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Prioritizing risk events of a large hydroelectric project using fuzzy analytic hierarchy process

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C H R O N I C L E

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A B S T R A C T

The existence of hydroelectric plants along Amazon River tributaries is a solution to satisfy the energy demand in Brazil. However, these plants are subjected to multiple risk events because of the geographic and socioeconomic characteristics of this region. In helping to address these escalating challenges, this paper presents a framework that assesses the risk events of service packs relevant to the plant. This framework presents a transparent approach for prioritizing risk events in large projects. The weights of importance of risk events are estimated using the fuzzy analytic hierarchy process. Chang's extent analysis method takes into consideration the vagueness and imprecision of subjective human judgments. The convergence of decisions is evaluated using two aggregation approaches, namely the maximum-minimum method based on an arithmetic mean and a geometric mean. The performances of the original and modified extent analysis methods are compared using group Euclidean distance and distance between weights metrics. The degree of similarity between the evaluation metrics is examined using Spearman's rank correlation coefficient and average overlap approaches. Due to the inconsistency of the reported results, the final rankings of the aggregation approaches are determined using a new aggregated multiple criteria decision making method. The results indicate that the original extent analysis method using the maximum-minimum method (arithmetic mean) is the best aggregation method. A Santo Antonio hydroelectric plant in Brazil is used to demonstrate the application of the proposed framework.

1. Introduction

An infrastructure project is exposed to multiple risk events arising from the environment. Achieving the project's targets is hindered by the uncertainty and complexity caused by the uncontrollable environment. Besides, the project comprises multiple varying tasks with respect to time, size, and complexity (Kalinina et al., 2016; San Cristóbal et al., 2018). Therefore, infrastructure projects are subjected to diverse risks arising from many causes, with multiple consequences. This diversity calls for adopting risk management to identify and control the causes and consequences of risk events (Peddada, 2013). Risk refers to the possibility of occurrence and severity of consequences for an uncertain event (Aven, 2016). This term includes the positive and negative outcomes of the event, which could be seen as an opportunity or a threat. In this regard, risk management is crucial for managing a construction project successfully because it helps mitigate the possible unexpected events. Otherwise, the project will be subjected to cost and time overruns as well as failure to satisfy project objectives. Risk can be categorized into (PMI, 2013): a) organizational such as lack of funds and conflicts with other projects, b) technical such as application of complex technology, c) project management such as lack of technical and managerial skills, and d) external such as changes in laws and regulations and unclear ownership rights. Hydroelectric plants are subjected to unpredictable events such as hydrological instability arising from seasonal rainfall and flow patterns and conflicts with social movements like the anti-dam movements (Braga & Molion, 1999; Sobreiro Filho et al., 2016).

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The paper is organized as follows: In the next section, the multiple criteria decision analysis is introduced. The decision analysis systems in risk assessment of hydroelectric projects are summarized in Section 3. The methodology employed in this research is presented in Section 4. Sections 5 briefly explains each method used in the results section. Section 6 reports the results of applying different decision analysis methods. The last section presents the major conclusions of the research study.

2. Multi-criteria decision analysis

Multi-criteria decision analysis (MCDA) methods compare the available alternatives against multiple conflicting criteria. For example, a decision maker needs to evaluate criteria such as social strategies, health and safety, and stakeholder involvement of the available suppliers to account for the social sustainability dimensions in supplier selection. There is no universal method for classifying MCDA methods (Sen and Yang, 1998). These methods can be classified into multi-objective decision making (MODM) and multi-attribute decision making (MADM) methods. The MODM method, unlike the MADM method, does not require a pre-defined set of alternatives (Abdel-Malak et al., 2017). Another method categorized MCDA methods into three classes (Belton and Stewart, 2002): a) value measurement models that assign numerical scores to the alternatives and rank them accordingly, b) outranking models that conduct pairwise comparisons among the alternatives and set the strength of preference of one alternative over another, and c) goal, aspiration and reference level models that select the closest alternative to the goal. It is difficult to determine the merits and demerits of using one model over another in a specific research problem (Zanakis et al., 1998). Besides, different results are obtained from the application of different methods to the same problem. Therefore, it is important to conduct a comparative analysis of different multi-criteria decision making (MCDM) methods in a particular decision problem (Malczewski and Rinner, 2015). The analytic hierarchy process (AHP), which belongs to the value measurement class, was developed to decide the best alternative through conducting pairwise comparisons among tangible and intangible factors (Saaty, 1980). It is the most widely-used decision making method because it has the highest number of scientific publications compared to other MCDM methods (Forman, 2001; Wallenius et al., 2008). However, human judgment cannot be expressed using exact values as in the classical AHP. Therefore, fuzzy logic was introduced by Zadeh (1965) to deal with vague inputs. In this regard, fuzzy AHP (FAHP) was proposed by Van Laarhoven and Pedrycz (1983) to deal with the imprecision and uncertainties of the judgment. The FAHP technique was reported to be the most popular fuzzy MCDM technique (Kahraman et al., 2015; Gul, 2018). Therefore, FAHP is employed in this research to reflect the vagueness indicated in the pairwise comparisons. Maharani et al. (2019) used FAHP with an unsymmetrical triangular fuzzy number to express the expert judgment for each pairwise comparison. The applicability of the proposed method was examined using a case study for resin supplier selection in a fiberglass company. The decision hierarchy structure involved three suppliers and four criteria, namely price, delivery lead time, payment method, and quality. The results confirmed the ability of the FAHP technique to handle this fuzzy number. Tavana et al. (2020) proposed an integrated framework to select the optimum manufacturer of consumer electronic goods while maximizing benefits and mitigating risks, simultaneously. The suppliers were selected based on operational, supply, financial, and technological aspects. FAHP was utilized to compute the weights of importance of the supply chain risks and benefits and fuzzy multi-objective optimization on the basis of ratio analysis (MOORA) was applied to rank the suppliers. The output uncertainty was examined using sensitivity analysis. The results yielded robust rankings, reflecting the model stability. Verdecho et al. (2020) applied an AHP technique to support supplier selection based on two criteria which are; supply chain's sustainability performance and sustainable supplier assessment criteria. The methodology was applied to an agri-food supply chain to assess the development of suppliers towards sustainability. The research recommended incorporating uncertainty into the developed model and validating this methodology in other supply chains.

Few studies compared the results of different decision making methods. Elshaboury et al. (2020a) compared between MOORA and technique for order preference by similarity to the ideal solution (TOPSIS) with respect to rehabilitation strategies of water distribution networks. The correlation between rankings obtained from different decision making methods was assessed using the Spearman correlation coefficient. The results showed that there was a very strong relationship between the aforementioned techniques. However, Spearman's rank correlation places equal emphasis on the top and bottom of the ranked list; therefore, it cannot be considered as a good comparative method. In another study, Elshaboury and Marzouk (2020) applied complex proportional assessment (COPRAS) and operational competitiveness ratings analysis (OCRA) to rank the available fleets required for construction and demolition waste transportation. The time, cost, energy, and emissions generated from transporting wastes to a recycling plant in New Cairo, Egypt were assessed. The rankings were aggregated using a half-quadratic-based approach, yielding a consensus index and a trust level of 0.999 for the final ranking. Therefore, the ensemble ranking could be accredited because there was a high level of agreement between the rankings.

3. Multi-criteria decision analysis methods in risk assessment

Large-scale hydroelectric projects are subjected to complex risk evaluations (Tang et al., 2018). Sharma and Kar (2018) conducted questionnaire surveys among different experts in several organizations to analyze the technical, construction, socio-political, and environmental risks in the hydroelectric projects. The collected data was utilized to rank the identified risk events based on their probabilities of occurrences and severities of impact. The major risk factors were identified to be resettlement and rehabilitation, land acquisition, flooding, non-availability of hydrological data, and project complexity.

MCDA has been widely used in risk assessment (Arce et al., 2015; Govindan et al., 2015). Beltrão and Carvalho (2019) used FAHP technique to prioritize the risk factors in Brazilian public enterprises. The model comprised risk identification, categorization, and prioritization through conducting pairwise comparisons. The "difficulty in environmental licensing" was found to be the most important risk. This model could be extended to suit risk assessment in various construction projects worldwide. Ribas et al. (2019a) identified the risk events in a Brazilian hydroelectric plant using the FAHP technique. The model hierarchy comprised one level of service packs and risk factors in the work breakdown structure and risk breakdown structure, respectively. The proposed model had proved its efficiency in ranking the risk events from the perspective of the owner consortium and the builder consortium.

Serrano-Gomez and Munoz-Hernandez (2019) combined the application of probabilistic fuzzy sets with AHP to conduct a comprehensive risk assessment for a large renewable energy project. The probabilistic approach utilized Monte Carlo method to extract data from the expert opinion. Additionally, the coherence of opinions was assessed using the confidence level parameter. The model was tested at a 250-megawatt photovoltaic solar plant located in Spain. The results affirmed the accuracy of the developed model compared to the classic fuzzy methodology. Agarwal and Kansal (2020) presented a fuzzy TOPSIS methodology to estimate the initial cost of a hydropower project at the planning stage. The likelihood and impact of risk factors were analyzed to evaluate the cost intervals per megawatt capacity. This methodology was applied to an Indian hydropower project of 126-megawatt capacity. The research recommended computing the relative weights of the criteria using the AHP technique.

The existing research in this area lacks one or more of the followings:

- Applying and comparing the performance of multiple FAHP aggregation methods.
- Suggesting suitable evaluation metrics to quantify the results of various aggregation methods.
- Measuring the similarity among the results of the applied performance evaluation metrics.
- Ranking the aggregation methods by deploying a decision analysis method.

In an attempt to address these limitations, this research computes the weights of risk events relevant to the plant using various FAHP aggregation methods. The weights are obtained using the original and modified Chang's extent analysis methods. The maximum-minimum aggregation method using arithmetic and geometric means is applied to derive the group decision matrix. Besides, the performance of these methods is evaluated using group Euclidean distance (GED) and distance between weights (WD) metrics. The degree of similarity between the evaluation metrics is examined using Spearman's rank correlation coefficient and average overlap approaches. Due to the difference in the reported results, the final rankings of the aggregation methods are determined using a weighted aggregated sum product assessment and TOPSIS (WASPAS-TOPSIS) method. This framework is expected to provide a rational and transparent approach for risk evaluation in hydropower projects. A Santo Antonio hydroelectric plant, which lies in the Brazilian Amazon rainforest, is used to demonstrate the application of the proposed framework.

4. Research methodology

The framework to prioritize the risk factors of service packs in hydroelectric projects is illustrated in Fig. 1. The framework comprises these components: a) fuzzifying and defuzzifying the pairwise comparisons to check their consistencies, b) forming the group matrix using several FAHP aggregation methods, c) determining the priority weights of risk factors, d) comparing the weights obtained from the aggregation methods using evaluation metrics, and e) measuring the similarity of the results obtained from the evaluation metrics. However, the aggregation methods do not perform consistently throughout the evaluation metrics. Therefore, this can be regarded as an MCDM problem which involves: a) computing the weights of evaluation metrics, b) establishing the decision making model, and c) ranking the aggregation methods.

5. Materials and methods

5.1 Fuzzy analytic hierarchy process

The pairwise comparison matrices are constructed based on the gathered responses from the questionnaires. The pairwise comparisons are conducted between the service packs and the related risk factors. The linguistic terms in pairwise comparisons are translated into triangular fuzzy numbers using Saaty's fuzzification scale (see Table 1). The triangular membership function has been adopted because it is the simplest membership model defined by only three numbers (Pedrycz et al., 2011). It is represented by $M = (l, m, u)$, where l, m and u stand for the lower, modal, and upper values, respectively. The fuzzy pairwise comparison matrices are converted into crisp matrices using a centroid defuzzification method called "center of gravity" or "center of area", as per Eq. 1 (Awasthi et al., 2018).

$$D = (l + 4m + u)/6 \tag{1}$$

where; D represents the defuzzified value of the triangular fuzzy number.

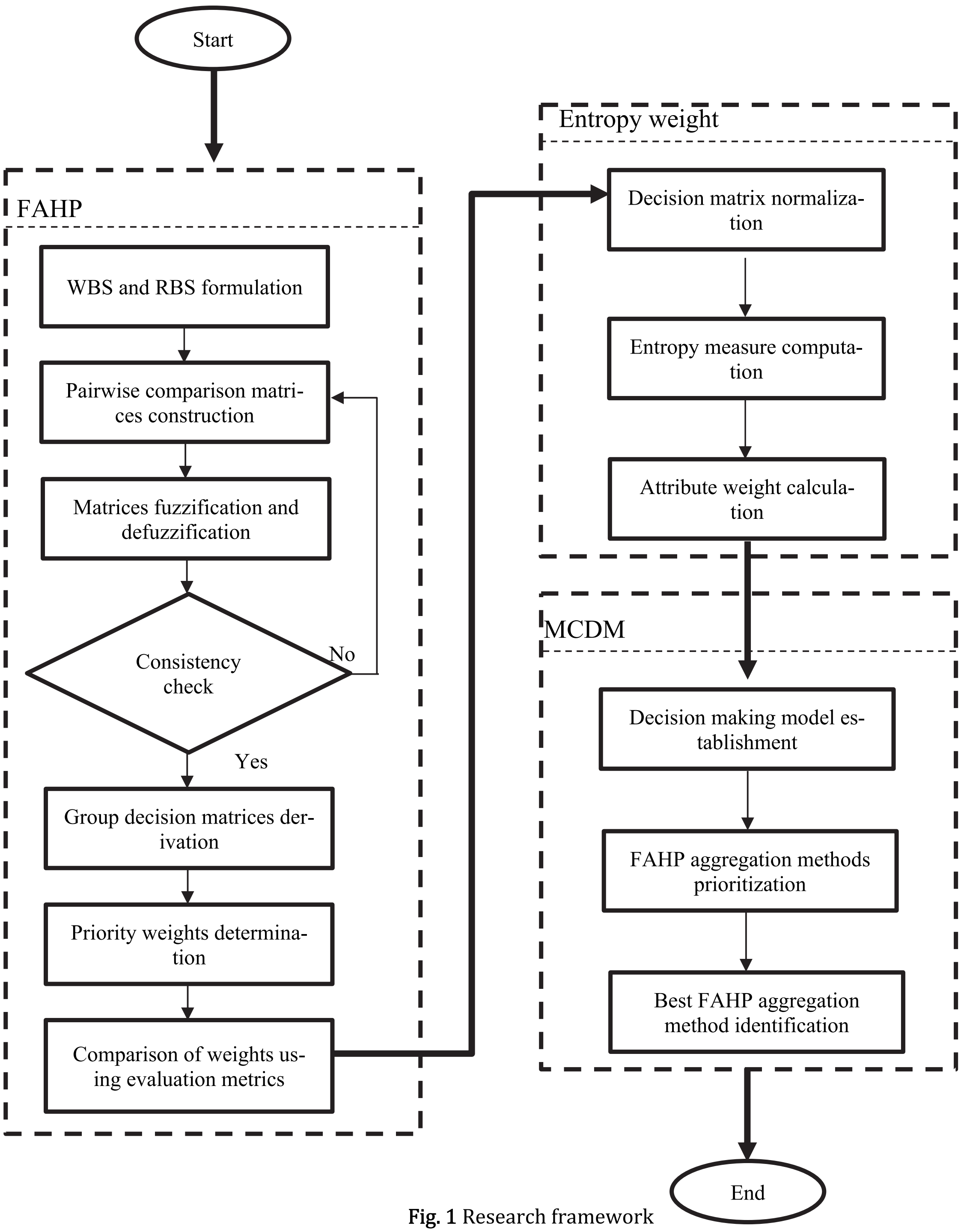

Fig. 1 Research framework

The consistency of pairwise comparisons is checked by calculating the consistency ratio as per Eq. 2 (Zadeh, 1965). It shall be noted that only matrices with consistency ratios of less than or equal to 0.1 are involved in the analysis process.

$$CR = \frac{CI}{RI}, \qquad CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

Where; CR refers to the consistency ratio, CI refers to the consistency index, RI refers to the random inconsistency index, λ_{max} refers to the average of the consistency vector components, and n is the matrix size.

The individual consistent pairwise comparisons are aggregated into a group comparison matrix using a) maximum-minimum method with arithmetic mean as per Eq. 3-5 (Awasthi et al., 2018) and b) maximum-minimum method with geometric mean as per Eq. 3-4, 6 (Liu et al., 2020).

$$l_{ij}{}^{group} = min\,\{l_{ij}{}^{(k)}\} \tag{3}$$
$$u_{ij}{}^{group} = max\,\{u_{ij}{}^{(k)}\} \tag{4}$$
$$m_{ij}{}^{group} = {m_{ij}{}^{(k)}}/{m} \tag{5}$$
$$m_{ij}{}^{group} = (\prod_{k=1}^{m} m_{ij}{}^{(k)})^{1/m} \tag{6}$$

Where; $l_{ij}{}^{(group)}$, $m_{ij}{}^{(group)}$, and $u_{ij}{}^{(group)}$ represent the smallest, most likely, and largest possible values for the group fuzzy comparison matrix, respectively. Besides, $l_{ij}{}^{(k)}$, $m_{ij}{}^{(k)}$, and $u_{ij}{}^{(k)}$ represent the minimum, most probable, and maximum values for the k^{th} decision maker, respectively, and m refers to the number of decision makers.

Table 1
Saaty's fuzzifying scale (Saaty 1980)

Saaty scale	Linguistic terms	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
1	Equally important	(1,1,2)	$\left(\frac{1}{2},1,1\right)$
2	Equally to moderately important	(1,2,3)	$\left(\frac{1}{3},\frac{1}{2},1\right)$
3	Moderately important	(2,3,4)	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$
4	Moderately to strongly important	(3,4,5)	$\left(\frac{1}{5},\frac{1}{4},\frac{1}{3}\right)$
5	Strongly important	(4,5,6)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
6	Strongly to very strongly important	(5,6,7)	$\left(\frac{1}{7},\frac{1}{6},\frac{1}{5}\right)$
7	Very strongly important	(6,7,8)	$\left(\frac{1}{8},\frac{1}{7},\frac{1}{6}\right)$
8	Very strongly to extremely important	(7,8,9)	$\left(\frac{1}{9},\frac{1}{8},\frac{1}{7}\right)$
9	Extremely important	(8,9,9)	$\left(\frac{1}{9},\frac{1}{9},\frac{1}{8}\right)$

Chang's (1996) extent analysis method has been used extensively to derive FAHP weights because of its computational simplicity (Wang et al., 2008). The value of the fuzzy synthetic extent with respect to the i^{th} object is calculated using Eq. (7).

$$S_i = \left(\frac{\sum_{j=1}^{m} l_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} u_{ij}}, \frac{\sum_{j=1}^{m} m_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} m_{ij}}, \frac{\sum_{j=1}^{m} u_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} l_{ij}}\right) \tag{7}$$

The modified extent analysis method updated the normalization process as per Eq. (8) (Wang et al., 2006).

$$S_i = \left(\frac{\sum_{j=1}^{n} l_{ij}}{\sum_{j=1}^{n} l_{ij} + \sum_{k=1,k\neq i}^{n}\sum_{j=1}^{n} u_{kj}}, \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} m_{kj}}, \frac{\sum_{j=1}^{n} u_{ij}}{\sum_{j=1}^{n} u_{ij} + \sum_{k=1,k\neq i}^{n}\sum_{j=1}^{n} l_{kj}}\right) \tag{8}$$

The possibility degree that a fuzzy triangular number is the greatest among several fuzzy numbers $V(M_2 \geq M_1)$ can be obtained using Eq. (9).

$$V(M_2 \geq M_1) = \begin{cases} 1 & if\ m_2 \geq m_1 \\ 0 & if\ l_1 \geq u_2 \\ \mu_{M1}(d) = \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases} \tag{9}$$

where; d is the ordinate of the highest intersection point D between the two membership functions μ_{M1} and μ_{M2}.

The degree of possibility that a convex fuzzy number is greater than K convex fuzzy numbers M_i *(i=1, 2, 3….k)* can be defined as per Eq. (10).

$$V(M \geq M_1, M_2, \ldots M_k) = V[(M \geq M_1)\ and\ (M \geq M_2)\ and \ldots and\ (M \geq M_k)] = min\ V(M \geq M_i), \quad i=1, 2, 3, \ldots .k \tag{10}$$

The minimum of these possibilities is used as the overall score of each criterion as per Eq. 11.

$$d'(M_i) = min\ V(S_i \geq S_k), \quad k = 1, 2, 3, \ldots n\ and\ k \neq i \tag{11}$$

Finally, these scores are normalized to obtain the non-fuzzy weights of the criteria as per Eqs. (12-13).

$$d(M_i) = \frac{d'(M_i)}{\sum_{i=1}^{n} d'(M_i)} \tag{12}$$

$$W = \left(d(M_1),\ d(M_2),\ d(M_3), \dots\dots\dots\dots\dots\dots,\ d(M_n)\right)^T \tag{13}$$

The modeling performance of the different FAHP aggregation methods needs to be evaluated. The application of group minimum violation and GED was illustrated in some examples (Yang et al., 2018). Elshaboury et al. (2020b) used the satisfactory, group minimum violation, GED, and WD indices to assess different FAHP aggregation methods in the water engineering field. In this research, two evaluation metrics are proposed to evaluate group FAHP methods. These metrics are GED "Eq. 14" and WD "Eq. 15" (Grošelj et al., 2015). It shall be noted that lower values of these metrics indicate a higher consistency of the derived weights.

$$GED = \frac{1}{m}\sum_{k=1}^{m}\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{1}{3}\left[\left({l_{ij}}^{(k)} - \frac{w_i}{w_j}\right)^2 + \left({m_{ij}}^{(k)} - \frac{w_i}{w_j}\right)^2 + \left({u_{ij}}^{(k)} - \frac{w_i}{w_j}\right)^2\right]} \tag{14}$$

$$WD = \frac{1}{m}\sum_{k=1}^{m}\sqrt{\sum_{i=1}^{n}(w_{ki} - w_i)^2} \tag{15}$$

where; n refers to the number of criteria, w_i and w_j refer to the weights of importance of the i^{th} and j^{th} criterion, respectively, and w_{ki} refers to the weight of the i^{th} criterion from the perspective of the k^{th} decision maker.

5.2 Similarity measurement approaches

It is necessary to quantify the degree of similarity between the ranked lists of alternatives obtained from the evaluation metrics (Sarraf & Mcguire, 2020). In this research, two evaluation approaches are employed, namely Spearman's rank correlation coefficient and average overlap (AO). The Spearman's rank correlation coefficient (R) is defined as per Eq. (16).

$$R = 1 - \frac{6\sum_{i=1}^{n} {d_i}^2}{n(n^2 - 1)} \tag{16}$$

where; d_i refers to the rank difference at the i^{th} position and n is the number of ranks. The major drawback of Spearman's rank correlation coefficient is that it does not consider the relative importance of the top listed alternatives compared to the bottom listed alternatives. Accordingly, any changes in the ranks of the alternatives are treated similarly. In an attempt to overcome this limitation, the AO approach was proposed by Webber et al. (2010) to assign more weights to the top listed alternatives. This approach compares the overlap between two rankings at incrementally increasing depths as per Eq. (17).

$$AO(S,T,K) = \frac{1}{k}\sum_{d=1}^{k}\frac{|S_d \cap T_d|}{d} \tag{17}$$

where; S and T are the two ranking lists, d is the depth, and k is the evaluation depth. It is worth mentioning that this metric ranges from zero, indicating no similar rankings, to one indicating identical rankings.

5.3 Shannon entropy

Shannon entropy method is one of the most common methods for computing weights in the literature (Shannon, 1948). The computation procedures of this method are shown in the below steps (Hwang and Yoon, 1981):

The normalized score of the i^{th} alternative with respect to the j^{th} attribute (P_{ij}) is calculated using Eq. 18.

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}\ (1 \le i \le m, 1 \le j \le n) \tag{18}$$

where; x_{ij} represents the measure of performance of the i^{th} alternative with respect to the j^{th} attribute, m represents the number of alternatives, and n represents the number of attributes.

The entropy value of the j^{th} attribute (e_j) is computed using Eq. 19.

$$e_j = -k \times \sum_{j=1}^{n} P_{ij} \times lnP_{ij}\ , k = \frac{1}{ln\,(m)} \tag{19}$$

Finally, the weight of each attribute (W_j) is obtained using Eq. 20. It shall be noted that higher weights reflect higher relative importance from the decision makers' perspectives and vice versa.

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, d_j = 1 - e_j \quad (20)$$

where; d_j represents the variation coefficient of the j^{th} attribute.

5.4 WASPAS-TOPSIS method

A new aggregated method that integrates between WASPAS and TOPSIS, namely WT method, is proposed. This method is employed to rank the alternatives (i.e., FAHP aggregation methods) based on weights of attributes (i.e., evaluation metrics) and measures of performance of alternatives. The computation process of this method involves (Davoudabadi et al., 2020): a) calculating the WASPAS index for each alternative "Eq. 21", b) determining the positive and negative ideal solutions "Eq. 22-23", and c) computing the closeness coefficient for each alternative "Eq. 24". It shall be noted that a better alternative is associated with a higher value of closeness coefficient.

$$\psi_i = \Gamma \sum_{k=1}^{K} \left(\varphi^{(k)}(A_i) \times W_j\right) + (1 - \Gamma) \prod_{k=1}^{K} \varphi^{(k)}(A_i)^{W_j} \quad (21)$$

where; ψ_i stands for the WASPAS index of the i^{th} alternative, $\Gamma \in [0,1]$, $\{A_1, \dots, A_i\}$ refers to a set of alternatives, $\{W_1, \dots, W_j\}$ refers to the weights of attributes, $\varphi^{(k)}(A_i)$ is the measure of performance for the i^{th} alternative from the perception of the k^{th} decision maker.

$$r^+ = min_i(\psi_i) \quad (22)$$

$$r^- = max_i(\psi_i) \quad (23)$$

where; $r^+$and r^- refer to the positive and negative ideal solutions, respectively.

$$C_i = \frac{|\psi_i - r^-|}{|\psi_i - r^+| + |\psi_i - r^-|} \quad (24)$$

where; C_i refers to the closeness coefficient for the i^{th} alternative.

6. Results and discussion

The data used in this research was acquired from the article, titled "Data and calculation approach of the fuzzy AHP risk assessment of a large hydroelectric project" (Ribas et al., 2019b). The service packs under the work breakdown structure (WBS) and the potential risk events under the risk breakdown structure (RBS) are used for the risk assessment process. The service packs represent the activities necessary for satisfying the legal and contractual requirements while the risk events refer to the negative actions that might affect the service packs. Six questionnaire surveys were conducted among representatives of the builder consortium; project manager, contracts and civil works manager, electromechanical equipment manager, electromechanical assembly manager, contract administration manager, and environmental manager. The experts were asked to fill pairwise comparison matrices of service packs and related risk events.

The WBS consists of five main service packs; contractual modality, river management, electromechanical assembly, civil works, and workforce. The contractual modality illustrates the type of used contract while the river management refers to the combination of sustainability, construction, and ecological principles to minimize the project impacts on the ecosystem. The electromechanical assembly involves the installation of electromechanical elements such as turbines and generators. All the construction works such as the dam and cofferdam belong to the civil works service pack. The last service pack, workforce, describes the human resources necessary for electromechanical assemblies, civil works, and management/supervision services.

The RBS comprises five risk sources or events; hydrological cycle, product specification, quality of service, interface, and stoppages. The hydrological cycle describes the impact of climate seasonality on the planning and construction of projects. The product specification covers the technical and functional characteristics of the materials, components, and equipment involved in the plant. The quality of service ensures the compliance of the executed work, while the interface risk highlights the importance of ensuring consistency among services and equipment to finish a product. The last risk factor, stoppages, refers to the unscheduled work stoppages such as strikes leading to structural uniformity and delay problems.

The weights of importance of the risk events for an under-construction hydroelectric plant are computed in this section. The service packs are arranged into a square matrix and their relative importance is measured using Saaty scale. This scale ranges between 1 (i.e., equal importance) and 9 (i.e., extreme importance). Table 2 depicts the scores indicated by the contracts and civil works manager. For example, river management is moderately more important than civil works, thus 3 must be placed in row 2 column 4. Besides, the workforce is extremely more important than the contractual modality, as a result 1/9 is placed for contractual modality against workforce in the matrix. Finally, electromechanical assembly is very strongly more important than contractual modality; therefore, 1/7 is entered in row 1 column 3.

Table 2
Pairwise comparison matrix of the service packs from the contracts and civil works manager's perception

Service packs	Contractual modality	River management	Electromechanical assembly	Civil works	Work force
Contractual modality	1	1/7	1/7	1/5	1/9
River management	7	1	1	3	1/3
Electromechanical assembly	7	1	1	3	1/3
Civil works	5	1/3	1/3	1	1/5
Work force	9	3	3	5	1

The resulted pairwise comparisons are then fuzzified using Saaty's fuzzifying scale. For instance, the triangular fuzzy value of the entry that reflects the degree of importance of river management over civil works is (2, 3, 4). Besides, the fuzzy value of contractual modality over workforce is (1/9, 1/9, 1/8). The last crisp value while comparing contractual modality with respect to electromechanical assembly is converted into (1/8, 1/7, 1/6). The fuzzy matrices are then defuzzified using the center of area method to check for their consistencies. The crisp pairwise comparison matrix is normalized by dividing the elements of a given column by the sum of that column. The average of each row in the normalized matrix represents the vector of priorities. The relative importance of the service packs is calculated as (0.03, 0.21, 0.21, 0.10, 0.45). The priority vector indicates that the most influential service pack is the workforce (0.45), followed by the river management and electromechanical assembly (0.21), then the civil works (0.10), and finally the contractual modality (0.03). The principal eigenvalue (λ max) is calculated by multiplying the crisp comparison matrix by the vector of priorities and dividing the new vector by elements of the priority vector. The average of the elements in the new vector (5.13, 5.36, 5.36, 5.13, 5.42), referred to as λ max, is calculated to be 5.28. The consistency index is computed as follows: (5.28 –5) / (5 –1) = 0.07. Finally, the consistency ratio is calculated by dividing the consistency index by the random index, 0.07 / 1.12= 0.06. Therefore, this judgment is considered consistent because the associated consistency ratio is less than 0.10. It is found that only four surveys are consistent and will be included in the next steps of the analysis. The consistent matrices are aggregated to build a representative matrix of all decision makers using the maximum-minimum method. This method decides the upper and lower bounds of the triangular fuzzy values in the individual matrices. Besides, this method utilizes either arithmetic or geometric mean for the group middle bound. The aggregated matrix for the service packs using the maximum-minimum method (arithmetic mean) is depicted in Table 3. These calculations are performed in this research using Microsoft Excel.

Table 3
Aggregated matrix for the service packs using the maximum-minimum method (arithmetic mean)

Service packs	Contractual modality	River management	Electromechanical assembly	Civil works	Work force
Contractual modality	(1.0,1.0,1.0)	(0.1,4.3,8.0)	(0.1,1.6,4.0)	(0.2,4.3,9.0)	(0.1,3.1,8.0)
River management	(0.1,1.9,8.0)	(1.0,1.0,1.0)	(0.2,0.4,2.0)	(0.3,2.3,6.0)	(0.1,1.0,4.0)
Electromechanical assembly	(0.3,2.7,8.0)	(1.0,3.5,6.0)	(1.0,1.0,1.0)	(2.0,4.5,8.0)	(0.3,2.7,8.0)
Civil works	(0.1,1.4,6.0)	(0.2,1.1,4.0)	(0.1,0.3,0.5)	(1.0,1.0,1.0)	(0.1,0.4,2.0)
Work force	(0.1,3.6,9.0)	(0.3,3.3,8.0)	(0.1,1.6,4.0)	(1.0,4.0,8.0)	(1.0,1.0,1.0)

Concerning the maximum-minimum method using the arithmetic mean, the weighted vectors as a result of comparing the service packs using the original and modified extent analysis method are shown below:
The fuzzy weights of the contractual modality, river management, electromechanical assembly, civil works, and workforce service packs are calculated as follows:

$$S_1 = (1.53,\ 14.28,\ 30.00) \times \left(\frac{1}{125.50}, \frac{1}{52.97}, \frac{1}{11.72}\right) = (0.01, 0.27, 2.56)$$

$$S_2 = (1.67,\ 6.60,\ 21.00) \times \left(\frac{1}{125.50}, \frac{1}{52.97}, \frac{1}{11.72}\right) = (0.01, 0.12, 1.79)$$

$$S_3 = (4.50,\ 14.33,\ 31.00) \times \left(\frac{1}{125.50}, \frac{1}{52.97}, \frac{1}{11.72}\right) = (0.04, 0.27, 2.64)$$

$$S_4 = (1.53,\ 4.22,\ 13.50) \times \left(\frac{1}{125.50}, \frac{1}{52.97}, \frac{1}{11.72}\right) = (0.01, 0.08, 1.15)$$

$$S_5 = (2.50, 13.54, 30.00) \times \left(\frac{1}{125.50}, \frac{1}{52.97}, \frac{1}{11.72}\right) = (0.02, 0.26, 2.56)$$

The degree of possibility between the service packs can be obtained as described below:

$$V(S_1 \geq S_2) = 1.00, \quad V(S_1 \geq S_3) = 1.00, \quad V(S_1 \geq S_4) = 1.00, \quad V(S_1 \geq S_5) = 1.00$$

$$V(S_2 \geq S_1) = 0.93, \quad V(S_2 \geq S_3) = 0.92, \quad V(S_2 \geq S_4) = 1.00, \quad V(S_2 \geq S_5) = 0.93$$

$$V(S_3 \geq S_1) = 1.00, \quad V(S_3 \geq S_2) = 1.00, \quad V(S_3 \geq S_4) = 1.00, \quad V(S_3 \geq S_5) = 1.00$$

$$V(S_4 \geq S_1) = 0.86, \quad V(S_4 \geq S_2) = 0.96, \quad V(S_4 \geq S_3) = 0.85, \quad V(S_4 \geq S_5) = 0.87$$

$$V(S_5 \geq S_1) = 0.99, \quad V(S_5 \geq S_2) = 1.00, \quad V(S_5 \geq S_3) = 0.99, \quad V(S_5 \geq S_4) = 1.00$$

The overall score for each service pack is determined by computing the minimum of these possibilities as follows:

$$d'(M_1) = \min V(S_1 \geq S_2, S_3, S_4, S_5) = 1.00 \quad d'(M_2) = \min V(S_2 \geq S_1, S_3, S_4, S_5) = 0.92 \quad d'(M_3) = \min V(S_3 \geq S_1, S_2, S_4, S_5) = 1.00$$

$$d'(M_4) = \min V(S_4 \geq S_1, S_2, S_3, S_5) = 0.85 \quad d'(M_5) = \min V(S_5 \geq S_1, S_2, S_3, S_4) = 0.99$$

Finally, the normalized weight vectors of the service packs can be obtained as follows:

$$d(M_1) = \frac{1.00}{1.00 + 0.92 + 1.00 + 0.85 + 0.99} = 0.210 \quad d(M_2) = \frac{0.92}{1.00 + 0.92 + 1.00 + 0.85 + 0.99} = 0.194$$

$$d(M_3) = \frac{1.00}{1.00 + 0.92 + 1.00 + 0.85 + 0.99} = 0.210 \quad d(M_4) = \frac{0.85}{1.00 + 0.92 + 1.00 + 0.85 + 0.99} = 0.179$$

$$d(M_5) = \frac{0.99}{1.00 + 0.92 + 1.00 + 0.85 + 0.99} = 0.208 \quad W = (0.210, 0.194, 0.210, 0.179, 0.208)$$

The normalization stage differs in the modified extent analysis method than that in the original method. The weighted vectors as a result of comparing the service packs are obtained as shown below:

$$S_1 = \frac{(1.53, 14.28, 30.00)}{((21.00 + 31.00 + 13.50 + 30.00), 52.97, (1.67 + 4.50 + 1.53 + 2.50))} = (0.02, 0.27, 2.94)$$

$$S_2 = \frac{(1.67, 6.60, 21.00)}{((30.00 + 31.00 + 13.50 + 30.00), 52.97, (1.53 + 4.50 + 1.53 + 2.50))} = (0.02, 0.12, 2.09)$$

$$S_3 = \frac{(4.50, 14.33, 31.00)}{((30.00 + 21.00 + 13.50 + 30.00), 52.97, (1.53 + 1.67 + 1.53 + 2.50))} = (0.05, 0.27, 4.29)$$

$$S_4 = \frac{(1.53, 4.22, 13.50)}{((30.00 + 21.00 + 31.00 + 30.00), 52.97, (1.53 + 1.67 + 4.50 + 2.50))} = (0.01, 0.08, 1.32)$$

$$S_5 = \frac{(2.50, 13.54, 30.00)}{((30.00 + 21.00 + 31.00 + 13.50), 52.97, (1.53 + 1.67 + 4.50 + 1.53))} = (0.03, 0.26, 3.25)$$

$$V(S_1 \geq S_2) = 1.00, \quad V(S_1 \geq S_3) = 1.00, \quad V(S_1 \geq S_4) = 1.00, \quad V(S_1 \geq S_5) = 1.00$$

$$V(S_2 \geq S_1) = 0.94, \quad V(S_2 \geq S_3) = 0.93, \quad V(S_2 \geq S_4) = 1.00, \quad V(S_2 \geq S_5) = 0.94$$

$$V(S_3 \geq S_1) = 1.00, \quad V(S_3 \geq S_2) = 1.00, \quad V(S_3 \geq S_4) = 1.00, \quad V(S_3 \geq S_5) = 1.00$$

$$V(S_4 \geq S_1) = 0.87, \quad V(S_4 \geq S_2) = 0.97, \quad V(S_4 \geq S_3) = 0.87, \quad V(S_4 \geq S_5) = 0.88$$

$$V(S_5 \geq S_1) = 0.99, \quad V(S_5 \geq S_2) = 1.00, \quad V(S_5 \geq S_3) = 0.99, \quad V(S_5 \geq S_4) = 1.00$$

$$d'(M_1) = \min V(S_1 \geq S_2, S_3, S_4, S_5) = 1.00 \quad d'(M_2) = \min V(S_2 \geq S_1, S_3, S_4, S_5) = 0.93$$

$d'(M_3) = \min V(S_3 \geq S_1, S_2, S_4, S_5) = 1.00 \quad d'(M_4) = \min V(S_4 \geq S_1, S_2, S_3, S_5) = 0.87$

$d'(M_5) = \min V(S_5 \geq S_1, S_2, S_3, S_4) = 0.99$

$$d(M_1) = \frac{1.00}{1.00 + 0.93 + 1.00 + 0.87 + 0.99} = 0.208 \qquad d(M_4) = \frac{0.87}{1.00 + 0.93 + 1.00 + 0.87 + 0.99} = 0.181$$

$$d(M_2) = \frac{0.93}{1.00 + 0.93 + 1.00 + 0.87 + 0.99} = 0.195 \qquad d(M_5) = \frac{0.99}{1.00 + 0.93 + 1.00 + 0.87 + 0.99} = 0.207$$

$$d(M_3) = \frac{1.00}{1.00 + 0.93 + 1.00 + 0.87 + 0.99} = 0.208 \qquad W = (0.208, 0.195, 0.208, 0.181, 0.207)$$

For the maximum-minimum method using the geometric mean, the weighted vectors using the original extent analysis method are as follows: $W = (0.207, 0.192, 0.215, 0.177, 0.209)$. On the other hand, the weighted vectors using the modified extent analysis method are as follows: $W = (0.206, 0.193, 0.213, 0.179, 0.208)$. The results show that the electromechanical assembly is the most important service pack because of the application of advanced technologies in the project. The workforce and contractual modality are also major concerns from the builder consortium's perspective. The workforce problem occurs because of the strikes resulting in a shortage of qualified manpower. Additionally, the contract type used in this project (i.e., lump sum) transfers all the risks to the builder, who is responsible for satisfying the environmental and operational requirements of the power plant. The normalized weights of the risk events for each service pack are calculated in the same manner. The normalized weights of the service packs are multiplied by the normalized weights of the related risk events, resulting in the final risk event weights. The final risk event weights using the four aggregation approaches are presented in Table 4. The results show that the stoppages and quality of service are the most crucial risk events. The stoppages are incurred, leading to project delay. Besides, the quality of service problem refers to the failure to comply with the requirements in civil and electromechanical works. The hydrologic cycle is affected by pivotal risk factors because of the ability of the built dam and cofferdam to mitigate the flooding impact during the wet season. The product specification is the next in order risk factor because of the problems encountered in elements, requiring repair or replacement actions. The interface, reflecting the importance of consistent services and equipment to finish a product, is the lowest risk factor.

Table 4

Final weights of risk events using FAHP aggregation methods

	Original extent analysis method		Modified extent analysis method	
	Aggregated (Max-Min) - Arithmetic	Aggregated (Max-Min)- Geometric	Aggregated (Max-Min) - Arithmetic	Aggregated (Max-Min)- Geometric
Hydrological cycle	20.9%	20.6%	20.8%	20.6%
Product specification	19.3%	19.2%	19.4%	19.3%
Quality of service	21.0%	21.4%	20.9%	21.2%
Interface	17.6%	17.7%	17.8%	17.9%
Stoppages	21.2%	21.0%	21.0%	20.9%

The performance of the FAHP aggregation methods is evaluated using the GED and WD measures. The values and ranking results of the performance metrics are presented in Table 5. The GED and WD indices indicate that the original extent analysis method using the maximum-minimum method (arithmetic mean) is the best FAHP aggregation method. Besides, the ranking result of the modified extent analysis method using the maximum-minimum method (geometric mean) is identical with respect to the applied metrics. However, the evaluation metrics yield different rankings for the remaining alternatives. Therefore, this can be regarded as an MCDA problem that aims at prioritizing the FAHP aggregation methods.

Table 5

Evaluation metrics and associated rankings of the FAHP aggregation methods

	Original extent analysis method		Modified extent analysis method	
	Aggregated (Max-Min) - Arithmetic	Aggregated (Max-Min)- Geometric	Aggregated (Max-Min) - Arithmetic	Aggregated (Max-Min)- Geometric
Group Euclidean distance	12.852	12.880	12.879	12.903
Rank	1	3	2	4
Distance between weights	0.338	0.338	0.339	0.340
Rank	1	2	3	4

Table 6

Average overlap calculation between the performance metrics [(1)]

Depth	Group Euclidean distance	Distance between weights	Intersection	Overlap at depth	Average overlap
1	A	A	{A}	1	1
2	AC	AB	{A}	0.5	0.75
3	ACB	ABC	{ABC}	1	0.833
4	ACBD	ABCD	{ABCD}	1	0.875

[1] A= Original (Max-Min) – Arithmetic, B= Original (Max-Min) – Geometric, C= Modified (Max-Min) – Arithmetic, D= Modified (Max-Min) – Geometric

Spearman's correlation coefficient between the evaluation metrics is computed to be 0.80. Besides, the average overlap result between the evaluation metrics is calculated as 0.875 (see Table 6). The similarity measurement approaches indicate that the results of the evaluation metrics are very close to each other. In the MCDA problem, the FAHP aggregation methods are regarded as the alternatives and the performance metrics are considered as the attributes. The weights of the attributes are calculated using the Shannon entropy method, as depicted in Table 7. It is found that the WD metric represents the highest weight of importance (i.e., 76.76%) while the GED metric is associated with the lowest weight of importance (i.e., 23.24%). The numerical outputs of the WT technique are described in Table 8. The results indicate that the original extent analysis method using the maximum-minimum method (arithmetic mean) is the first-ranked FAHP aggregation method.

Table 7
Weights of the evaluation metrics using Shannon entropy method

Terms	Group Euclidean distance	Distance between weights
Entropy value	1.00E+00	1.00E+00
Variation coefficient	7.11E-07	2.35E-06
Weights of criteria	23.24%	76.76%

Table 8
WT rankings of the FAHP aggregation methods

FAHP aggregation method	Group Euclidean distance	Distance between weights	WASPAS index	Closeness coefficient	Rank
Original (Max-Min) - Arithmetic	12.852	0.338	2.016	1.00	1
Original (Max-Min) - Geometric	12.880	0.338	2.021	0.53	2
Modified (Max-Min) - Arithmetic	12.879	0.339	2.021	0.42	3
Modified (Max-Min) - Geometric	12.903	0.340	2.025	0.00	4

7. Conclusion

Hydroelectric plants are subjected to serious risk events because of the geographic and socioeconomic characteristics of these unique projects. Therefore, this research presents the comparative analysis of various aggregation methods for deriving weights of the risk events in a large hydroelectric plant. The fuzzy analytic hierarchy process (FAHP) technique was employed to calculate the weights of importance of the risk events. This method accounted for the imprecision and vagueness between the factors. In this research, the original and modified extent analysis methods were applied using two aggregation methods, namely the maximum-minimum method using an arithmetic mean and the maximum-minimum method using a geometric mean. The former approach used the arithmetic mean of individual judgments, while the latter used a geometric mean for the group modal value. Moreover, the performance of these aggregation methods was assessed using two evaluation measures, namely group Euclidean distance and distance between weights. The degree of similarity between the evaluation metrics was examined using Spearman's rank correlation coefficient and average overlap approaches. The similarity measurement approaches indicated that the outcomes of the evaluation metrics were very close to each other. However, the results of the evaluation measures were not consistent and therefore were further examined using a new aggregated multiple criteria decision making method. The results indicated that the original extent analysis method using the maximum-minimum method (arithmetic mean) was the best FAHP aggregation method. A Brazilian hydroelectric plant was used to demonstrate the application of the proposed framework. The proposed framework could assist decision makers in conducting an objective and transparent risk assessment of large hydroelectric projects.

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