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A fuzzy-TOPSIS model for maintenance outsourcing considering the quality of submitted tender documents

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Highlights

- The study presents a Fuzzy-TOPSIS model for solving the maintenance outsourcing problem.
- The study integrates fuzzy opinions of experts on the importance of selection criteria.
- The study allows multiple decision-makers to integrate their fuzzy evaluations.
- Disagreements among experts may result in a major change to the final decision.

Abstract

The paper provides a multiple-experts Fuzzy-TOPSIS decision-making model for the selection among maintenance contractors based on the quality of tendering documents. The study introduces a set of selection criteria utilizing benefit and cost criteria from literature. The proposed model aggregates subjective linguistic assessments of multiple experts that express their opinions on the degree of importance of criteria and allows multiple decision-makers to evaluate the compliance of contractors' documents. For a case study, the model is applied to select among contractors tendering to maintain the heavy-duty cranes of an international steel company from literature. Several decision-making scenarios are investigated, and major changes in the final decision are observed. The changes in obtained results illustrate the need to better address uncertainties in rating and tendering an overqualified contractor at a higher cost.

Keywords

contractor selection; maintenance outsourcing; MCDM; Fuzzy-TOPSIS; decision-making.

1. Introduction

Maintenance plays a fundamental role in preserving the safety, quality, and productivity of service for industrial and governmental facilities. Maintenance actions vary in complexity, and accordingly, the associated costs, time, skills, and machinery required to perform the job right the first time differ. Therefore, many companies outsource some or all of their maintenance activities to enhance value [1]. While selecting the maintenance services, the decision-maker (DM) must primarily consider the technical abilities of the maintenance contractors in addition to several other time and financial compliance attributes to guarantee maximum safety and quality for money.

The maintenance contractor selection process accounts for several technical and non-technical strategic and operational decision criteria based on the organization's requirements such as price and payment terms, experience in similar work, ability to supply spare parts, etc. Since the adequate selection of the contractors directly influences maintenance performance, outsourcing is a crucial decision for any organization. Tendering is one of the most used selection methods to inform and invite maintenance contractors to apply and compete for the maintenance contract. Among the many obligations of the project owners, they should notify contractors of the process by which tenders will be considered and selected. The selection process must be transparent, verifiable, and liable. Moreover, owners must provide clear and adequate documentation that specifies requirements and specifications. Consequently, interested contractors must adequately address all the information required by the project owners to ensure compliance, and they must provide evidence of professional capabilities to ensure safety, quality, and timely delivery [26].

The information presented in tender documents about contractors is evaluated by DMs, i.e., organizations, and then the best-fit contractor among alternatives is selected. Basically, the evaluation process includes determining the selection criteria (e.g., price, experience), their relative importance, and selecting the best contractor that meets DM's demand. Therefore, selecting the best maintenance contractor that fulfills DM's need among possible alternatives is considered under multi-attribute decision-making problems [10]. The selection of the decision-making method is essential since it directly influences the performance of the maintenance. Additionally, evaluating the degree of compliance based on tender documents is rather vague, imprecise, or sometimes inconsistent since the evaluation depends on the subjective judgments of the different DMs. Given the diverse backgrounds of the DMs, and their degree of influence on the decision, the great proximity of the candidate qualities makes the decision hard to agree

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upon. These risks originated from subjective preferences of different DMs hamper the applicability of the deterministic approaches. In response, fuzzy logic is proposed as an alternative that allows incorporating uncertain, vague information in the decision-making process. According to Jasiulewicz-Kaczmarek et al. [14], by combining fuzzy with AHP (analytical hierarchy process) and/or fuzzy with TOPSIS (technique for order preference by similarity to ideal solution), DMs can incorporate the specific requirements of their company in deciding key maintenance factors to enhance sustainability. Moreover, the authors declared that the opinions of multiple DMs on multiple criteria can be incorporated using Fuzzy-AHP, and that the use of Fuzzy-TOPSIS allows the rating of a large number of alternatives and finding the "best" alternative.

In this study, we present a multiple-criteria multiple-experts Fuzzy-TOPSIS model for evaluating the performance of the maintenance contractors. Given that tender documents are the main source of information, tendering information is used to set the decision criteria. Accordingly, the degree of compliance of the provided information to requirements is set as the measure to select among contractors. In the proposed Fuzzy-TOPSIS model, Fuzzy logic is deployed to capture the subjectivity in the evaluating the degree of compliance based on tender documents, and TOPSIS allows the rating of alternative contractors based on the trade-off among the different criteria. For a case study, the model is applied for the maintenance of the maritime heavy-duty cranes at the steel company. This study contributes to the literature both theoretically and practically in the following aspects. From the theoretical point of view, the study integrates experts' preferences on criteria important to contractors' selection. The resulting fuzzy set "better" addresses experts' disagreements on the importance of criteria. The Fuzzy-TOPSIS model allows multiple DMs to integrate their uncertain evaluations of contractors' documents. From the practical point of view, the study introduces various decision-making scenarios through a case study from literature to illustrate the usability of the solution methodology. Moreover, the study shows a potentially major change in the final decision due to the change in the evaluation process.

The remainder of this paper is structured as follows. Section 2 reviews the literature on maintenance contractor selection. Section 3 addresses the solution method, Fuzzy-TOPSIS. The application for maritime heavy-duty cranes is presented by a case study in Section 4. Finally, Section 5 concludes the paper.

2. Literature review

Maintenance management plays a significant role in increasing the organization's assets by preventing failures and reducing possible hazards. Therefore, making appropriate maintenance decisions, including outsourcing, is key to enhance a company's resilience [4]. In the literature, researchers utilized several combinations of decision-making tools to help DMs decide regarding outsourcing. Such tools include TOPSIS, AHP, analytical network process (ANP), decision-making trial and evaluation laboratory (DEMATEL), balanced score-card (BSC), and Fuzzy logic [12]. Several recent studies addressed the applications of these tools in outsourcing of parts supply in vehicle production [27] and [13], complex system building in aviation [22], software development [21], catering [8], hospitals [5], cast iron part supply used in manufacturing catalytic converters [18], airline retail industry [23], supplier selection in steel industry [3] and in maintenance contractor selection [11]. Moline and Coves [19] presented a review of literature until 2007 on supplier evaluation and selection. In a recent study, Jasiulewicz-Kaczmarek et al. [14] used the matrix of crossed impact multiplications applied to a classification (MICMAC), Fuzzy-AHP, and Fuzzy-TOPSIS in identifying the maintenance factors critical to enhance manufacturing sustainability.

Hammudah [10] proposed a TOPSIS model to select among contractors bidding for a contract to maintain maritime heavy-duty cranes at a steel company. In its first phase, the study surveyed maintenance professionals from various companies to identify key criteria that guide the outsourcing decision. Key criteria were further filtered by company project, and maintenance managers and contractors were evaluated based on information they listed in their tender documents. The company officials divided the selection criteria into technical and non-technical criteria as they are itemized in the company's maintenance tender. Information cards were used to summarize information about each contractor, and the proposed TOPSIS model was used to select the most competent contractor. Mahdi et al. [17] identified several qualifying factors for the selection. The factors include criteria concerning cash flows, managerial capability, equipment accessibility, contractor's business strategy, professional staff capability, and organizational structure, workforce scheduling, supply scheduling, access to the workforce, logistic capability, percentage, and type of work that is assigned to the contractor, quality control, equipment scheduling, and guarantee program. Singh and Tiong [25] suggested past performance, characteristics of the contractor's company, potential performance, financial capability, and specific project criteria. Hafeez et al. [9] proposed intellectual properties, physical assets, cultural capitals, quality, delivery time, and cost to distinguish among contractors. Darvish et al. [7] used criteria concerning equipment and technology, work experience, operations team knowledge and experience, quality, financial stability, reputation, familiarity with the area and domestication, innovation, and creativity in contractor evaluation. Jaskowsk et al. [15] suggested using financial capacity, organizational experience, labor and equipment, a managerial system including safety policy, quality system, and performance in previous projects. Lam and Yu [16] used quantitative criteria including current workload, human resources and financial capacity, and qualitative criteria including environmental concern, equipment, and resources, management capacity, complaint history, safety aspects, quality management, past performance, and experience. In [2], Alzahrani and Emsley used quality, safety, environment, past performance, resources, experience, organization, management, and technical aspects, finance, and the type and size of previous projects. Nieto-Morote and Ruz-Vila [20] suggested using technical capacity, experience, staff qualifications, labor and equipment, method innovation, experience, and managerial capacity. Moreover, the authors used financial stability, credit and liquidity, financial capability, past performance, previous relationship, reputation, and health and safety. [23] used cost, delivery time, product quality, cooperate social responsibility, and financial stability. In [13], the authors utilized criteria concerning product quality, cost, on-time delivery, brand name, environmental performance, manufacturing capability, warranty, and quality of a relationship. [21] used cost, vendor reputation, recoverability, scalability, portability, requirement rate, technical support, quality, risk analysis, changeability, analyzability, and response time. Hua et al. [11] classified criteria into (1) financial perspective: maintenance cost and maintenance value, (2) customer perspective: before, during, and after maintenance customer services, (3) internal business perspective: serviceability, customer management and innovation ability, and (4) learning and growth perspective: human capital, information capital and organizational capital.

3. Research methodology

The research methodology includes two phases. In the first phase, the authors utilized the literature search (studies from [1-27]) to identify the essential tendering criteria considered in the selecting a maintenance contractor. Table 1 divides surveyed criteria into "Benefit criteria" and "Cost criteria" and provides descriptions of the specifics to be present in tender documents for each of the criteria. In phase two, the project owner is expected to evaluate each of the benefit criteria against the owner's expected or minimum level of requirement for that criteria. On the other hand, the project owner is expected to evaluate each of the cost criteria against the owner's expected or maximum limit of obligation the owner expects to bear. To this end, the multi-

Table 1 Selection criteria

Criteria		Description of specifics to be present in tender documents
Benefit Criteria	Technical capability	Documents demonstrate evidence of the contractor's ability to comply with requirements and technical specifications. Information includes: • Technically accurate work methods and procedures. • Number of skilled workers, their qualifications, and their roles during the implementation period. • Types and the quantities of all equipment needed during the execution period, and • Number, scope, and schedules of projects that will share same resources during the lifetime of the project.
	Logistics plan	Documents demonstrate: • A logistics plan, and • Lists of required tools, spare parts and materials, quantities and prices and lists of manufacturers and suppliers.
	Time schedule	Documents demonstrate: • A detailed schedule of sequence and time of activities. • Expected date of completion of the project, and • A risk management plan.
	Past experience	Documents demonstrate evidence of previous experience in the execution of similar works. Information includes: • Number of years in business. • Number of previous similar size projects completed and that failed to complete. • Certificates of successful completion and delivery of works, and • Certificates of "good" relations with previous projects' beneficiaries.
	Training	In case of development of new equipment/system, documents demonstrate: • Contractor's commitment to providing training to a sufficient number of company's staff, and • Contractor's commitment to providing necessary operations and maintenance manuals.
	Tests and audits	Documents demonstrate: • Contractor's commitment to adhere to test and audit types and procedures, including third-party tests and audits required in tender throughout the project to ensure quality and time commitment, and • Contractor's commitment to perform corrective actions based on test and audit results.
	Warranty	Documents demonstrate: • The obligation of the contractor to ensure the proper performance of the installations over a period of time, and • The period of the time of validity.
	Financial capacity	Documents demonstrate financial performance and liquidity. Information includes: • Working capital. • Current assets. • Credit rating, and • Financial risk management plan.
	Workplace Practices	Documents demonstrate: • Industrial relations practices and management. • Occupational health and safety plan, policy, human and tangible resources, procedures and management, and previous reports. • Environmental practices and management, and • Community relations practices and management.
Cost Criteria	Technical Obligations of Owner	Documents clearly identify contractor's special requirements from project owners over the time period of the project to enhance a successful completion of the project.
	Project costs	In financial offer, documents demonstrate information that clearly states: • The total project cost with a stated value of the foreign and/or domestic monetary currency required • Itemized direct costs such as supplying and execution costs, and • Itemized indirect costs such as electricity and transportation costs.
	Financial obligations of the owner	Documents demonstrate the financial obligations of the project owner. Information includes: • Advance payment as an amount or a percentage of total payment, and • Schedule of payments and amounts.

ple-criteria multiple-expert Fuzzy-TOPSIS technique, section 3.1, is utilized to capture the uncertainties in the evaluations of the multiple experts. The winning contractor is then identified as the one with the "best" trade-offs among criteria.

3.1. Fuzzy-TOPSIS

Fuzzy-TOPSIS is a multi-criteria decision-making technique that accounts for the subjective judgment of humans in finding the alternative that is closest to the fuzzy positive ideal solution (FPIS) and farthest from the fuzzy negative ideal solution (FNIS) [6] and [24]. Utilizing the fuzzy theory, DMs use linguistic assessments to overcome the need to provide crisp numerical values that they are not able to estimate in the first place. Like other decision-making models, Fuzzy-TOPSIS uses human judgment to find the normalized weights of qualitative and quantitative criteria, find the normalized scores of alternatives including FPIS and FNIS, determine the distance between each alternative and the ideal alternatives (FPIS and FNIS) and finally select the alternative with best-combined score measured by the closeness coefficient [6] and [24].

Fuzzy set A in a universe of discourse B is characterized by a membership function $\mu_A(B)$ that gives each element *b* in B a real number between 0 and 1. Triangular fuzzy number (TFN) membership function is widely used in the literature [13]. Equation 1 and Figure 1 illustrate TFN (x, y, z) and the membership function $\mu_A(B)$, respectively.

$$\mu_A(b) = \begin{cases} \dfrac{b-x}{y-x} & \text{if } x \le b \le y \\ \dfrac{z-b}{z-y} & \text{if } y \le b \le z \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

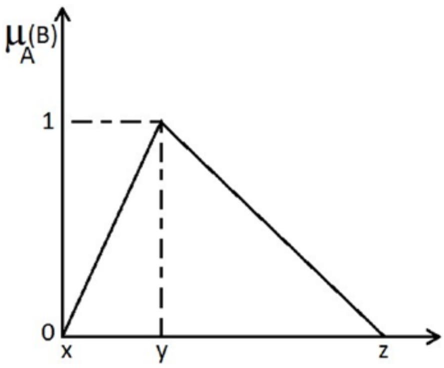

Fig. 1. Triangular fuzzy number (TFN)

Let (x_1, x_2, x_3) and (y_1, y_2, y_3) be two TFN, Equation 2 defines the distance between the two TFNs:

$$d(x,y) = \left(\frac{1}{3}\left[(x_1 - y_1)^2 + (x_2 - y_2)^2 + (x_3 - y_3)^2\right]\right)^{0.5} \quad (2)$$

The following steps briefly explain the Fuzzy-TOPSIS model used in this study. The work steps are adapted from Chen [6] and Saghafian and Hejazi [24]:

***Step 1 – The evaluation process**:* In this step, each DM involved in the outsourcing process is asked to evaluate the contractors' tender documents using linguistic assessment. The scale of linguistic assessment may vary from one company to another. Let *K* be the number of the outsourcing DMs in the company, *L* be the number of maintenance experts surveyed, *m* be the number of contractors, and *n* be the number of selection criteria.

- Following the inspection of vending documents associated with criteria j; $j = 1 \dots n$, each DM k; $k = 1 \dots K$, turns in a fuzzy rating $b_{ij}^k = \left(x_{ij}^k, y_{ij}^k, z_{ij}^k\right)$ representing her/his assessment on the degree of fulfillment of contractor i; $i = 1\dots m$, with respect to each criteria j.
- For the L maintenance-outsourcing experts surveyed, within and outside the company, each expert l; $l = 1 \dots L$, turns in a fuzzy weight $w_j^l = (w_{j1}^l, w_{j2}^l, w_{j3}^l)$ for each criteria j.

  The associated TFNs for combinations of i, j, k and l are obtained from Table 2.

***Step 2 – Combining evaluations**:* The different assessments from the DMs are integrated into this step to form mutual decisions for criteria. Several aggregation techniques are presented in the literature. For the purpose of this study, the evaluations are combined such that

- Given the limited number of DMs, Equation 3 is utilized to capture the range of disagreement among the DMs better.

$$b_{ij} = (\min_k x_{ij}^k,\ \frac{1}{K}\sum_{k=1}^{K} y_{ij}^k, \max_k z_{ij}^k); \forall ij \quad (3)$$

- For the large number of maintenance experts surveyed in [10], Equation (4) is utilized to aggregate their inputs on the degree of importance of criteria to narrow the range of expected disagreements. If, alternatively, Equation (3) is used, all TFNs are expected to have the same minimums and maximums since feedbacks are expected to cover all the evaluation options:

$$w_j = (\frac{1}{L}\sum_{l=1}^{L} w_{j1}^l,\ \frac{1}{L}\sum_{l=1}^{L} w_{j2}^l, \frac{1}{L}\sum_{l=1}^{L} w_{j3}^L); \forall j \quad (4)$$

***Step 3** – **Score normalization**:* Aggregated scores are normalized in this step to enhance accurate calculations. Normalized scores are computed as follows:

$$\tilde{r}_{ij} = \begin{cases} \left(\dfrac{b_{ij1}}{\max\limits_i b_{ij3}}, \dfrac{b_{ij2}}{\max\limits_i b_{ij3}}, \dfrac{b_{ij3}}{\max\limits_i b_{ij3}}\right) \\ \left(\dfrac{\min\limits_i b_{ij1}}{b_{ij3}}, \dfrac{\min\limits_i b_{ij1}}{b_{ij2}}, \dfrac{\min\limits_i b_{ij1}}{b_{ij1}}\right) \end{cases} \quad (5)$$

The weighted normalized scores are such that:

$$\tilde{v}_{ij} = \left(\tilde{r}_{ij1}\, w_{j1}, \tilde{r}_{ij2}\, w_{j2}, \tilde{r}_{ij3}\, w_{j3}\right) \quad (6)$$

Each fuzzy number is defuzzified using the centroid method such that the centroid value for $\tilde{v}_{ij}$ is $\bar{v}_{ij} = \frac{1}{3}\left(\tilde{r}_{ij1}\, w_{j1} + \tilde{r}_{ij2}\, w_{j2} + \tilde{r}_{ij3}\, w_{j3}\right)$.

***Step 4** – **Closeness to FPIS and to FNIS**:* Using normalized scores, TOPSIS graph is constructed and related distances and closeness coefficients are computed. The distance between each alternative and the FPIS and that between the alternative and the FNIS are computed using Equation (2) such that:

$$d_i^{FPIS} = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, FPIS_j\right) \quad (7)$$

$$d_i^{FNIS} = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, FNIS_j\right) \quad (8)$$

where:

$$FPIS_j = \left[\left(\max_i\ \tilde{v}_{ij3}, \max_i\ \tilde{v}_{ij3}, \max_i\ \tilde{v}_{ij3}\right)_j, j = 1\ ..n\right] \quad (9)$$

and:

$$FNIS_j = \left[\left(\min_i \tilde{v}_{ij1}, \min_i \tilde{v}_{ij1}, \min_i \tilde{v}_{ij1}\right)_j, j = 1\ ..n\right] \quad (10)$$

The closeness coefficient for each alternative, CC_i, is computed as:

$$CC_i = \frac{d_i^{FNIS}}{d_i^{FNIS} + d_i^{FPIS}} \quad (11)$$

The alternative with the highest closeness coefficient is considered the best alternative.

4. Application to the crane maintenance tendering problem

Cranes are widely used for various hoisting operations conducted in multiple industries. Cranes vary in capacity and can be used to handle heavy weight loads. Since cranes can cause serious hazards, cranes need to be frequently monitored and maintained to enhance safe use and to satisfy regulatory measures. Therefore, outsourcing maintenance services of cranes must consider the technical abilities of maintenance contractors and several other time and financial compliance attributes to ensure maximum safety and quality for the service.

The proposed Fuzzy-TOPSIS model is applied to the study presented in [10] to select among three contractors bidding for a maintenance contract of the heavy-duty cranes of an international steel company. According to Hammudah [10], the evaluation process of the contractors goes through two main phases. Figure 2 illustrates the flow of the selection process. In the first phase, the DMs at the company prequalify a number of contractors through a screening process. Utilizing their market intelligence, past experiences with the contractors, and submitted tender documents, only contractors with a "good" reputation, enough experience, and complete tender documents are qualified. In the second phase, DMs undergo lengthy discussions until a decision is made considering the subjectivity of the evaluation criteria and influence of the rank of each of the DMs. The company's DMs consisted of the director of mechanical maintenance, the head of the department of crane maintenance, and the head of the department of project development. Although [10] presented a feasible solution to the problem, the author did not account for the uncertainties in the evaluation process.

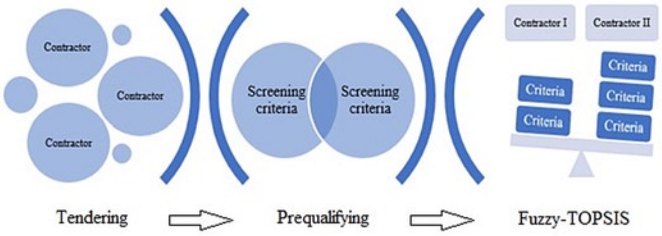

Fig. 2. Flow of the selection process

For this study, a subset of the criteria in Table 1 is selected in consistency with the current tendering process of the company and the 32 criteria presented in [10]. As a result, ten criteria are selected. Figure 3 presents the hierarchy of the selection process based on selected criteria.

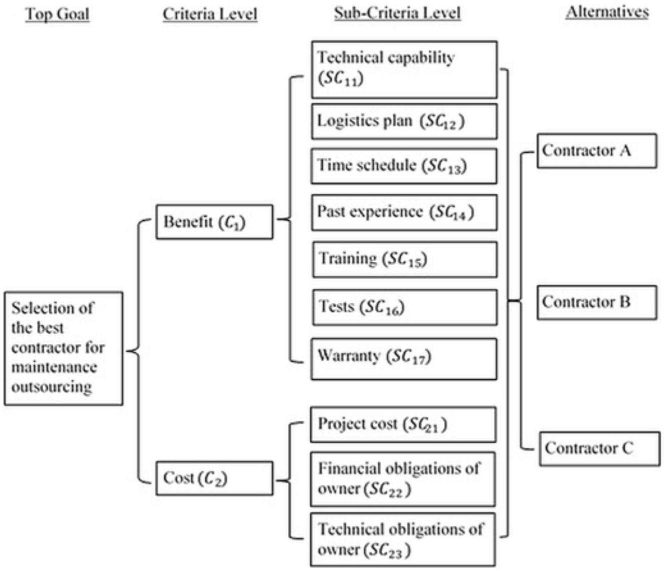

Fig. 3. Hierarchy of selection criteria

Unlike AHP, the weights of the criteria and the ratings of contractors with respect to criteria are evaluated independently and not relative to each other in TOPSIS. Knowing that contractors passed the prequalification stage of the contractor selection process, each of the contractors is at least at the expected level of technical abilities, and they probably will score very close if not exactly the same when a standard Likert scales are used, as was clearly the case in [10]. Building on the formers, we propose modified scales of weights and ratings that are sensitive to medium to minor differences to distinguish between close alternatives, especially at the high ends of the scales. Table 2 shows the proposed fuzzy mapping of the linguistic assessments of weights and ratings to its associated TFNs.

Utilizing the raw data and the Likert scales of the responses of surveyed maintenance experts and company DMs in [10], fuzzy weights and ratings are computed to feed the Fuzzy-TOPSIS algorithm. Hammudah [10] surveyed 92 maintenance experts and maintenance managers, quality experts and quality managers, operations managers, finance, and general managers involved in maintenance outsourcing from nine companies. Experts and managers were surveyed for their assessments on the degree of importance of their 32 maintenance outsourcing criteria obtained from the literature. Table 3 presents the raw data of experts' responses on the degrees of importance of criteria in Figure 3, and it shows the computations for the combined fuzzy weight vectors using Equation (4).

Table 2 Linguistic variables for the degree of importance of criteria and for the rating of alternatives

Degree of the importance of criteria		**Rating of contractor's documents/offers against benefit criteria**		**Rating of contractor's documents/offers against cost criteria**	
Linguistic variable	**TFN**	**Linguistic variable**	**TFN**	**Linguistic variable**	**TFN**
Low (LW)	(0.01, 1, 1)	Poor (PR)	(0.01, 1, 1)	Very Low (VL)	(0.01, 1, 2)
Medium (MD)	(2, 3, 3)	Somewhat Poor (SP)	(1, 2, 2)	Low (LW)	(3, 4, 4)
Medium High (MH)	(4, 5, 5)	Medium Low (ML)	(2, 3, 3)	Acceptable (AC)	(4, 5, 5)
High (HI)	(6, 7, 7)	Medium (MD)	(3, 4, 4)	Somewhat High (SH)	(6, 7, 7)
Very High (VH)	(8, 9, 10)	Medium High (MH)	(4, 5, 5)	High (HI)	(7, 8, 8)
		Somewhat Good (SG)	(5, 6, 6)	Very High (VH)	(8.5, 9, 9)
		Good (GD)	(6, 7, 7)	Extremely High (EH)	(9.5, 10, 10)
		Very Good (VG)	(7, 8, 8)		
		Excellent (EX)	(8.5, 9, 9)		
		Distinguished (DI)	(9.5, 10, 10)		

Table 3. Combined weights of criteria

Sub-Criteria	% rating of importance by maintenance experts					Fuzzy weights of sub-criteria
	LW	MD	MH	HI	VH	
SC_{11}	3	3	16	40	38	(6.14, 7.14, 7.52)
SC_{12}	3	6	21	37	33	(5.82, 6.82, 7.15)
SC_{13}	5	6	24	32	33	(5.64, 6.64, 6.97)
SC_{14}	3	5	24	42	26	(5.66, 6.66, 6.92)
SC_{15}	11	7	25	32	25	(5.06, 6.06, 6.31)
SC_{16}	4	6	29	28	33	(5.60, 6.60, 6.93)
SC_{17}	2	5	18	28	47	(6.26, 7.26, 7.73)
SC_{21}	5	2	37	19	37	(5.62, 6.62, 6.99)
SC_{22}	5	11	31	27	26	(5.16, 6.16, 6.42)
SC_{23}	7	12	34	23	24	(4.90, 5.90, 6.14)

To rate contractors with respect to criteria for the international steel company, Hammudah [10] surveyed three outsourcing DMs; one maintenance manager, one quality manager, and one finance manager from the company. We present three scenarios to combine the DMs' ratings of contractors' documents against criteria: (Section 4.1) Agreement among the three DMs on one evaluation as in [10], (Section 4.2) independent evaluations by DMs, and (Section 4.3) evaluation based on sufficient qualification of a contractor. Results obtained in the three sections illustrate the potential change in the final decision due to a change in the rating of the winning contractor with respect to criteria, or change in the way the ratings of the DMs are aggregated.

4.1. Agreement among DMs on one evaluation

As claimed in [10], the three DMs jointly discuss each tender document and agree on a single evaluation against related criteria. The process allows the DMs to discuss and vote on or agree on their evaluations to eliminate possible biases. This eliminates the need for decision aggregation using Equation (3). Essentially, evaluations are assumed to be made for each contractor independently from that of other contractors. Alternatively, the DMs may tend to rank order similar documents from the various contractors and assign the evaluations accordingly. Utilizing scales in Table 2, a step difference between two contractors may significantly influence the overall decision.

Tables 4 and 5 show intermediate and final computations using the proposed Fuzzy-TOPSIS model. The mutual evaluation matrix and the weighted decision matrix (Table 4) illustrate the close competition among the three contractors. Computations show that the three contractors closely scored at the upper range for most benefit criteria. Moreover, the contractors were elected similarly for a number of criteria. Consequently, Table 5 shows that the three contractors arrived at the same distance from the FPIS and similarly from the FNIS for these sub-criteria. As a result, SC_{15}, SC_{16}, SC_{17}, and SC_{23} had no effect on selecting the best contractor.

Table 4. Weighted normalized fuzzy decision matrix

Sub-Criteria	Rating of contractor			Normalized weights of contractor			FPIS	FNIS
	A	B	C	A	B	C		
SC_{11}	EX	DI	VG	(5.22, 6.43, 6.77)	(5.83, 7.14, 7.52)	(4.30, 5.71, 6.02)	(7.52, 7.52, 7.52)	(4.30, 4.30, 4.30)
SC_{12}	EX	EX	VG	(5.50, 6.82, 7.15)	(5.50, 6.82, 7.15)	(4.53, 6.06, 6.36)	(7.15, 7.15, 7.15)	(4.53, 4.53, 4.53)
SC_{13}	SG	VG	GD	(3.53, 4.98, 5.23)	(4.94, 6.64, 6.97)	(4.23, 5.81, 6.10)	(6.97, 6.97, 6.97)	(3.53, 3.53, 3.53)
SC_{14}	VG	DI	VG	(3.96, 5.33, 5.54)	(5.38, 6.66, 6.92)	(3.96, 5.33, 5.54)	(6.92, 6.92, 6.92)	(3.96, 3.96, 3.96)
SC_{15}	DI	DI	DI	(4.81, 6.06, 6.31)	(4.81, 6.06, 6.31)	(4.81, 6.06, 6.31)	(6.31, 6.31, 6.31)	(4.81, 4.81, 4.81)
SC_{16}	DI	DI	DI	(5.32, 6.60, 6.93)	(5.32, 6.60, 6.93)	(5.32, 6.60, 6.93)	(6.93, 6.93, 6.93)	(5.32, 5.32, 5.32)
SC_{17}	DI	DI	DI	(5.95, 6.90, 7.73)	(5.95, 6.90, 7.73)	(5.95, 6.90, 7.73)	(7.73, 7.73, 7.73)	(5.95, 5.95, 5.95)
SC_{21}	LW	HI	AC	(4.22, 4.97, 6.99)	(2.11, 2.48, 3.00)	(3.37, 3.97, 5.24)	(6.99, 6.99, 6.99)	(2.11, 2.11, 2.11)
SC_{22}	SH	LW	AC	(2.21, 2.64, 3.21)	(3.87, 4.62, 6.42)	(3.10, 3.70, 4.82)	(6.42, 6.42, 6.42)	(2.21, 2.21, 2.21)
SC_{23}	VL	VL	VL	(0.03, 0.06, 6.14)	(0.03, 0.06, 6.14)	(0.03, 0.06, 6.14)	(6.14, 6.14, 6.14)	(0.03, 0.03, 0.03)

Table 5. Separation of each alternative from the FPIS and the FNIS

Sub-criteria	Distance from FPIS for contractor			Distance from FNIS for contractor		
	A	B	C	A	B	C
SC_{11}	1.53	1.00	2.30	1.96	2.63	1.28
SC_{12}	0.97	0.97	1.70	2.09	2.09	1.38
SC_{13}	2.51	1.19	1.79	1.29	2.80	2.03
SC_{14}	2.10	0.90	2.10	1.20	2.45	1.20
SC_{15}	0.88	0.88	0.88	1.13	1.13	1.13
SC_{16}	0.95	0.95	0.95	1.19	1.19	1.19
SC_{17}	1.06	1.06	1.06	1.28	1.28	1.28
SC_{21}	1.98	4.48	2.90	3.49	0.56	2.23
SC_{22}	3.76	1.80	2.65	0.63	2.96	1.80
SC_{23}	4.98	4.98	4.98	3.53	3.53	3.53
Total	20.723	18.216	21.315	17.780	20.618	17.055
Relative closeness to the ideal solution				Contractor		
				A	B	C
				0.462	0.531	0.444

The relative closeness to the ideal solution, Table 5 clearly distinguishes "Contractor B" with the highest score of 0.531. The obtained result is consistent with that obtained by Hammudah [10] since the study captures the most critical criteria and utilizes similar joint ratings. Although "Contractor B" was least favorable with respect to project cost, SC_{21}, many of the technical qualities of "Contractor B" outperformed that of the other two contractors and hence qualified them to win the tender. It is worth mentioning here that the final decision does not change if a "Very High" (VH) weight is assigned to the cost criteria SC_{21} and SC_{22} that least favor "Contractor B." Further investigations of cost criteria show that SC_{22} played a higher role in deciding the winning contractor. That is, if the documents of "Contractor A" showed that their "Financial obligations of the owner" (SC_{22}) are "Very Low" (VL), then "Contractor A" would have won the tender. The same argument is true for Contractor C. Similarly, if the documents of "Contractor B" showed that their "Financial obligations of the owner" (SC_{22}) are "Very High" (VH) or "Extremely High" (EH), then "Contractor A" would have won the tender.

4.2. Independent evaluations by DMs

In this scenario, each of the three DMs separately evaluates contractors' documents against related criteria. The process allows the

Table 6. Inputs and evaluations for the first experiment

Contractor A			Contractor B			Contractor C			Distance from FPIS for contractor			Distance from FNIS for contractor		
DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3	A	B	C	A	B	C
VG	EX	DI	EX	DI	DI	GD	VG	EX	1.96	1.38	2.49	2.75	3.02	2.13
VG	EX	DI	VG	EX	DI	GD	VG	EX	1.87	1.87	2.36	2.63	2.63	2.04
MH	SG	GD	GD	VG	EX	SG	GD	VG	3.10	1.95	2.49	2.01	3.32	2.65
GD	VG	EX	EX	DI	DI	GD	VG	EX	2.27	1.25	2.27	1.98	2.81	1.98
EX	DI	DI	EX	DI	DI	EX	DI	DI	1.19	1.19	1.19	1.47	1.47	1.47
EX	DI	DI	EX	DI	DI	EX	DI	DI	1.29	1.29	1.29	1.56	1.56	1.56
EX	DI	DI	EX	DI	DI	EX	DI	DI	1.45	1.45	1.45	1.70	1.70	1.70
AC	LW	VL	VH	HI	SH	SH	AC	LW	5.69	6.98	5.70	4.03	0.00	4.03
HI	SH	AC	AC	LW	VL	SH	AC	LW	6.41	5.23	5.23	0.01	3.70	3.70
LW	VL	VL	LW	VL	VL	LW	VL	VL	5.00	5.00	5.00	3.54	3.54	3.54
									30.231	27.585	29.465	21.674	23.753	24.806
Relative closeness to the ideal solution												Contractor		
												A	B	C
												0.418	0.463	0.457

DM to introduce her/his own expertise and/or bias in the evaluations without any influence from other DMs. This necessitates decision aggregation using Equation (3). Essentially, the DM may separately evaluate documents for each contractor, or assign the evaluations in association with similar documents from other contractors. Using Table 2, Equation (3) allows the capture of the widening fuzziness in the joint evaluations of the DMs that may impact the final decision.

Since no data are available in [10] on the individual ratings of the company DMs, several combinations of ratings were tested. In the first set of experiments, all ratings were addressed similarly for all contractors. For each contractor, one TFN or a DM rating was fixed, and the other two TFNs were engineered to indicate a one scale "better" and a one scale "worse" rating. Although the scenarios widen the fuzziness of ratings, results favored "Contractor B" as illustrated in Table 6. Obtained results narrowed the gap between "Contractor B" and "Contractor C."

The second set of experiments was carried out to imbed uncertainty in the evaluations of the documents of "Contractor B" only. This aims at finding the minimum level of uncertainty necessary to change the final decision that favors "Contractor B." To this end, two scenarios are investigated. In the first scenario, the ratings of the three DMs are set equal to it in Table 4 for "Contractor A" and "Contractor C," the ratings of one DM are set equal to it in Table 4 for "Contractor B," and the ratings of the other two DMs are set one TFN below the original ratings in Table 4 for "Contractor B." As illustrated in Table 7, results favored "Contractor A" with a relative closeness to the ideal solution of 0.484 and placed "Contractor B" second with a relative closeness to the ideal solution of 0.48.

In the second scenario, the ratings of the three DMs are set equal to it in Table 4 for "Contractor A" and "Contractor C," the ratings of two DMs are set equal to it in Table 4 for "Contractor B," and the ratings of the last DM are set two TFNs below the original ratings in Table 4 for "Contractor B." As illustrated in Table 8, results favored "Contractor A" with a relative closeness to the ideal solution of 0.522 and placed "Contractor B" last with a relative closeness to the ideal solution of 0.47.

Table 7. Inputs and evaluations for the first scenario of the second experiment

Contractor A			Contractor B			Contractor C			Distance from FPIS for contractor			Distance from FNIS for contractor		
DM1	**DM2**	**DM3**	**DM1**	**DM2**	**DM3**	**DM1**	**DM2**	**DM3**	**A**	**B**	**C**	**A**	**B**	**C**
EX	EX	EX	EX	EX	DI	VG	VG	VG	1.53	1.42	2.30	1.96	2.37	1.28
EX	EX	EX	VG	VG	EX	VG	VG	VG	0.97	1.59	1.70	2.09	1.83	1.38
SG	SG	SG	GD	GD	VG	GD	GD	GD	2.51	1.66	1.79	1.29	2.51	2.03
VG	VG	VG	EX	EX	DI	VG	VG	VG	2.10	1.28	2.10	1.20	2.20	1.20
DI	DI	DI	EX	EX	DI	DI	DI	DI	0.88	1.22	0.88	1.57	1.40	1.57
DI	DI	DI	EX	EX	DI	DI	DI	DI	0.95	1.33	0.95	1.67	1.49	1.67
DI	DI	DI	EX	EX	DI	DI	DI	DI	1.06	1.50	1.06	1.82	1.62	1.82
LW	LW	LW	VH	VH	HI	AC	AC	AC	1.98	4.63	2.90	3.71	0.69	2.45
SH	SH	SH	AC	AC	LW	AC	AC	AC	3.76	2.39	2.65	0.63	2.68	1.80
VL	VL	VL	LW	LW	VL	VL	VL	VL	4.98	5.00	4.98	3.54	3.54	3.54
									20.722	22.010	21.314	19.475	20.338	18.749
												Contractor		
Relative closeness to ideal solution												**A**	**B**	**C**
												0.484	0.480	0.468

Table 8. Inputs and evaluations for the second scenario of the second experiment

Contractor A			Contractor B			Contractor C			Distance from FPIS for contractor			Distance from FNIS for contractor		
DM1	**DM2**	**DM3**	**DM1**	**DM2**	**DM3**	**DM1**	**DM2**	**DM3**	**A**	**B**	**C**	**A**	**B**	**C**
EX	EX	EX	VG	DI	DI	VG	VG	VG	1.53	1.92	2.30	1.96	2.31	1.28
EX	EX	EX	G	EX	EX	VG	VG	VG	0.97	1.95	1.70	2.70	2.35	1.94
SG	SG	SG	SG	VG	VG	GD	GD	GD	2.51	2.05	1.79	1.29	2.48	2.03
VG	VG	VG	VG	DI	DI	VG	VG	VG	2.10	1.76	2.10	1.20	2.15	1.20
DI	DI	DI	VG	DI	DI	DI	DI	DI	0.88	1.64	0.88	2.28	2.01	2.28
DI	DI	DI	VG	DI	DI	DI	DI	DI	0.95	1.79	0.95	2.46	2.17	2.46
DI	DI	DI	VG	DI	DI	DI	DI	DI	1.06	2.01	1.06	2.70	2.38	2.70
LW	LW	LW	EH	HI	HI	AC	AC	AC	1.98	4.70	2.90	3.88	0.83	2.63
SH	SH	SH	SH	LW	LW	AC	AC	AC	3.76	2.89	2.65	0.63	2.58	1.80
VL	VL	VL	AC	VL	VL	VL	VL	VL	4.98	5.00	4.98	3.54	3.54	3.54
									20.722	25.716	21.314	22.655	22.788	21.876
												Contractor		
Relative closeness to the ideal solution												**A**	**B**	**C**
												0.522	0.470	0.507

Table 9. Inputs and evaluations for the third experiment

Contractor A			Contractor B			Contractor C			Distance from FPIS for contractor			Distance from FNIS for contractor		
L	M	H	L	M	H	L	M	H	A	B	C	A	B	C
9	10	10	9	10	10	9	10	10	1.17	1.17	1.17	1.48	1.48	1.48
9	10	10	9	10	10	9	10	10	1.12	1.12	1.12	1.43	1.43	1.43
1	2	2	9	10	10	9	9	10	5.89	1.11	1.23	0.65	5.72	5.50
9	10	10	9	10	10	9	10	10	1.06	1.06	1.06	1.39	1.39	1.39
9	10	10	9	10	10	9	10	10	1.02	1.02	1.02	1.33	1.33	1.33
9	10	10	9	10	10	9	10	10	1.11	1.11	1.11	1.41	1.41	1.41
9	10	10	9	10	10	9	10	10	1.24	1.24	1.24	1.53	1.53	1.53
1	1	2	9	10	10	2	2	3	2.42	6.32	4.16	5.26	0.14	2.44
9	10	10	1	1	2	2	2	3	5.81	2.22	3.81	0.13	4.86	2.26
1	1	2	1	1	2	1	1	2	2.13	2.13	2.13	2.92	2.92	2.92
									22.977	18.518	18.068	17.540	22.224	21.695
												Contractor		
Relative closeness to the ideal solution												A	B	C
												0.433	0.545	0.546

4.3. Sufficient qualification of a contractor

Prior to tendering, project owners are required to set their expectations regarding the qualities of an acceptable contractor that they think is qualified to complete the job successfully. Therefore, if all tendering contractors are below expectation, project owners may disqualify all contractors and look for a new alternative contractor. Consequently, the project owners may qualify a contractor with expected qualities over another with superior qualities and a contractor with qualities beyond need if their price is "right." To illustrate, a contractor with a capacity of 20 technicians is as qualified for the job as another with a capacity of 50 technicians if only 10 technicians are needed to complete the job.

In this scenario, we utilize three ratings; "below expectations," "within expectations" and "above expectations" to prevent qualifying a superior contractor at a high price. Therefore, each contractor document is scaled against the expectations of the project owners for that document. In this evaluation, a contractor's document that shows a quality beyond expectations, regardless of its magnitude, is given a slight advantage over another that shows a quality within the expectations. On the other hand, a contractor's document that shows a quality below expectations, regardless of its magnitude, is given a significant disadvantage over another that shows a quality within expectations. For benefit criteria, TFNs for "below expectations," "within expectations" and "above expectations" are set to (1, 2, 2), (9, 9, 10), and (9, 10, 10) respectively, and the reference (expected) benefit rating is set at "GD" (6, 7, 7). That is for all criteria, contractors who originally scored "VG" or better will be assigned a TFN of (9, 10, 10), contractors who originally scored "GD" will be assigned a TFN of (9, 9, 10), and contractors who originally scored "SG" or worse will be assigned a TFN of (1, 2, 2). For cost criteria, (9, 10, 10), (2, 2, 3) and (1, 1, 2) are used respectively for "above expectations," "within expectations" and "below expectations" respectively, and the reference (expected) cost rating is set at "AC" (4, 5, 5). That is for all criteria, contractors who originally scored "SH" or worse will be assigned a TFN of (9, 10, 10), contractors who originally scored "AC" will be assigned a TFN of (2, 2, 3), and contractors who originally scored "LW," or "VL" will be assigned a TFN of (1, 1, 2).

As expected, most of the documents show that each of the contractors has qualities superior to that required or expected at the corresponding criteria. As illustrated in Table 9, results slightly favor "Contractor C" (with a relative closeness to the ideal solution of 0.546) over "Contractor B" (0.545) and "Contractor A" (0.433). Let us replace "Contractor A" by a hypothetical contractor "Contractor AA" with all of their evaluations "within expectation" levels of (9, 9, 10) for benefit criteria and (2, 2, 3) for cost criteria. Results do not favor "Contractor AA" over "Contractor C." Moreover, results do not favor "Contractor AB," a hypothetical contractor with all of their evaluations for benefit criteria at "above expectation" level of (9, 10, 10) and at "within expectation" (2, 2, 3) for cost criteria, over "Contractor C." On the other hand, results favor "Contractor AC," a hypothetical contractor with all of their evaluations for benefit criteria at "within expectation" level of (9, 9, 10) and at "below expectation" (1, 1, 2) for cost

4.4. Discussion

In the case study in this section, the three contractors, "Contractor A," "Contractor B," and "Contractor C," were prequalified following the screening process by the company. This indicates that minor differences may favor one contractor over another when evaluating their contract documents. Following the process of deciding on the decision criteria that are more fit to the company among the many suggested by experts, three company DMs were elected to rate the documents of contractors against decision criteria. Sections 4.1 through 4.3 experimented with several decision-making scenarios that differently rate and/or combine ratings from the DMs, where results show a major change in the final decision for each scenario.

In Section 4.1, all DMs were required to discuss and agree on a single rating per document per contractor. In this experiment, results clearly distinguished "Contractor B" for their superior qualities even though "Contractor B" had the highest tendering cost. Obtained results were consistent with Hammudah [10] where experts agree to provide single crisp ratings. The section discusses several scenarios that may qualify another contractor as a result in change in the ratings of some of the documents. Therefore, DMs are advised to test scenarios that may highly impact their decision, especially if it may result in cost savings without jeopardizing the quality of the work.

In Section 4.2, the original ratings of "Contractor B" in Section 4.1 are challenged by introducing disagreements among DMs. In this experiment, each DM evaluates documents independently and provides a separate rating per document per contractor. The study tested several forms of disagreements among the DMs by introducing inferior and/or superior ratings of contractors with respect to criteria. In the first scenario, ratings were engineered such that one-scale inferior, original, and one-scale superior ratings were used for criteria. Results, as expected, favored “Contractor B” since they were rated “DI” in most of the benefit criteria and were rated “HI” in their worst cost criteria. In the second scenario, all of the ratings of “Contractor A” and “Contractor C” are set equal to original ratings. For “Contractor B,” one rating of is set equal to the original, and the other two ratings were set one-scale inferior to the original for all criteria. Results slightly favored “Contractor A” over “Contractor B,” which shows a form of disagreement among DMs that may result in a significant change in the decision. The last scenario, also, sets ratings of “Contractor A” and “Contractor C” to original. For “Contractor B,” two ratings were set equal to the original, and the third was set two-scales inferior to the original. Results significantly favored “Contractor A” over “Contractor B,” who came last. The scenario shows the significance of the “odd” rating that might be biased by the trade of the DM while evaluating documents from different trades. It is common to see such forms of disagreements among DMs in the many studies in the literature where clusters of evaluations may be highly influenced by one or more outliers, which can be clearly seen through computed TFNs. Therefore, although disagreements are healthy, data must be cleaned, and clear outliers must be excluded.

Section 4.3 introduces a new scale to narrow the chances of favoring a contractor with superior qualities that will not significantly benefit the project owner. In a job setting, if a worker with two years of experience is considered qualified to complete the job, there will be no significant advantage to hiring a worker with more than two years of experience, especially at a higher rate of pay. In this scenario, ratings are set to slightly favor a contractor with qualities superior to expected, while it largely penalizes the one with inferior qualities. Since all contractors in the study were prequalified, many scored similarly for most of the criteria. The results of the scenario favored “Contractor C” over the other two contractors mainly for their ratings in cost criteria. The change of the results calls upon DMs to look back to the screening stage where they might disqualify a contractor solely because others provided better documents.

5. Conclusion

The paper presents a Fuzzy-TOPSIS decision-making model for selecting maintenance contractors based on the quality of submitted tender documents. The model allows multiple DMs with different influences to use linguistic (Fuzzy) assessments to arrive at a common decision. The proposed model is applied to a case study from the literature [10]. Several decision scenarios are tested, where each result qualified a different contractor for the job. Results obtained from the study scenarios illustrate a potentially major change in the decision based on the way the decision-making process is performed. This calls upon DMs to better address uncertainties in their ratings to avoid crisp over- or under-rating of qualities and costs. Moreover, DMs must ensure a healthy disagreement to reduce potential biases and to prevent outsourcing mistakes, including tendering an over-qualified contractor at a higher cost. Since only three DMs and three contractors were included in the study, future work will focus on conducting real-life experiments that will include more DMs and more contractors. Moreover, future studies may utilize AHP, or ANP to captures dependencies, to obtain results based on relative comparisons. Furthermore, future studies will be conducted around several forms of disagreement among the DMs to better embed and control biases.

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