depth exploration into the cost-effectiveness of various risk control measures is welcomed.

As for the implications for policy and practice, it is crucial to integrate findings into existing policy frameworks within the construction industry. Policymakers could develop guidelines that promote personalized ergonomic interventions and advanced technologies such as virtual reality and mobile health systems. Regulatory frameworks should encourage the adoption of innovative solutions like human-robot collaboration and exoskeletons to reduce physical strain. Moreover, economic incentives should be clearly outlined, emphasizing long-term benefits such as reduced healthcare costs, decreased absenteeism, and improved productivity. More importantly, policies need to be adaptable to various geographical contexts to accommodate local variations in construction practices, regulatory environments, and cultural norms. For example, while advanced technologies such as virtual reality training are effective in some regions, they may not be feasible in areas with limited technological infrastructure or prohibitive costs. Therefore, simpler, cost-effective managerial strategies such as optimized work-rest schedules or job rotation may be more suitable. Notably, the implementation plan for these interventions should be customized to local conditions, taking into account existing work schedules, local climate and environmental characteristics, and worker demographics like age and health status. In addition, in cultures with high respect for authority, top-down changes like the introduction of new safety equipment may be readily adopted, whereas in cultures valuing individual choice, personalized risk management strategies aligning with individual preferences might be necessary. Thus, while our systematic approach to identifying and prioritizing risks offers a universal framework, specific strategies should be tailored to fit the technological, regulatory, and cultural realities of each region to ensure effective and sustainable ergonomic risk management.

6. Conclusions

Given the significant ergonomic risks faced by construction workers and their impact on occupational health and safety, a comprehensive understanding of ergonomic risk factors is crucial for sustainable workforce development. Thus, this study proposes a risk assessment method based on the MCDM framework to consider diverse ergonomic hazards regarding multiple practical criteria for construction projects, and SFSs and AQM are integrated to rank the risk factors effectively. The practicability has been demonstrated given the implementation of a real-life viaduct project. Eleven ergonomic hazards and six risk criteria were recognized based on the existing literature in the field of applied ergonomics and characteristics of construction projects. The results identified that "overexertion due to unreasonable task organization", "hypertension and heart diseases", and "existing WMSD record" are the top three ergonomic hazards for this project, which can support the design of further risk assessment and intervention strategy. Moreover, an in-depth discussion on intervention strategies for various risk categories is provided aimed at enhancing the development and effective implementation of ergonomic interventions, which also highlights the importance of risk prioritization.

The contribution of this study can be summarized below. First, this study contributes to the state of knowledge by developing an applicable decision-making framework to analyze ergonomic risk priority by leveraging the knowledge from practitioners as a complement to measured data. The obtained risk priority can provide a project-specific risk perception, which is instrumental in guiding both the design and implementation of targeted intervention strategies. Second, this study provides a comprehensive and broader view of ergonomic risk hazard analysis, especially bridging the gap in current research regarding non-postural risk factors. Third, the proposed method is capable of fusing the linguistic assessments of multiple experts, capturing their hesitance, and effectively navigating the challenges of subjective evaluations, such as uncertainty, fuzziness, and randomness. This study also contributes to exploring the integration of fuzzy theory with the ranking method, which is an effective and efficient decision-making tool and can be generalized to risk ranking problems of different industries. The proposed framework and findings may contribute to the occupational health and safety management of construction workers and potentially benefit the sustainable development of the industry.

Admittedly, there are still several limitations to be addressed in future studies. First, considering the complexity of the ergonomic assessment and obstacles in collecting data in actual construction sites, this study relies on the engineering and management experience of domain experts and may lack objectivity to some extent. Future studies, with increased data availability on construction sites, could integrate subjective judgment and objective input and are anticipated to establish a more informed decision-making framework. In addition, while this study initiates a discussion on intervention strategies, it does not explicitly formulate a detailed and practicable intervention plan. A valuable follow-up study would be to develop a systematic framework for evaluating and prioritizing ergonomic interventions based on the ergonomic hazard investigation conducted in this study.

Author Contributions: Conceptualization, Y.T. and H.H.; data curation, Y.T. and J.X.; formal analysis, Y.T.; methodology, Y.T. and H.H.; project administration, F.X.; supervision, H.H.; visualization, Z.Z.; writing—original draft, Y.T.; writing—review and editing, J.X., Z.Z. and F.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author subject to reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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