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## **A new hybrid supplier selection model**

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**Abstract:** Selecting the right supplier is one of the most challenging tasks for organisations as it essentially reduces purchasing cost and improves corporate competitiveness. This study aims at developing a hybrid model in supplier selection for a non-homogeneous group decision-making process to select a supplier that best satisfies the purchaser. The analytical hierarchy process (AHP), house of quality (HOQ), and linguistic ordered weighted averaging (LOWA) operator are applied in the proposed model. This model is illustrated with a real world example by applying it to a mechanical manufacturing company in Vietnam. It is found that supplier selection does not only depend on a low price offer, but also on supplier's quality, technological capability, capability of on-time delivery, flexibility and good relationship. This study makes new methodological and practical contributions to supplier selection research and applications through development of a hybrid model for non-homogeneous group decision making in supplier selection, and for the first time this study applies the LOWA operator in aggregating linguistic terms of non-homogeneous group decision making in a supplier selection process.

**Keywords:** supply chain management; decision making; supplier selection; analytic hierarchy process; house of quality; HOQ; linguistic ordered weighted averaging; LOWA.

**Reference** to this paper should be made as follows: Nguyen, T.S., Mohamed, S. and Rahman, A. (xxxx) 'A new hybrid supplier selection model', *Int. J. Operational Research*, Vol. X, No. Y, pp.xxx-xxx.

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This paper is a revised and expanded version of a paper entitled 'A hybrid supplier selection model considering non-homogeneous group decision makers' presented at 2016 IEEE International Conference on Industrial Engineering and Engineering Management, Bali, Indonesia, 4–7 December 2016.

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## 1 Introduction

In today's competitive world, one of the most challenging tasks for organisations is to select the 'right' supplier. This involves much more than scanning a series of price lists. It incorporates a wide range of criteria such as quality, reliability, availability, timeliness, associated risks, company's business policies, etc. Supplier selection decisions are often complicated by the fact that diverse criteria must be considered (Karsak and Dursun, 2015); thus, making the evaluation and selection of an appropriate supplier is a complex problem (Cárdenas-Barrón et al., 2015; Büyüközkan and Göçer, 2016). However, it is also critical for organisations to ensure that their supplier selection process is a robust one, as it essentially reduces purchasing cost and improves corporate competitiveness (Ho et al., 2011). In addition, supplier selection directly affects an organisation's business continuity (Rezaei et al., 2016). The main goals of the supplier selection process are to: mitigate purchase risk, maximise value to the purchaser, and build and sustain long-term relationships between suppliers and purchasers (Chen et al., 2006). Hence, selecting a supplier that best satisfies the purchaser is significantly important.

Challenges with supplier selection may be constructed as a group decision-making problem based on the evaluation of multiple criteria – some of which could be conflicting. As such, the consensus is an essential indication of group agreement among the decision makers (DMs) involved in the selection process. Historically, research on supplier selection favours an approach with an overarching focus on homogeneous group decision-making problems where the DMs are indifferent to making a decisions or choices. However, the DMs tend to mirror the pervading viewpoints, opinions and influences unique to their department within the broader organisation, with attendant implications on each selection criteria. Notwithstanding, their impact on the decision may not correlate with their rank/importance and/or influence level; collectively, these attributes are characteristic of stakeholders in a non-homogeneous decision-making group. In such a group, DMs are typically independent of each other in making a decision

and are expected to differ in their opinion. To reflect the real behaviour of the DMs, therefore, a final decision should be made on a significant level of consensus which represents the outcome of the aggregation of the DMs' opinions (Dursun and Karsak, 2013). Only a very few researchers have focused on the non-homogeneous decision-making group in supplier selection (Nguyen, 2014). As a result, *research into a supplier selection considering non-homogeneous decision making is needed*.

Therefore, 'this paper aims to develop a hybrid supplier selection model by combining the analytical hierarchy process (AHP), the quality function deployment (QFD) and the linguistic ordered weighted averaging (LOWA) operator for a non-homogeneous decision-making group'. In this model, the AHP is used to determine the influence weightings of a company function department (CFD). The house of quality (HOQ), as an essential part of the QFD concept, is then applied to transfer company function department requirements (CFDRs) to suppliers' attributes. Finally, the LOWA operator is applied for aggregating the linguistic opinions of the non-homogeneous group. The important weightings of the CFDRs, criteria and final score of suppliers are calculated by applying a mathematical algorithm.

This section has introduced the purpose and approach of a new method of supplier selection. The rest of the paper is structured as follows:

- The methodology section briefly introduces the different components of the proposed model and describes, step by step, how the different components are incorporated in the model.
- The application section demonstrates the model's application in a real-world scenario.
- The results section summarises the outcomes of the numerical application.
- The key outcomes of the research are summarised in the conclusion section.

## 2 Literature review

A comprehensive review has been conducted to examine the published literature on supplier selection. The goal was to determine the most widely reported evaluating criteria, and the methodologies/techniques adopted in supplier selection over time. Table 1 lists and ranks the commonly cited evaluating criteria as quoted by the reviewed 41 journal articles where the criteria are ranked-based exclusively on the frequency of criteria citation in the reviewed articles. 'Price/cost', 'delivery', and 'quality' appear to be the three highest ranked evaluating criteria. Table 1 also provides a snapshot comparison between this literature review and other reviews reported by Ho and Xu (2010), Weber et al. (1991) and Dickson (1966). As shown in Table 1, both 'quality' and 'delivery' have been the most commonly used criteria in supplier selection since 1966. Interestingly, criteria such as 'flexibility', 'relationship', and 'risk', which did not feature explicitly in earlier studies (Dickson, 1966; Weber et al., 1991), have been highlighted in more recent studies.

In addition to the evaluating criteria, several research efforts in the past two decades have focused on supplier selection techniques (SSTs). In this study, the 41 reviewed journal articles were categorised by the reported SST, resulting in six categories, namely;

AHP, analytic network process (ANP), QFD, data envelopment analysis (DEA), and artificial neural networks (ANNs), and fuzzy-based decision approach. About half of the reviewed articles reported applying the fuzzy concepts in supplier selection. However, hybrid decision approaches were the most commonly applied across a majority of all studies.

**Table 1** Evaluating criteria and their ranking

<i>Rank</i>	<i>Dickson (1966)</i>	<i>Weber et al. (1991)</i>	<i>Ho and Xu (2010)</i>	<i>Literature review</i>
1	Quality	Net price	Quality	Price/cost
2	Delivery	Delivery	Delivery	Delivery
3	Performance history	Quality	Price/cost	Quality
4	Warranties and claim policies	Production facilities and capacity	Manufacturing capability	Flexibility
5	Production facilities and capacity	Geographic location	Service	Service
6	Price	Technical capability	Management	Partnership relationships
7	Technical capability	Management and organisation	Technology	Capability
8	Financial position	Reputation	R&D	Technology
9	Procedural compliance	Financial position	Finance	Finance
10	Communication system	Performance history	Flexibility	Management and organisation
11	Reputation	Repair service	Reputation	Environment
12	Desire for business	Attitude	Relationship	Risk
13	Management and organisation	Packaging ability	Risk	Defect rate
14	Operating controls	Operational controls	Safety and environment	Location
15	Repair service	Training aid		Reputation and Experience
16	Attitude	Bidding procedural compliance		Product characteristic
17	Impression	Labour relations record		Demand
18	Packaging ability	Communication system		
19	Labour relations record	Reciprocal arrangements		
20	Geographical location	Impression		
21	Amount of past business	Desire for business		
22	Training aids	Amount of past business		
23	Reciprocal arrangements	Warranties and claims		

As a result of the advantages of the AHP, it is commonly applied in supplier selection. In the comprehensive reviews, Chai et al. (2013) and Ho and Xu (2010) identified the AHP as the most frequently reported SST. Researchers widely use the AHP method to integrate with the Taguchi loss functions (Ordoobadi, 2010), the DEA (Kang and Lee, 2010), the QFD (Bhattacharya et al., 2010; Ho et al., 2011, 2012; Haldar et al., 2012), the structural equation modelling (Punniyamoorthy et al., 2012), the interpretive structure modelling (Parthiban et al., 2012), the technique for order preference by similarity to ideal solution (Zouggari and Benyoucef, 2012; Kannan et al., 2013), and the fuzzy multi-objective linear programming (Shaw et al., 2012, 2013) in supplier selection. The AHP has been applied to diverse application areas, including manufacturing, engineering, industry, management, education, finance, government, personal, social, political and sports, in the last 20 years (Ho et al., 2011). This varied applicability is because of its simplicity, ease of use and flexibility (Ho et al., 2011). Hence, taking the advantages from AHP in supplier selection is robust.

As indicated previously, supplier selection can be seen as a multi-criteria decision-making (MCDM) problem that, in practice, is affected by three factors, namely conflicting criteria, multi DMs and uncertainty (Karsak and Dursun, 2015). To address these factors, extensive studies have been conducted on various MCDM methods for supplier selection (Ho and Xu, 2010; Govindan et al., 2015; Rezaei et al., 2016) in order to address real world decision-making scenarios (Venkatesh et al., 2015).

Research has examined the group decision making for supplier selection mainly in the context of a homogeneous group, but to a much less extent in non-homogeneous group decision making (Dalalah et al., 2011; Ho et al., 2011, 2012; Zouggari and Benyoucef, 2012; Dursun and Karsak, 2013; Dymova et al., 2013; Kannan et al., 2013). In practice, it is admitted that the diverse opinions given by different individuals are not equally important (e.g., reliable) (Herrera et al., 1998). In these circumstances, it is called non-homogeneous group decision-making problem; otherwise it is a homogeneous group (Herrera et al., 1998). Realistic decision-making problems are hard to define because their objectives and parameters are not precisely known. In fact, group decision making is a non-homogeneous group decision-making process because individuals in the group have different attitudes, perception, skill, and knowledge. By considering group decision making as a homogeneous group, however, researchers ignore this fact. Therefore, the final result might be affected by this assumption. The advantage of the model that is developed based on a homogenous group is that it can be easily applied. However, with the development of the information technology, the calculation and application is no longer such an issue, so, therefore non-homogeneous group decision making should be considered in supplier selection process.

Interestingly, the concept of QFD has featured strongly in recent SST studies (Bhattacharya et al., 2010; Ho et al., 2011, 2012; Haldar et al., 2012; Dursun and Karsak, 2013; Palanisamy and Zubar, 2013). In Ho et al. (2011), the QFD is applied to transform the company stakeholder requirements into the evaluating factors for supplier selection. Also, the fuzzy QFD is used to decrease the number of possible suppliers by screening them on certain basic criteria (Palanisamy and Zubar, 2013). Regarding Bhattacharya et al. (2010), by applying the QFD in their model, the DMs can rank suppliers considering both the cost measure factor and the subjective factors. In Dursun and Karsak (2013), the QFD is applied because the purchased activities should satisfy the company's needs, and as seeks to establish the relevant supplier assessment criteria. Therefore, the

HOQ, as an essential part of the QFD concept, should be applied to transfer stakeholders' requirements to suppliers' attributes in supplier selection.

Research demonstrate that the fuzzy concepts are widely used in a supplier selection process (Montazer et al., 2009; Díaz-Madroño et al., 2010; Dalalah et al., 2011; Yu et al., 2012; Dymova et al., 2013; Ghorbani et al., 2014; Liou et al., 2014; Mukherjee, 2016). Fuzzy linguistic terms are used to deal with linguistic group decision-making problems (Hatami-Marbini et al., 2013) that are not precisely known and they are reported in different supplier selection models (Yang et al., 2008; Shih et al., 2009; Amindoust et al., 2012; Ho et al., 2012; Zouggari and Benyoucef, 2012). However, applying the LOWA operator to deal with linguistic terms is still missing in SSTs. In fact, the LOWA operator has proposed to deal with non-weighted linguistic information (Herrera et al., 1998).

Also, many SSTs have been applied in the manufacturing industry (Lin et al., 2010; Ho et al., 2011; Bruno et al., 2012; Palanisamy and Zubar, 2013; Kannan et al., 2013). Palanisamy and Zubar (2013) have developed a hybrid model that employed fuzzy QFD, mathematic modelling and the ANP for supplier selection which is applied to an automotive component manufacturing company in India. Ho et al. (2011) propose an integrated analytical approach, combining the QFD and the AHP approach for supplier selection, in which applied it to a UK-based automobile manufacturing company. Kannan et al. (2013) have developed an integrated model that is applied in an Iranian automobile manufacturing company. However, limitations in previous research require that, a hybrid model for non-homogeneous group DMs in supplier selection in mechanical manufacturing industry should be focused on.

Building on these identified trends and research problems, 'the objective of this paper is to propose a hybrid model for non-homogeneous group decision making in supplier selection'. The model uses the AHP in determining the important weightings of CFDs; then the HOQ, as an essential part of the QFD concept, is applied to transfer CFDs to suppliers' attributes. Finally, the LOWA operator is applied for aggregating the linguistic opinions of the non-homogeneous group. The important weightings of the CFD requirements, criteria and final score of suppliers are calculated by applying a mathematical algorithm.

### **3 Methodology**

In the following subsections, we introduce techniques that are applied in our proposed model, namely: the AHP, QFD, fuzzy linguistic term and LOWA operator. In this model, the AHP is used to determine the influence weightings of a CFDs. In line with Ho et al. (2011), three HOQ are applied to transfer CFD requirements to suppliers' attributes. The LOWA operator is applied for aggregating the linguistic opinions of the non-homogeneous group in each HOQ. The important weightings of the CFD requirements, criteria and final score of suppliers are calculated by applying a mathematical algorithm.

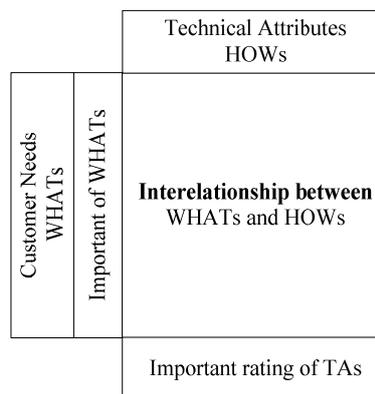
### 3.1 Analytic hierarchy process

Since the introduction of the AHP by Saaty (1980), it has been widely employed in decision-making analysis across a broad range of sectors such as social, political, economic and management sciences (Kang and Lee, 2010). It is a general theory of measurement that depends on individual as well as group values and judgments (Bruno et al., 2012). Kang and Lee (2010) highlight the popularity of the AHP as a choice technique for data analysis and model verifications useful in providing critical information for managers to make business decisions. In this sense, the AHP is a structured technique for handling complex decision problems (Deng et al., 2014). Both quantitative and qualitative factors are combined in the decision-making process. The application of AHP involves six important steps, three of which – as submitted by researchers, especially Ho et al. (2011) – are applied in this proposed model. [Please refer to Ho et al. (2011) for equations and example of calculations]. These steps are: employ pairwise comparisons between decision elements and form comparison matrices; use the eigenvalue method to estimate the relative weights of the decision elements; check the consistency property of matrices to ensure the judgments of DMs are reliable.

### 3.2 Quality function deployment

The QFD is a strategic tool which enables organisation to develop products which satisfy customer requirements (Bhattacharya et al., 2010) by developing better products and services tailored to customer needs (CNs) (Dursun and Karsak, 2013). The main idea of QFD is to translate the requirement of customers into technical attributes (TAs) and, thereafter, into part characteristics, process plans and production requirements (Karsak, 2004). In the proposed model, the focus is on the first and the most widely used of the four matrices; product planning, part deployment, process planning, and production/operation planning, collectively regarded as the HOQ (see Figure 1). Once the CNs, together with the associated influence weighting, and the interrelationship between CNs and TAs are determined, the importance rating of TAs can be calculated (Dursun and Karsak, 2013).

**Figure 1** House of quality



Source: Dursun and Karsak (2013)

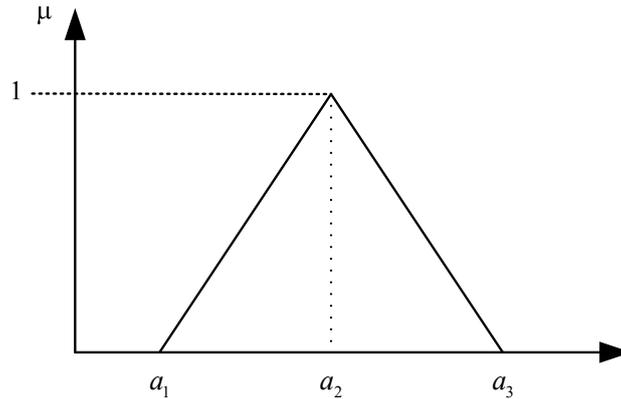
### 3.3 Fuzzy linguistic terms and LOWA operator

#### 3.3.1 Triangular fuzzy number

Among the fuzzy numbers, the triangular fuzzy number is the most common, due to its simplicity in both concept and calculation, and it is widely applied in the MCDM application (Yager, 1988; Yaghoubi and Hajihosseini, 2011; Kannan et al., 2013; Yu and Goh, 2014). As shown in Figure 2, a triangular fuzzy number is represented with three points as  $\tilde{A} = (a_1, a_2, a_3)$ , where  $a_1 < a_2 < a_3$ . A triangular fuzzy number is a convex fuzzy set (Zadeh, 1965), and its membership function is defined as:

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{x - a_1}{a_2 - a_1} & \text{if } a_1 \leq x \leq a_2, \\ \frac{a_3 - x}{a_3 - a_2} & \text{if } a_2 \leq x \leq a_3, \\ 0 & \text{otherwise.} \end{cases}$$

**Figure 2** Triangular fuzzy number  $\tilde{A} = (a_1, a_2, a_3)$



#### 3.3.2 Defuzzification

Defuzzification is the stage which transfers a fuzzy set (output of fuzzy systems) into a crisp output value. Leekwijck and Kerre (1999) review 18 defuzzification methods and classify them into four categories: area method, maxima methods and derivatives, distribution methods, and miscellaneous methods. The next section gives a brief review of centre-of-area (COA), the most commonly used method derived from the first category. The COA method gives a numerical value  $x_0 = x_{COA}(A)$  for a fuzzy set  $A$ , which divides the area under membership function in two approximately equal parts. To deduce the best non-fuzzy performance value (BNP), the COA is a practical and simple method because it does not need to bring in the preferences of any evaluators (Leekwijck and Kerre, 1999; Yang et al., 2008; Lin and Twu, 2012; Qi et al., 2013). Hence, a triangular

fuzzy number  $\tilde{A} = (a_1, a_2, a_3)$  – the crisp output value BNP by COA method – can be calculated by  $BNP(\tilde{A}) = \frac{(a_2 - a_1) + (a_3 - a_1)}{3} + a_1$  or  $BNP(\tilde{A}) = \frac{a_1 + a_2 + a_3}{3}$ .

### 3.3.3 Fuzzy linguistic terms

Linguistic terms have been regarded as intuitively easy-to-use concepts in expressing subjective and imprecise assessments of DMs (Zadeh, 1975a, 1975b). The fuzzy linguistic method, which promotes interaction with qualitative aspects, represented by means of linguistic variables in qualitative terms, provides an important technique for solving decision-making problems in different fields (Zadeh, 1975a). Herrera et al. (2008) point out that in each fuzzy linguistic approach, appropriate linguistic descriptions for the term set and their semantics have to be selected.

The semantics of linguistic terms are represented by the fuzzy numbers defined in  $[0, 1]$  intervals that are usually described by the membership functions. Table 2 presents, for instance, two sets of five linguistic terms represented by triangular fuzzy numbers that are used for fuzzy assessment and the crisp outputs of those fuzzy numbers. A 1 to 9 ratio scale is used as it has been proven an effective measurement scale for reflecting the qualitative information of decision problems (Yeh and Chang, 2009).

**Table 2** Linguistic terms represented by fuzzy numbers

Linguistic terms set 1	Very poor (VP)	Poor (P)	Fair (F)	Good (G)	Very good (VG)
Linguistic terms set 2	Very low (VL)	Low (L)	Moderate (M)	High (H)	Very high (VH)
Fuzzy number	(1, 1, 3)	(1, 3, 5)	(3, 5, 7)	(5, 7, 9)	(7, 9, 9)
Crisp outputs	1.67	3	5	7	8.33

### 3.3.4 LOWA operator

Herrera et al. (1998) proposed the LOWA operator to aggregate non-weighted linguistic information. In a non-weighted linguistic information scenario, only one set of linguistic values is available for aggregation.

*Definition of the LOWA operator:*

Let  $A = \{a_1, \dots, a_m\}$  is a set of labels to be aggregated, then LOWA operator,  $\phi$  is defined as:  $\Phi(a_1, \dots, a_n) = W.B^T = C^m \{w_k, b_k, k = 1, \dots, m\} = w_1 \odot b_1 \oplus (1 - w_1) \odot C^{m-1} \{\beta_h, b_h, h = 2, \dots, m\}$  where  $W = [w_1, \dots, w_m]$ , is a weighting vector, such that:

- 1  $w_i \in [0, 1]$
- 2  $\sum_i w_i = 1, \beta_h = w_h / \sum_2^m w_k, h = 2, \dots, m$  and  $B = \{b_1, \dots, b_m\}$  is a vector associated to  $A$ , such that,  $B = \sigma(A) = \{a_{\sigma(1)}, \dots, a_{\sigma(n)}\}$  where  $a_{\sigma(j)} \leq a^{\sigma(i)} \forall i \leq j$ , with  $\sigma$  being a permutation over the set of labels  $A$ .

$C^m$  is the convex combination operator of  $m$  labels,  $\odot$  is the general product of a label by a positive real number and  $\oplus$  is the general addition of labels defined in Delgado et al. (1993).

If  $m = 2$ , then  $C^2$  is defined as:

$$C^2\{w_i, b_i, i = 1, 2\} = w_1 \odot s_j \oplus (1 - w_j) \odot s_i = s_j, s_i \in S, (j \geq i)$$

where  $S = \{s_i\}, i = (1, \dots, T)$  is a finite and totally ordered label set (Herrera et al., 1998).

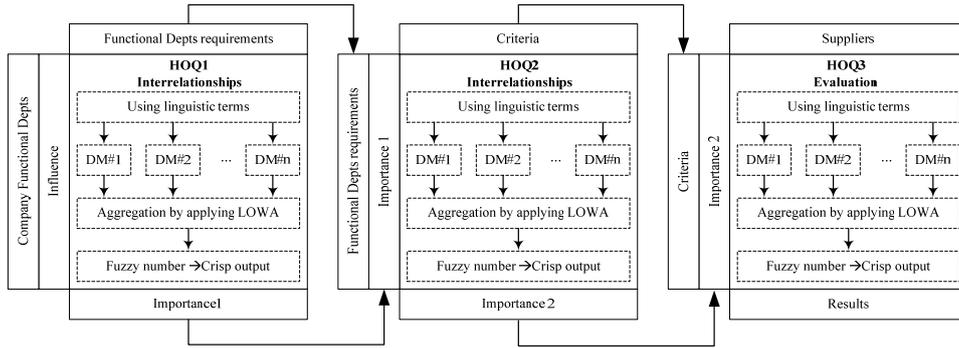
Such that  $k = \min\{T, i + \text{round}(w_1(j - i))\}$ , where ‘round’ is the usual round operation, and  $b_1 = s_j, b_2 = s_i$ .

If  $w_j = 1$  and  $w_i = 0$  with  $i \neq j \forall i$ , then the convex combination is defined as:  $C^m\{w_i, b_i, i = 1, \dots, m\} = b_j$ .

### 3.4 The proposed model

To reflect the non-homogeneous group decision making in supplier selection and to select a supplier that best satisfies the purchaser, a new structured approach is developed as shown in Figure 3. The proposed model can be described as follows: The DMs representing various CFDs and who have independent and unequal influence in the selection process are identified first. Subsequently, the influence (importance) weighting of CFD is determined by DMs using the AHP, assuming that the influence weighting of a particular DM equals the influence weighting of the CFD that he/she represents. The DMs then use the linguistic terms set to identify the interrelationship between CFDs and CFDRs, as well as CFDRs and criteria to evaluate potential suppliers based on a set of evaluating criteria. In each HOQ, the LOWA operator is applied for aggregating the linguistic terms from the DMs to a single linguistic term. The aggregated linguistic terms are transferred to fuzzy numbers for calculating the crisp outputs to compute the important weighting of CFDRs, criteria, and score of suppliers. The following section presents the step-by-step implementation of the proposed model.

**Figure 3** Proposed model for non-homogeneous group in supplier selection



### 3.4.1 Building the first house of quality (HOQ1)

- 1 *Setup HOQ1*: DMs are identified (DMs are representative of the CFDs). Thereafter, the influence weighting of CFDs is determined by using the AHP. Finally, the CFDRs with the detailed descriptions of each requirement are identified.
- 2 *Determine the relationship between CFDs and CFDRs, and calculate the importance weighting of CFDRs*: Firstly, the DMs, using the linguistic terms set 2 (see in Table 2), determine the relationships between the CFDs and CFDRs. Secondly, the linguistic assessments from DMs are aggregated by applying the LOWA operator. Thirdly, the aggregated linguistic terms results are transferred into the fuzzy numbers and then crisp outputs by using Table 2. Finally, the score of each

CFDR is calculated by using the equation:  $S_k = \sum_{j=1}^n w_j * z_{jk}; (k = 1, \dots, p)$ , where  $S_k$

denotes score of the CFDR  $k$ ,  $w_j$  denotes the influence weighting of CFD  $j$ ,  $n$  denotes the number of DMs,  $z_{jk}$  denotes a crisp output which represents the relationship between the CFD  $j$  and CFDR  $k$ . Thereafter, the influence rating of each CFDRs is calculated by using the equation:  $w_k = S_k / \sum_{k=1,p} S_k$  where  $w_k$  denotes the influence rating of CFD requirement  $k$ .

### 3.4.2 Building the second house of quality (HOQ2)

- 1 *Setup HOQ1*: The CFDRs and their influence ratings in the HOQ1 are used as input of the HOQ2. Thereafter, the criteria for the functional requirement of the HOQ2 are identified.
- 2 *Determine the relationship between CFDRs and supplier selection criteria (SSC), and calculate the important weighting of criteria*: Firstly, the DMs, using the linguistic terms set 2, determine the relationships between CFDRs and criteria. Like building HOQ1, the linguistic assessments from DMs are aggregated by applying the LOWA operator. The aggregated linguistic terms results are transferred into the fuzzy numbers and then crisp outputs. Finally, the score for each criterion is

calculated using the equation  $S_x = \sum_{k=1}^p w_k * z_{kx}; (x = 1, \dots, q)$ , where  $S_x$  denotes the

score of criterion  $x$ .  $z_{kx}$  denotes the crisp output that represents the relationship between CFDR  $k$  and criterion  $x$ . Thereafter, the influence rating of each criterion is calculated by using equation  $w_x = S_x / \sum_{x=1,q} S_x$ , where  $w_x$  denotes influence rating of criterion  $x$ .

### 3.4.3 Building the third house of quality (HOQ3)

- 1 *Setup HOQ1*: The criteria and their influence ratings in the HOQ2 are used as input of the HOQ3. Thereafter, potential suppliers are placed as a functional requirement of the HOQ3.

- 2 *Evaluate suppliers based on SSC and suppliers ranking:* Firstly, the DMs, using linguistic terms set 1 (see in Table 2) evaluate the suppliers based on the criteria. Secondly, in the same way as described earlier in building HOQ1 and HOQ2, the LOWA operator is applied, and crisp outputs which represent the evaluation suppliers based on criteria is determined. Finally, the score of each supplier is

calculated using the equation  $S_y = \sum_{x=1}^q w_x * z_{xy}$ ; ( $y = 1, \dots, t$ ), where  $S_y$  denotes the

score of the supplier  $y$ ,  $z_{xy}$  denotes the crisp output that represents the evaluation supply  $y$  based on a criterion  $x$ . After that, suppliers are ranked in order based on the score of suppliers.

#### 4 An empirical application

MMC is a mechanical manufacturing company in Vietnam that regularly procures equipment and raw materials for its production lines. MMC's procurement policy stipulates that the responsibility for supplier selection lies with a committee comprising representatives from various functional departments within MMC. The committee has no fixed membership; it has flexible procedures for substituting members on the committee based on purchase type and value. Committee members, therefore, tend to have unequal powers or influence in the decision-making process, relating directly to the influence level of their functional departments. The main goal of the committee is to select the most appropriate supplier that best meets the CFDRs and criteria.

The proposed model is applied herein to demonstrate its applicability. Four DMs who are executive heads of CFDs at MMC participated in this empirical practice. A total of seven CFDRs applying industry standards (AIS), sustainable development/corporate social responsibility (SDC), electronics transaction capability (ETC), financial stability and company reputation (FCR), quality of product (QOP), risk and safety management (RSM), total cost ownership (TCO), and eight criteria 'price', 'quality', 'delivery', 'flexibility', 'service', 'partnership', 'capability', and 'technology' were identified for evaluating eight potential suppliers.

##### 4.1 Building the first house of quality (HOQ1)

- 1 *Determine the important weighting of CFDs:* The four identified CFDs are; financial control department (FCD), quality control department (QCD), product development department (PDD), and procurement control department (PCD). The executive head (DM) of each department was selected to participate in this process. The influence weightings of CFD are determined by applying the AHP. According to the AHP strategy, the pairwise comparison matrixes are constructed and then the consistency ratios are checked. If the consistency ratios are accepted, the consolidated matrixes are formed. Otherwise, the pairwise comparisons need to be conducted again. The four pairwise comparison matrixes  $A_1, A_2, A_3, A_4$  are constructed;

$$A_1 = \begin{bmatrix} 1 & 1/3 & 1/2 & 2 \\ 3 & 1 & 1 & 3 \\ 2 & 1 & 1 & 1 \\ 1/2 & 1/3 & 1 & 1 \end{bmatrix}; A_2 = \begin{bmatrix} 1 & 1/2 & 1 & 2 \\ 2 & 1 & 2 & 2 \\ 1 & 1/2 & 1 & 2 \\ 1/2 & 1/2 & 1/2 & 1 \end{bmatrix};$$

$$A_3 = \begin{bmatrix} 1 & 3 & 2 & 2 \\ 1/3 & 1 & 2 & 2 \\ 1/2 & 1/2 & 1 & 1/2 \\ 1/2 & 1/2 & 2 & 1 \end{bmatrix}; A_4 = \begin{bmatrix} 1 & 2 & 1 & 3 \\ 1/2 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \\ 1/3 & 1/2 & 1/2 & 1 \end{bmatrix};$$

then a consolidated pairwise comparison matrix is constructed; column vector is calculated as follows:

$$A = \begin{bmatrix} 1 & 1 & 1 & 11/5 \\ 1 & 1 & 7/5 & 11/5 \\ 1 & 5/7 & 1 & 6/5 \\ 4/9 & 4/9 & 5/6 & 1 \end{bmatrix}; \text{column vector } C = \begin{bmatrix} 0.294 \\ 0.318 \\ 0.234 \\ 0.154 \end{bmatrix}.$$

The consistency ratio  $CR = 0.009 < 0.1$ , therefore, the important weighting of FCD (DM 1), QCD (DM 2), PDD (DM 3), and PCD (DM 4) are 0.294, 0.318, 0.234, and 0.154, respectively. As indicated earlier, the influence weighting of DMs is directly related to the influence (importance) weighting of the CFD, which they represent.

- 2 Determine the relationship between CFDs and CFDRs, and calculate the importance weighting of CFDRs: In this step, the four DMs were asked to participate in a simple survey to determine the relationships between the four CFDs and the seven CFDRs by using linguistic terms set 2 (see in Table 2). The results are shown in Table 3.

**Table 3** Estimation of relationship between CFDs and CFD requirements

	<i>AIS</i>	<i>SDC</i>	<i>ETC</i>	<i>FCR</i>	<i>QOF</i>	<i>RSM</i>	<i>TCO</i>
FCD	L, H, M, H	M, L, VL, M	L, VL, L, M	H, VH, M, VH	M, H, H, H	L, M, VL, L	VH, VH, VH, VH
QCD	VH, VH, H, VH	M, H, M, H	M, VL, VL, L	H, H, VH, H	VH, VH, VH, VH	H, H, M, M	L, L, VL, M
PDD	VH, VH, M, H	VH, VH, M, H	L, VL, VL, VL	H, H, M, M	H, VH, VH, H	H, M, M, L	H, H, H, M
PCD	M, L, VL, VL	L, L, VL, M	VL, VL, VL, L	L, M, L, VL	L, H, M, H	VH, VH, M, H	M, M, VL, VL

After that, to aggregate four linguistic terms into one linguistic term, the LOWA operator is applied. In this study, we developed a program which is run in MATLAB R2014a to calculate the LOWA operator. For instance, considering the relationship between FCD and AIS (shown in Table 3), and by means of the LOWA operator we need to aggregate the following labels  $\{L, H, M, H\}$  with the influencing weighting vector (influence weighting of DMs)  $W = [0.294, 0.318, 0.234, 0.154]$ .

The general expression of aggregation of labels is

$$\begin{aligned}\phi(L, H, M, H) &= [0.294, 0.318, 0.234, 0.154](L, H, M, H) \\ &= C^4 \{(0.318, H), (0.154, H), (0.234, M), (0.294, L)\}\end{aligned}$$

Consequently, we obtain the result applying the recursive definition of the convex combination,  $C^4$ , as follows. Firstly, we develop  $C^4$  until its simpler expression is reached in the following steps:

- For  $m = 4$ ,

$$\begin{aligned}& C^4 \{(0.318, H), (0.154, H), (0.234, M), (0.294, L)\} \\ &= 0.318 \odot H \oplus C^3 \left\{ \left( \frac{0.154}{1-0.318}, H \right), \left( \frac{0.234}{1-0.318}, M \right), \left( \frac{0.294}{1-0.318}, L \right) \right\} \\ &= 0.318 \odot H \oplus C^3 \{(0.2258, H), (0.3431, M), (0.4311, L)\}\end{aligned}$$

- For  $m = 3$ ,

$$\begin{aligned}& C^3 \{(0.2258, H), (0.3431, M), (0.4311, L)\} \\ &= 0.2258 \odot H \oplus C^2 \left\{ \left( \frac{0.3431}{1-0.2258}, M \right), \left( \frac{0.4311}{1-0.2258}, L \right) \right\} \\ &= 0.2258 \odot H \oplus C^2 \{(0.4432, M), (0.5568, L)\}\end{aligned}$$

Now, we return to solving the simpler cases until we obtain the final result:

- For  $m = 2$ ,

$$C^2 = \{(0.4432, M), (0.5568, L)\} = 0.4432 \odot M \oplus (1-0.4432) \odot L = L(s_2)$$

Since as  $M = s_3$  and  $L = s^2$  then

$$\min\{4, 2 + \text{round}(0.4432 * (3-2))\} = \min\{4, 2 + \text{round}(0.4432)\} = \min\{4, 2\} = 2$$

- For  $m = 3$ ,

$$\begin{aligned}& C^3 \{(0.2258, H), (0.3431, M), (0.4311, L)\} \\ &= 0.2258 \odot H \oplus C^2 \{(0.4432, M), (0.5568, L)\} = L(s_2)\end{aligned}$$

Since as  $H = s_4$  and  $L = s_2$  then

$$\min\{4, 2 + \text{round}(0.2258 * (4-2))\} = \min\{4, 2 + \text{round}(0.4516)\} = \min\{4, 2\} = 2$$

- Finally, we obtain the result for  $m = 4$ ,

$$\begin{aligned}& C^4 \{(0.318, H), (0.154, H), (0.234, M), (0.294, L)\} \\ &= 0.318 \odot H \oplus C^3 \{(0.2258, H), (0.3431, M), (0.4311, L)\} = M(s_3),\end{aligned}$$

Since as  $H = s_4$  and  $L = s_2$  then

$$\min\{4, 2 + \text{round}(0.318(4-2))\} = \min\{4, 2 + \text{round}(0.636)\} = \min\{4, 3\} = 3$$

Aggregation by means of the LOWA operator labels  $\{L, H, M, H\}$ , with the weighting vector  $W = [0.294, 0.318, 0.234, 0.154]$ , is  $M$  (as shown in Table 4). The aggregated linguistic terms are presented in Table 4.

**Table 4** Aggregated relationship between CFDs and CFD requirements

	<i>AIS</i>	<i>SDC</i>	<i>ETC</i>	<i>FCR</i>	<i>QOF</i>	<i>RSM</i>	<i>TCO</i>
FCD	M	L	VL	H	M	L	VH
QCD	H	M	L	H	VH	M	L
PDD	H	H	VL	M	H	M	H
PCD	L	L	VL	L	M	H	L

Finally, the crisp outputs are calculated from fuzzy numbers, as seen in Table 5, which are transferred from the aggregated linguistic terms in the above step. Finally, by applying weighted average (WA), the important weighting of CFDRs are presented in Table 5.

**Table 5** Importance weighting of CFD requirements

$w_j$		<i>AIS</i>	<i>SDC</i>	<i>ETC</i>	<i>FCR</i>	<i>QOF</i>	<i>RSM</i>	<i>TCO</i>
0.294	FCD	5	3	1.67	7	5	3	8.33
0.318	QCD	7	5	3	7	8.33	5	3
0.234	PDD	7	7	1.67	5	7	5	7
0.154	PCD	3	3	1.67	3	5	7	3
$S_k$		5.796	4.572	2.093	5.916	7.115	4.720	5.503
$w_k$		0.165	0.130	0.060	0.168	0.186	0.134	0.157

#### 4.2 Building the second house of quality (HOQ2)

- 1 *Setup the HOQ2*: The CFDRs and their influence weightings in the HOQ1 are transferred to the HOQ2 and the eight SSC identified in the previous section are used for the 'functional requirement' of the HOQ2.
- 2 *Determine relationship between CFDRs and SSC and calculate the important weighting of criteria*: The same four DMs were asked to participate in another simple survey, where they were asked to determine the relationships between seven CFDRs and eight SSC, by using linguistic term set 2 (as shown in Table 2). Table 6 presents the relationship between CFDRs and SSC by four DMs. Similar to HOQ1, the LOWA operator is applied to aggregate the linguistic terms supplier by four DMs. Thereafter, the crisp outputs and important weighting of criteria are calculated. The important weighting of criteria is shown in Table 6.

**Table 6** Relationship between CFD requirements and criteria, and importance weighting of criteria

	<i>Price</i>	<i>Quality</i>	<i>Delivery</i>	<i>Flexibility</i>
AIS	VH, H, M, H	H, VH, H, VH	H, H, M, M	VL, L, VL, VL
SDC	H, M, M, H	H, H, H, VH	M, L, L, L	H, VH, M, H
ETC	H, VH, H, M	VL, VL, M, VL	VH, VH, H, VH	H, VH, M, H
FCR	H, M, VH, VH	VH, VH, L, H	H, H, M, M	VL, M, L, M
QOF	H, VH, H, H	VH, VH, VH, VH	L, M, VL, L	L, M, VL, VL
RSM	M, H, H, M	H, L, H, M	H, M, VH, M	H, H, M, M
TCO	VH, VH, VH, VH	H, VH, VH, H	H, H, H, H	L, M, M, VL
$w_x$	0.170	0.178	0.129	0.102
	<i>Service</i>	<i>Partnership</i>	<i>Capability</i>	<i>Technology</i>
AIS	L, H, M, H	L, L, VL, VL	L, M, VL, M	H, M, H, VH
SDC	VH, VH, H, H	VH, VH, VH, H	M, VH, VH, H	M, VH, VH, H
ETC	VH, VH, VH, VH	M, H, M, H	H, VH, M, M	H, VH, VH, H
FCR	VH, H, H, H	H, H, H, VH	H, VH, H, H	H, M, H, VH
QOF	H, H, VH, VH	M, VL, VL, M	M, VH, H, H	H, VH, H, VH
RSM	L, H, H, M	L, VL, L, L	VL, L, M, M	M, VH, M, M
TCO	H, H, M, L	L, L, VL, M	H, L, M, H	M, VH, VH, VH
$w_x$	0.165	0.109	0.147	0.170

### 4.3 Building the third house of quality (HOQ3)

- 1 *Setup the HOQ3*: The eight criteria and their important weightings in the HOQ2 are transferred to the HOQ3, and the eight potential suppliers (S1 through to S8) are placed in the ‘functional requirement’ of the HOQ3.
- 2 *Evaluate suppliers based on SSC and suppliers ranking*: The four DMs were asked to evaluate eight suppliers based on eight criteria using the linguistic terms set 1 (as seen in Table 2). Table 7 shows the evaluation of supplier based on eight SSC. After that, the linguistic terms given by the four DMs are aggregated by applying the LOWA operator. The crisp output of evaluations suppliers based on criteria is calculated in the same fashion covered earlier in building HOQ1 and HOQ2. Finally, the score of suppliers is calculated by applying a weighted sum. The score of suppliers is presented in Table 7.

In the above application, the levels of influence of departments at MMC have proven to be different, with the QCD appearing to be the most influential, followed closely by the FCD, then the product control department, and finally the PCD having calculated influence weights of 0.318, 0.294, 0.234, and 0.154, respectively. This outcome indicates that the role of each department in, and its contribution toward, the supplier selection process varies from one department to another.

The functional requirement QOF (i.e., QOP) was identified as the requirement with the highest influence (0.186), followed by other requirements such as; FCR, AIS, TCO, RSM, SDC, and ETC with weights of 0.168, 0.165, 0.157, 0.134, 0.130, and 0.060,

respectively. By deduction, therefore, the results indicate that MMC places a slight premium on the *QOP*. However, it assigns more or less equal weightings to supplier's *financial position and reputation*, and *ability to implement industrial standards* across its supply chain. Conversely, the emphasis on suppliers' *ETC* is relatively weak. The importance weighting was calculated for each and every one of the eight commercial and technical criteria. Based on the calculated values, the top four criteria namely 'quality', 'technology', 'price', and 'service' appear to attract equal weightings despite being assessed differently by various DMs.

**Table 7** Estimation suppliers based on criteria and supplier ranking

	<i>S1</i>	<i>S2</i>	<i>S3</i>	<i>S4</i>
Price	VG, G, VG, G	F, G, G, G	F, F, G, VG	G, VG, G, G
Quality	G, G, G, VG	G, G, G, G	P, G, VG, G	G, VG, G, VG
Delivery	F, F, VG, F	G, P, VG, G	P, G, G, F	F, G, VG, VG
Flexibility	F, P, G, G	G, F, G, F	G, G, F, F	P, F, F, G
Service	G, G, G, VG	VG, VG, VG, VG	F, VG, G, G	P, G, VG, G
Partnership	F, VG, G, G	G, VG, G, G	F, VG, G, G	P, VG, G, G
Capability	VG, VG, VG, VG	G, G, VG, VG	G, G, VG, VG	F, VG, VG, VG
Technology	G, F, G, VG	VG, P, G, G	F, F, VG, G	F, G, VG, G
$S_j$	7.378	7.606	6.691	7.110
Ranking	3	2	5	4
	<i>S5</i>	<i>S6</i>	<i>S7</i>	<i>S8</i>
Price	VG, P, F, G	P, F, P, F	F, F, P, F	F, F, P, G
Quality	VG, P, G, G	F, F, F, G	G, F, G, G	P, F, G, G
Delivery	G, G, G, G	G, G, G, G	P, G, F, G	P, F, F, F
Flexibility	VG, F, F, P	F, G, P, F	F, G, F, F	G, G, G, G
Service	G, F, G, G	G, F, G, G	F, P, G, G	F, G, F, G
Partnership	VG, G, G, G	P, F, G, G	P, F, G, G	F, G, G, G
Capability	VG, VG, VG, VG	F, F, F, F	P, G, F, F	G, G, G, F
Technology	G, G, G, G	P, P, F, G	P, G, G, G	G, F, F, VG
$S_j$	7.712	5.426	5.178	6.088
Ranking	1	7	8	6

Overall, it can be observed that supplier 5 (*S5*) is the highest ranked supplier obtaining a total score of 7.712. Interestingly, *S1* and *S4* have offered more competitive prices than that offered by *S5* but, their overall ranking is second and fourth, respectively. Notwithstanding, its relatively higher price, *S5* appears to compete strongly on criteria such as capability, quality, on-time delivery and technology utilisation.

To verify the developed model, it is assumed that the DMs constituted a homogeneous group and the fuzzy weighted averaging (FWA), which is traditional method for aggregating the assessment from DMs, was applied. Based on the resulting data, an empirically derived score indicated that *S1* outranked other suppliers. The results are presented in Table 8 for comparison only. Noteworthy is the fact that the result in

Table 8 differs from those obtained for a non-homogeneous group. By implication, in similar scenarios, if the difference(s) between levels of knowledge, or influence of the DMs are ignored, and the focus is exclusively on their assessment, the results might not lead to selection of the best supplier.

**Table 8** Score of supplier using a homogeneous group

<i>Suppliers</i>	<i>S1</i>	<i>S2</i>	<i>S3</i>	<i>S4</i>	<i>S5</i>	<i>S6</i>	<i>S7</i>	<i>S8</i>
<i>S<sub>y</sub></i>	8.447	8.304	7.724	8.237	7.985	6.333	6.561	6.914

## 5 Conclusions, limitations and future research

This paper has developed and proposed a new hybrid model for non-homogeneous DMs in a supplier selection process that best satisfies the purchaser. In developing the hybrid model, this study demonstrated a structured procedure based on the AHP, QFD, fuzzy set theory, and LOWA operators. In this model, the AHP has been applied to determine the influence weighting of company functional departments based on their influence in the selection process. The HOQ as a part of the QFD concept has been applied to identify how well each supplier characteristic succeeds in meeting the requirements established for the product/service being purchased. Also, the QFD has been used to determine the important weighting of CFDRs, and criteria, as well as a score for evaluating suppliers. To deal with the subjective judgment of DMs, the linguistic terms represented by triangular fuzzy numbers were used. The LOWA operator has been employed in aggregating the linguistic opinions of the non-homogeneous group decision making. The aggregated linguistic terms were transferred to the fuzzy numbers and then defuzzification was applied to calculate the crisp outputs of fuzzy numbers. The important weightings of CFDRs and SSC, as well as the final score for suppliers, were calculated by applying a mathematical algorithm. Finally, the feasibility of the proposed model was illustrated numerically. To the best of the authors' knowledge, this is the first study in applying the LOWA operator and considering the non-homogeneous group decision making in supplier selection.

### 5.1 Limitation of present study

The proposed hybrid model has addressed the key shortcoming in other reported models where the assumption is made that group members have the same level of influence in the decision-making process. In doing so, a number of well-established techniques have been adopted in developing the model. One of these is the 'COA' defuzzification technique which is proven to give rise to crisp outputs, but may also result in information loss.

The paper has the same limitations as all other MCDM research, including the verification of the model output. There may well also be an application gap in the geographic region because the paper applied the model in a single company located in Vietnam.

## 5.2 Managerial implications

To select the ‘appropriate’ supplier, managers should be able to capture selection criteria not only within their own units but also among other units with different and competing criteria, as well as various levels of influence. This means that traditional models of supplier selection, based on homogenous decision making, have their limitations, as these are not adequate to address the real behaviour of the DMs in the process. Another important managerial implication is the requirement for every DM to express their views and feel that their views are recognised as input in the process.

## 5.3 Future research

This paper has highlighted the following areas worthy for future studies. Further study might look into the robustness of the model itself and whether, due to the internal calculations and many multiplications, small changes in some numbers would lead to notable influence on results. Another study could explore and expand using the fuzzy linguistic ordered weighted averaging (FLOWA) operator in aggregating the linguistic terms from non-homogeneous group decision making to avoid the loss of information in using the COA defuzzification approach.

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