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Developing fuzzy expert system for supplier and subcontractor evaluation in construction industry

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Evaluation.

Abstract. Increasing competition in the global market to gain customer satisfaction and maximize profitability has been a challenge in the last decade for many construction corporations. In recent years, Supply Chain Management (SCM) has been introduced as one of the most effective approaches in the construction industry literature; further, the first step in SCM implementation is supplier evaluation and thus finding and resolving its weaknesses. In this regard, this research identified the criteria for evaluation of two types of suppliers in the construction industry (first, material and equipment suppliers named suppliers, and second, service suppliers named subcontractors) and their fuzzy membership functions, distinctly, through literature review, questionnaire survey, and statistical analysis of expert judgment. Since most of them are linguistic parameters, fuzzy approach through Mamdani's inference mechanism has been utilized to develop a new methodology of fuzzy expert system. Thus, the developed expert system would evaluate and select the subcontractors and suppliers, distinctly, through three main criteria which are Quality, Cost, and Work relations history-timely delivery. The developed system was tested in three major companies and the results revealed significant performance improvement of these construction companies.

1. Introduction

Nowadays, strong competitive pressure forces many companies to make strategic changes. Construction companies purify their organization, decrease their organizational vertical hierarchy, concentrate on specific activities, and provide their requirements with outsourcing. In the previous decades, companies have found that cooperation with the factories and service companies in the fields of collaboration, planning, and execution is vital. Therefore, companies can share technologies and planning information using the development of a vertical coalition of the organizations within the supply chain [1]. Rapid changes in environment convinced organizations to establish highly flexible, agile supply chains and prepare a fast response to evolutions. In this sequence, an effective supplier evaluation and selection is essential [2]. Guffin et al. believe that at the present time, the purchase is considered as a strategic task instead of the technical one. This can be assigned to the appreciable influence of suppliers on the success or failure of a firm. Hence, the process of purchasing should meet the following requirements: 1) Definition of criteria for supplier-selection; 2) Decision-making in supplier-selection; and 3) Evaluation of supplier performance [3]. Banki et al. presented that increasing the number of bidders would decrease the prices in tendering and purchase activities of construction firms [4]. Selecting suppliers and subcontractors depends just on tendering price and this would be risky and result in project failure; therefore,

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it is essential to evaluate based on multiple criteria to achieve satisfaction of owners. Due to the uncertain nature of construction projects and subjective judgment of the decision-makers, fuzzy decision models are developed for construction contractor selection through utilization of multiple criteria [5,6].

The evaluation of the performance of suppliers in a supply chain is a process to analyze and manage their performance as well as to reduce costs and risk and to maintain continual improvement. The supplier evaluation system enables the organization to:

1. Control and evaluate the performance of suppliers;
2. Employ the same criteria and methodology for the evaluation;
3. Select suppliers in a systematic framework; in other words, to select robust suppliers for long-term cooperation and improve weak suppliers to achieve an acceptable level of performance.

The performance evaluation systems should have three main characteristics:

1. They should be systematic;
2. They have to be integrated with other systems in the organization;
3. They should be efficient and applicable.

In traditional models, performance evaluation system is only based on the efficiency and production cost control. At the present time, due to the unpredictable changes in the work environment and managerial challenges, companies are involved in a competition which forces them to consider non-financial factors [7]. Chien-Ho et al. developed a Subcontractor Performance Evaluation Model (SPEM) by employing Evolutionary Fuzzy Neural Inference Model (EFNIM) [8].

Construction companies have close relationships with two groups of suppliers, namely suppliers and subcontractors. The first group supply materials, equipment, and machineries and the second group supply services. Therefore, evaluation of both suppliers seems essential. This study aims to develop a fuzzy expert system for evaluation and selection of suppliers based on the required criteria of the organization. First, the methodology is described; then, performance criteria are specified through literature review and expert judgment; next, the architecture of the system is represented; afterwards, fuzzy system membership functions and rules are described; and finally, the implementation results are presented.

1.1. Supply chain

Several definitions have been proposed in the literature. A system in which the raw suppliers, production processes, distributors, and customers are regulated in one direction and information flow in the other, which are related to each other and are called the supply chain [9]. In some cases, it includes pecuniary flow [10]. Indeed, supply chains include all the activities related to material flow and transformation, from the raw material preparation phase to customer product delivery phase. In correlation with material flow, there are also two other types of flow: information flow and financial resources flow or pecuniary flow [1]. Supply chain management is strategic; it provides the systematic trade coordination between companies and makes use of any correlated trade process which leads to performance improvement of each and every company and their supply chain [11]. Nowadays, supply chain improvement through partnership is widely known as an effective tool.

1.2. Supplier performance evaluation criteria

Supplier-selection decisions are very complicated because of various factors that must be considered in the decision-making process. Many researchers pointed out that the numbers and types of criteria totally depend on the corporate policy, objectives, and strategies [4,5,8,12,13]. Hence, in this research, the performance criteria are defined by reviewing literature and obtaining expert's knowledge. According to the studies carried out by Neely et al.[14,15], the favorable criteria should:

1. Be based on the organizational strategy;
2. Be simply understood;
3. Provide precise feedback;
4. Be based on the quantities which can be controlled by users;
5. Represent the business process - in other words, both client and supplier contribute to define them;
6. Be related to the organizational goals;
7. Be compatible;
8. Be a part of the management loop;
9. Be clearly defined;
10. Have distinct effects;
11. Focus on the development;
12. Be valid within the time;
13. Provide fast feedback;
14. Provide one definite goal.

The problem of determination of the supplier-selection criteria has been the focus of a significant amount of studies since 1960s [2,3,5-8,16-13,17,18]. Dickson presented 23 supplier-selection criteria, including [17,18]: (1) net price, (2) capability to provide all quality characteristics, (3) quality of maintenance

Table 1. Performance criteria as short term effect and capability criteria as long term effect on the achievement of the supply chain.

Capability factors	Performance factors
Quality systems for operation with the place/quality philosophy of the supplier	Ability to meet delivery promise/delivery lead time/consistent delivery
Financial capability of the supplier	Price
Technological capability/R&D capability	Quality/reliability of the product
Reputation for integrity/believability and honesty/vendor's image	Management sensitivity to requirements of the buyer/attitude
Management sensitivity to requirements of the buyer/attitude	After-sales support/the available technical support
Performance awards/performance history	Positive attitudes towards complaints
Bidding procedural compliance	
Profitability of suppliers	
Breadth of product line/ability of a supplier to supply a number of items	
Proximity of the supplier/geographic location	
Management and organization	
Contribution to productivity	
Conflict resolution	
Production facilities and capacity	
Communication openness	
Labor problems at the supplier's place	
Business volume/amount of past business	

services, (4) timely delivery, (5) geographical location, (6) financial stability, (7) production facilities, (8) commercial experience, (9) technological capability, (10) managing and organizing, (11) possible future purchases of each vendor, (12) employing communication system, (13) operational controls, (14) position of the vendor in industry, (15) work relations history, (16) organizational ethics, (17) job motivation, (18) complaint and warranty policies, (19) capabilities of product packaging, (20) rate of influence on the contact, (21) possibility to satisfy the educational demands, (22) improvement of the procedures, and 23) performance history.

Garvin explained the performance criteria in detail. He suggested the most dominant factors including: quality, cost, timely delivery, services, and flexibility [19].

Sarkar et al. divided the criteria of performance as short term effect and those of capability as long term effect on the achievement of the supply chain (Table 1) [16].

1.3. Fuzzy expert system

In recent years, expert systems or knowledge-based systems have been the focus of a significant amount of studies. These studies declare that expert system processes knowledge while other software processes data and information [20]. Expert systems are one of the most practical fields of the artificial intelligence that implicate a collection of the understandings and regulations in a special field and ultimately simulate the abilities of experts in specific problem domains [21]. These are some powerful and flexible tools which can solve many problems that could not be solved by traditional methods.

Fuzzy expert system is a knowledge-based system which uses fuzzy logic instead of Boolean logic in its knowledge-base and conclusions are made based on user inputs and fuzzy inference [22].

Further, some well-known methods such as partial completeness [23], optimized association rules [24], and CLIQUE [25] divided the qualitative attributes into many crisp partitions. Since there are no interactions between the partitions, this division does not seem favorable for linguistic and qualitative parameters; for example, if we tried to partition the range (70, 80) of the "COST" parameter for a supplier into two partitions, then the separable point would not be different between 75.01 and 74.99. Hence, interaction with any of the neighbor partitions can be promised. Moreover, we considered that the fuzzy association rules described by the natural language were well suited for thinking about human subjects. They enhance the flexibility of users in making decisions or designing the fuzzy systems for agility evaluation. Thus, a fuzzy partition method has been employed to find the fuzzy association rules [26]. Marsh et al. utilized the combination of fuzzy logic and expert system to evaluate contractors. Expert rules were used to capture the expert's reasoning and fuzzy logic and model both subjective and objective factors [12]. The characteristics of the developed fuzzy expert system are described in greater details in the next section.

2. Research methodology

The first step in the evaluation of supplier performance is to select the evaluation approach and then the evaluation criteria which should be identified [27]. The proposed method and criteria should have the following features:

1. They should have a logical basis;
2. They should have adequate acceptance in the work environment;
3. The required information and tools should be handy;
4. They should provide the possibility for review and continuous improvement.

In the developed expert system, the authors covered all the above steps; thus, after modeling the fuzzy expert system for evaluation of the suppliers, the criteria were specified by investigating a vast area of literature after holding several justification sessions with many experts to persuade them to cooperate in this research. Some meeting sessions were organized by a group of 14 construction industry managers (construction experts) and 6 university professors (fuzzy logic experts); the average age and average experience of the construction experts were almost 47 and 19 years, respectively, and for the fuzzy logic experts 44 and 17 years, respectively. By gaining benefit of one set of questionnaires and two sets of statistical analyses, the criteria were finalized and the membership functions were specified by the experts. Next, the fuzzy logic algorithms were developed by coding the rules using Mamdani's inference engine; after testing and confirming the results by the experts, the expert system was developed and the preparation phase was completed.

After final preparation of the fuzzy expert system, the validation and verification steps were performed in three major construction companies. These steps are mentioned in Section 4.

2.1. Supplier and subcontractor evaluation criteria

It is clear that effective and efficient application of evaluation criteria in the organizations requires acceptance by the users. On the other hand, applying different criteria is influential in the results. Furthermore, linguistic and fuzzy variables may have an appreciable influence on the decision-making process [7]. In this research, after collecting the criteria mentioned in the literature for supplier evaluation, the authors implemented two phases of criteria evaluation. In these phases, the chosen criteria were classified and filtered by the experts and the resulted criteria and their membership functions were analyzed through one set of questionnaires and two statistical analyses. At last, two final groups of criteria with their membership functions were specified, distinctly, for evaluation of suppliers and subcontractors. The two evaluation phases are mentioned in the following sections.

2.1.1. Evaluation phase

In this phase, the whole collected criteria (over 82 criteria) were evaluated by 20 experts. There were two meeting sessions for achieving this goal. In the first session, the research goals, plan, and collected criteria were presented to the experts; the authors wanted the experts to survey the criteria and prepare their preferred list with priorities for the next session. In the second session, the lists of experts were gathered and the rating was scaled and averaged; then, the compatibility of high-score criteria with construction industry was specified; thus, after improving compatibility between criteria and the construction industry, 19 criteria were chosen as essential criteria for the construction industry to post-evaluate in the next phase. These chosen criteria were classified in four groups, including quality, price, timely delivery, and flexibility.

2.1.2. Post-evaluation phase

In this phase, 18 criteria were classified in two groups for evaluation and selection of suppliers and subcontractors, distinctly. Then, the evaluation algorithm of the developed fuzzy expert system was presented.

Table 2. Selected criteria for suppliers.

Level 1 (overall evaluation)	Level 2	Level 3	Level 4
Supplier grade (material & equipment)	1) Quality	1- Process quality	1. System evaluation score
			2. Adaptation with standards
			3. Ability to improve quality
		2- Products quality	4. Products quality (return from customer)
			5. After-sale service quality
			6. Quality of initial materials
	2) Cost	7. Superiority of purchase costs compared to other suppliers	—
		8. Superiority of transportation costs compared to other suppliers	
		9. Flexibility in payment condition and discount	
	3) Work relations history and timely delivery	10. Company capabilities and proper flexibility in the timely delivery	—
		11. History of successful cooperation	
		12. Capacity	

After consideration of inference algorithm and investigation within criteria, 12 criteria were selected as the final essential criteria for each group of suppliers and subcontractors (including 5 common criteria), distinctly, which will be presented in the next section. For improvement in evaluation results, the experts suggested to merge flexibility criterion into all other three criteria and further combine timely delivery with work relations history. Thus, the final 12 criteria were classified in three groups of quality, cost, and timely delivery-work relations history, in which there were some flexibility-related sub-criteria. The criteria for both groups are illustrated in Tables 2 and 3.

After the agreement of experts with these 19 criteria, one questionnaire was circulated among them and the numbers in the range of values for each linguistic term in regard to the trapezoidal membership functions needed for the fuzzy inference engine were specified for each final criterion by the experts; the values and membership functions were finalized after statistical analysis for utilization in the expert system, which will represented in the next sections.

2.2. System architecture

Appropriate system architecture would lead to facilitation of the development process. System architecture specifies system components and their interaction with each other [28]. As it is shown in Figure 1, the proposed system architecture includes three main and two subsidiary modules. The main modules are as follows:

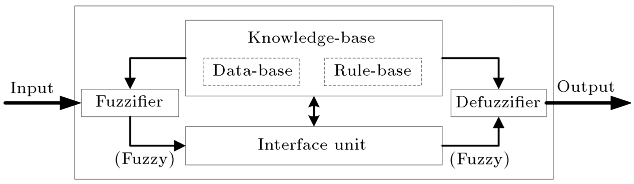

Figure 1. System architecture which include three main and two subsidiary modules.

- Fuzzy inference engine: a module which analyzes and interprets the rules, membership functions, and data in the database and logically concludes a result. There are several fuzzy inference engines; in this research, Mamdani's inference engine, which is suitable for capturing expert knowledge, has been utilized. It allows us to describe the expertise in a more intuitive, more human-like manner. In the following paragraphs, the fuzzy logic operations and Mamdani's inference engine mechanism are represented:

Fuzzy logic operations:

Fuzzy union operation or fuzzy OR:

$$\mu_{A+B}(x) = \max\left(\mu_A(x), \mu_B(x)\right).$$

Fuzzy intersection operation or fuzzy AND:

$$\mu_{A.B}(x) = \min\left(\mu_A(x), \mu_B(x)\right).$$

Table 3. Selected criteria for subcontractors.

Level 1 (overall evaluation)	Level 2	Level 3	Level 4
Supplier grade (service)	1) Quality	1- Process quality	1. Knowledge level and skills of the personnel 2. Certificates and standards of activity 3. Ability to improve quality
		2- Service quality	4. Service quality 5. Relevant background 6. Quality of initial materials
	2) Cost	7. The superiority of the service costs compared to other suppliers 8. Capabilities in minimizing waste of stuff and optimizing machinery consumption 9. Flexibility in payment condition	—
	3) Work relations history and timely delivery	10. Subcontractor capabilities and proper flexibility in the timely delivery 11. History of successful cooperation 12. Ethics	—

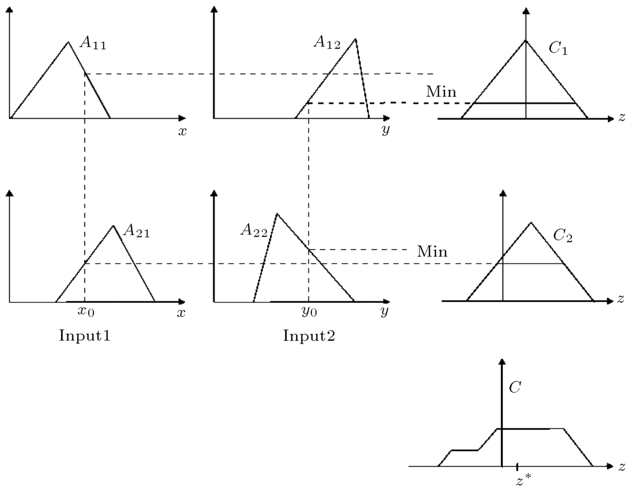

Figure 2. Mamdani inference mechanism.

Mamdani [30] uses the following mechanism (Figure 2):

- Rule 1: If input1 is A_{11} and input2 is A_{12} THEN output is C_1;
- Rule 2: If input1 is A_{21} and input2 is A_{22} THEN output is C_2;
- Fact: Input1 is x_0 and input2 is y_0 consequence: output is C.

The fuzzy implication is modeled by Mamdani [30] as:

$$A \text{ AND } B \rightarrow C = (A \cap B) \cap C.$$

The firing levels of the rules, denoted by αI, $i = 1, 2$, are computed by:

$$\alpha_1 = A_{11}(x_0) \cap A_{12}(y_0) = \min\{A_{11}(x_0), A_{12}(y_0)\},$$

$$\alpha_2 = A_{21}(x_0) \cap A_{22}(y_0) = \min\{A_{21}(x_0), A_{22}(y_0)\}.$$

The individual rule outputs are computed by:

$$C'_1(z) = \alpha_1 \cap C_1(z) = \min\{\alpha_1, C_1(z)\},$$

$$C'_2(z) = \alpha_2 \cap C_2(z) = \min\{\alpha_2, C_2(z)\}.$$

Then, the overall system output is computed by:

$$C(z) = C_1^{©}(z) \cup C_2^{©}(z) = \max\left\{C_1^{©}(z), C_2^{©}(z)\right\}.$$

- User interface: Users of the proposed fuzzy expert system are decision-makers who input the real value of each linguistic variable into the system through a user interface. However, user interface displays the grade and scores of producers and also offers the required guidelines for making a contract.
- Fuzzy rule base: This module includes two parts, namely data and rules, which provide a mechanism for sort fuzzy rules. These fuzzy rules are conditional statements which are represented as follow [29].

  If x is X_i and y is Y_i, THEN o is O_i., in which x and y are linguistic input variables; X_i and

Y_i are their linguistic quantities which have been determined for a fuzzy function. Similarly, o and O_i are respectively the fuzzy output variables and quantities [30].

In this fuzzy system, real values are employed for scoring suppliers. As a result, the system has two subsidiary modules. Firstly and foremost is a fuzzifier in the input that converts real variable to fuzzy set. In this research, we used trapezoidal membership functions which are based on the advices of experts and their reflections on their knowledge. Secondly is a defuzzifier in the output that converts the fuzzy set to a real value [31]. For defuzzifing, we used Center Of Gravity (COG) method which finds the geometrical center of the output variable.

$$Z^* = \left(\sum z.\mu_c(z)\right) / \left(\sum \mu_c(z)\right).$$

3. The proposed fuzzy expert system

The fuzzy expert system employs linguistic characteristics for the evaluation of factors such as quality, cost, flexibility, and work relations history. Then, these factors are merged by fuzzy inference and after conducting an overall evaluation, they are assigned to one of the grades A, B, C, D, or E according to the obtained scores. By clicking on each block, the system asks a series of questions about that block from the user. The consulting process is very user-friendly. Users can select a crisp within the range of 0-10 for each characteristic. Afterwards, the fuzzyfier converts the crisp variables into a fuzzy set which can be employed by fuzzy rule-base system and Mamdanis' inference engine for the evaluation of three criteria to determine the supplier grade. The fuzzyfier performs the fuzzification process using trapezoidal fuzzy membership functions (with low, medium, and high trapezoidal functions) available in the knowledge-based system. It should be noted that the above fuzzy functions have been determined separately for each characteristic, as mentioned in Section 2.1.2.

As shown in Table 4, the inference process is a combination of three stages (four levels) in this fuzzy expert system. After receiving input through level 4, the first stage of fuzzy inference begins and transfers the results to the higher stage within two sections cent X and cent Y. Fuzzy inference engine uses cent X

Table 4. Fuzzy inference stages for the evaluation of suppliers.

Level 1 (overall evaluation)	Stage 3	Level 2	Stage 2	Level 3	Stage 1	Level 4
Supplier grade	Fuzzy inference	1) Quality	Fuzzy inference	1- Process quality 2- Products quality	Fuzzy inference	1. System evaluation score 2. Adaptation with standards 3. Ability to improve quality 4. Products quality (return from customer) 5. After-sale service quality 6. Quality of initial materials
		2) Cost	Fuzzy inference	7. Superiority of purchase costs compared to other suppliers 8. Superiority of transportation costs compared to other suppliers 9. Flexibility in payment condition and discount	-	-
		3) Work relations history and timely delivery	Fuzzy inference	10. Company capabilities and proper flexibility in the timely delivery 11. History of cooperation 12. Capacity	-	-

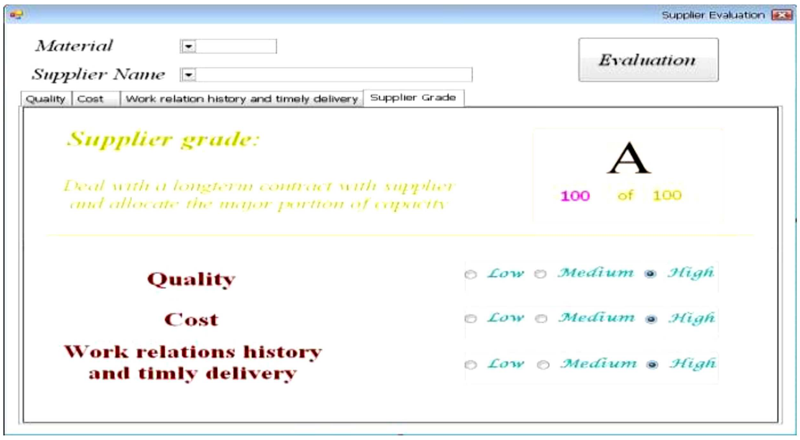

Figure 3. Fuzzy expert system for evaluation and selection of suppliers.

and cent Y to sort results of the previous level (within low, medium, or high) and transfer these sorted results to the upper level for the next fuzzy inference stage. Finally, through exchange of two final levels, the results of level 2 (within low, medium, or high) are sent to the inference engine and the final result will be determined at level 1, within very low, low, medium, high, and very high (Table 4).

Since software development has a high level of importance in the design of expert systems, an attempt is made in the present study to develop user-friendly software.

At the end, after inputting the information on all criteria, the final grade of the supplier as well as the required guidelines for making a contract with the supplier and the obtained scores by the company are displayed in the block. In addition, the condition of three main criteria is also displayed (Figure 3). The followings are some of the advantages of the proposed expert system:

1. The knowledge-base is reliable and easy to employ;
2. This system is cost-effective;
3. It can be utilized in different situations at the same time;
4. Reportage is easy by it;
5. It provides the possibility of analysis and interpretation of the results during the process and, accordingly, educates the experts.

3.1. Membership functions

A Membership Function (MF) is defined as a curve in which each input point is mapped by a membership value (or degree of membership) between 0 and 1; MFs play crucial role in the overall performance of fuzzy systems. The nature of problems determines shape of MFs; in this regard, triangular or trapezoidal shapes are simple to implement and fast for computation. In this research, the defined fuzzy MFs aim to utilize the knowledge of the experts. Therefore, trapezoidal MFs are chosen based on the judgment of experts; they believe that trapezoidal shape could better represent their objectives by the selected criteria and simplify and facilitate the judgment process.

A trapezoidal membership function is formulated, as follows, with four parameters a, b, c, and d:

$$\mu_F(x:a,b,c,d)=\begin{cases}0, & \text{if } x<a\\ (x-a)/(b-a), & \text{if } a\le x\le b\\ 1, & \text{if } b<x<c\\ (d-x)/(d-c), & \text{if } c\le x\le d\\ 0, & \text{if } d<x\end{cases}$$

A questionnaire survey was made to specify a, b, c, and d parameters for each criterion of membership function. After averaging and statistical analysis, the final results were classified and similar results were specified. Therefore, based on similarities, for facilitating the judgment process, experts decided to arrange trapezoidal input functions in four classes (Table 5); each criterion related function is shown in Table 6. Figures 4-8 illustrate the membership functions related to the variable; classes A, B, C, D; and output variables, respectively.

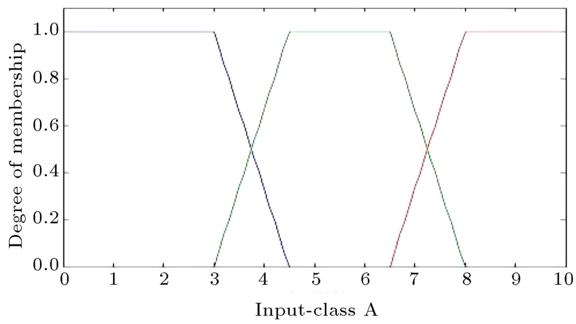

Figure 4. Input trapezoidal fuzzy MF (class A).

Table 5. Four classes of trapezoidal membership functions.

Linguistic variables	Fuzzy trapezoidal membership function (class A)	Fuzzy trapezoidal membership function (class B)	Fuzzy trapezoidal membership function (class C)	Fuzzy trapezoidal membership function (class D)
High	(6.5, 8, 10, 10)	(7.5, 8.5, 10, 10)	(8.5, 9.5, 10, 10)	(9, 9.8, 10, 10)
Medium	(3, 4.5, 6.5, 8)	(4.5, 5.5, 7.5, 8.5)	(6.5, 7.5, 8.5, 9.5)	(7, 8, 9, 9.5)
Low	(0, 0, 3, 4.5)	(0, 0, 4.5, 5.5)	(0, 0, 6.5, 7.5)	(0, 0, 7, 8)

Table 6. Classification of the criteria for suppliers within four classes of trapezoidal membership functions.

Class	Criteria
A	History of cooperation, and ability to improve quality.
B	Capacity, system evaluation score, adaptation with standards, quality of initial materials, superiority of purchase costs compared to other suppliers, and superiority of transportation costs compared to other suppliers.
C	Company capabilities and proper flexibility in the timely delivery, flexibility in payment condition and discount, and after-sale service quality.
D	Products' quality (return from customer).

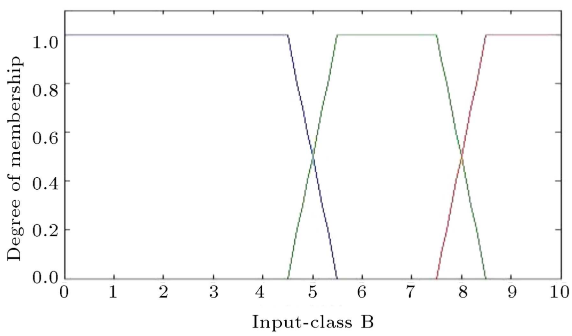

Figure 5. Input trapezoidal fuzzy MF (class B).

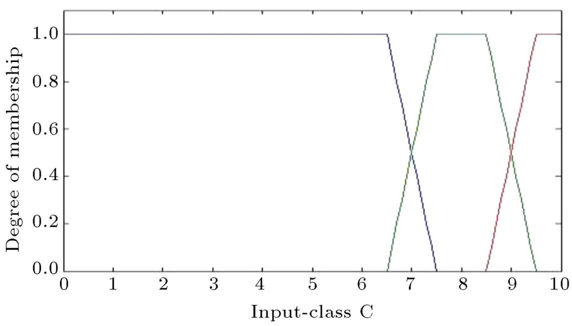

Figure 6. Input trapezoidal fuzzy MF (class C).

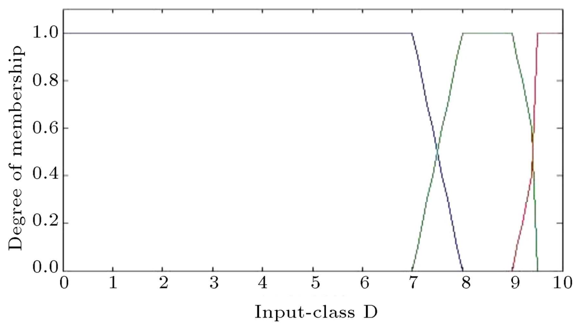

Figure 7. Input trapezoidal fuzzy MF (class D).

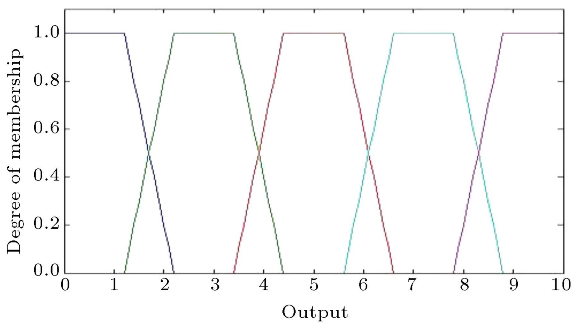

Figure 8. Output trapezoidal fuzzy membership function.

3.2. Description of fuzzy system rules

As stated before, the developed fuzzy expert system utilizes rules-data base and Mamdanis' inference engine for data inference. Since several parameters have been used for the evaluation of suppliers in this research, a great number of rules are ready to be fired in the system. Further, all the mentioned rules are presented symmetrically.

In this system, by arranging and subdividing each general parameter in the duplex and triplex groups,

Table 7. 27 rules of inference in a triplex group.

Rule's number	Ability to improve quality	Adaptation with standards	System evaluation score	Process quality
1	High	High	Fine	High
2	Hight	High	Medium	High
3	High	High	Weak	High
4	High	Medium	Fine	High
5	High	Medium	Medium	High
6	High	Medium	Weak	Medium
7	High	Low	Fine	High
8	High	Low	Medium	Medium
9	High	Low	Weak	Weak
10	Medium	High	Fine	High
11	Medium	High	Medium	High
12	Medium	High	Weak	Medium
13	Medium	Medium	Fine	High
14	Medium	Medium	Medium	Medium
15	Medium	Medium	Weak	Weak
16	Medium	Low	Fine	Medium
17	Medium	Low	Medium	Weak
18	Medium	Low	Weak	Weak
19	Low	High	Fine	High
20	Low	High	Medium	Medium
21	Low	High	Weak	Weak
22	Low	Medium	Fine	Medium
23	Low	Medium	Medium	Weak
24	Low	Medium	Weak	Weak
25	Low	Low	Fine	Weak
26	Low	Low	Medium	Weak
27	Low	Low	Weak	Weak

through combining them in the next levels and using fuzzy inference at each stage, the final evaluation result of each supplier will be determined.

Thus, at each triplex group, the system receives three inputs (in the form of low or medium or high states). Accordingly, there are 27 rules as well as 3 inputs for result inference, which are presented for one triplex group shown in Table 7.

In a similar way, the other triplex criteria groups have 27 registered rules in the rule base. As it is cited in Tables 2 and 3, the system involves a duplex criteria group including 9 rules. These groups for suppliers are represented in Table 8.

Inference of the last stage resulted in supplier grade. The difference between the inference of the three criteria of the group in the last stage and that of other groups lies in the division of the results into five categories, i.e. very low, low, moderate, high, and very high (E, D, C, B, and A). In other words, after changing the name of parameter in Table 4, output of rows 1, 2, 4, and 10 became very high and that of rows 18, 24, 26, and 27 turned into very low. It should be noted that for the sake of better determination of supplier grade in the last stage, the score of each reasoning was represented in a round number within 1:100 which was computed from deffuzification.

4. Implementation of fuzzy expert system

The presented expert system has been tested and used in three construction companies for three years. The obtained results from a fuzzy expert system were compared with those from the AHP expert system (which was designed by the authors, before) and validation of the results was approved by the experts. As a sample, the authors represent the application of fuzzy expert system for the selection and evaluation of vendors and subcontractors in three projects of one of the construction companies. The projects are introduced in Table 9.

Table 8. Triplex and duplex criteria groups for suppliers.

Inference result	Three criteria groups and two criteria groups
Supplier grade	1. Quality 2. Cost 3. Work relations history- timely delivery
Work relations history and timely delivery	1. Company capabilities and proper flexibility in the timely delivery 2. History of cooperation 3. Capacity
Cost	1. Superiority of purchase costs compared to other suppliers 2. Superiority of transportation costs compared to other suppliers 3. Flexibility in payment condition and discount
Quality of products	1. Quality of products (return from customer) 2. After-sale service quality 3. Quality of initial materials
Process quality	1. System evaluation score 2. Adaptation with standards 3. Ability to improve quality
Quality	1. Process quality 2. Quality of products

Table 9. Three projects in which fuzzy expert system was utilized.

Project	Utilization	Location (province-country)
Ofogh tower	Residential	Isfahan-Iran
Aqueduct	Porch water conduit	Isfahan-Iran
Mehr project	Residential in 14 blocks	Isfahan-Iran

In these companies, an overall review was performed on the past processes of subcontractor selection and purchases. Besides, the current and previous strategies of the company in regard to evaluation and selection of suppliers were determined by utilizing the available documents and performing a number of interviews. There were three clear strategies in the evaluation process of the company:

1. The supplier who has offered the lower price is preferable;
2. It is advisable to avoid dealing with a single supplier, which increases the risk parameter in project accomplishment;
3. It is recommended not to work with too many suppliers, because the supply chain management may get out of control.

The developed fuzzy expert system covers all the above three strategies. In other words, it deals with cost strategy through selecting the cost as a primary parameter. In addition, it considers two other strategies by presenting some guidelines and approaches in relation to how to make a contract with an evaluated supplier. Utilization of the developed fuzzy expert system in each construction company resulted in collection of a classified archive of powerful suppliers in different fields. The above-mentioned

Table 10. Evaluation of steel framework subcontractors.

Producer	Grade	Score	Recommendation
Supplier 1	A	85	Deal with a long term contract and allocate the major part of capacity
Supplier 2	B	81	Deal with a short term contract and allocate the major part of capacity
Supplier 3	B	68	Deal with a short term contract and allocate the major part of capacity

Table 11. Evaluation of steel framework subcontractors.

Framework contractor	Grade	Score	Recommendation
Contractor 1	B	79	Deal with a short term contract in a major project
Contractor 2	B	77	Deal with a short term contract in a major project
Contractor 3	B	69	Deal with a short term contract in a major project
Contractor 4	C	56	Deal with a short term contract in a minor project
Contractor 5	C	53	Deal with a short term contract in a minor project
Contractor 6	C	42	Deal with a short term contract in a minor project
Contractor 7	D	31	No deal

archive includes a wide range of supplier information such as technical specifications, capabilities, services or materials that they can provide, cost and product quality (service quality), and other specified criteria. As two examples, results of evaluation and selection of some steel framework producers and steel framework subcontractors (without mentioning their names) are presented in Tables 10 and 11.

5. Conclusion

In regard to the point that increases in the efficiency and service quality of suppliers and subcontractors strongly affect the performance of clients, revenue, and satisfaction, civil companies have increasingly employed SCM in recent years. Therefore, the evaluation and selection of the right supplier and subcontractor are crucial for construction projects. There are so many complaints in the literature on traditional supplier-selection based on the lowest tender price. Therefore, the first step in supplier evaluation and selection would be specifying the evaluation criteria. In this research, the criteria were specified through 3 phases. First, the literature was reviewed and the related supplier evaluation and selection criteria were gathered, comprehensively; next, the criteria database was transferred to the experts for the pre-evaluation phase; and finally, two sets of 12 criteria were selected, independently, for construction suppliers and subcontractors.

In this research, after specifying the criteria, the authors prepared a multi criteria fuzzy framework by utilizing the judgment of experts for supplier and subcontractor selection. As the proposed performance criteria were linguistic, the fuzzy numbers, membership functions, and fuzzy calculations were utilized to attain the results in a realistic manner. The membership functions which weighted the judgment process were specified through the judgment of experts. Therefore, the system user or client could utilize this facilitated judgment process through assigning his/her own score to each criterion for each supplier and attaining the supplier preferences and the end results.

The developed model was tested in three major construction companies for two years and the improvement results were satisfactory. Nevertheless, some challenges and improvement points exist for the identified system, due to the unique attributes of each construction project and in addition, the different interests and preferences of clients and stakeholders; the unique way of weighting the criteria could be inappropriate for all the circumstances. Therefore, the future research could work on a dynamic approach to involve the clients and main stakeholders in the weighing of criteria in each project, simultaneously. On the other hand, although Mamdani method is widely accepted for capturing expert knowledge, the Mamdani-type fuzzy inference entails a substantial computational burden, so, the future research could be concentrating on other inference mechanisms.

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