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成果報告

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供應鏈彈性評估之互動式群體決策模式

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供應鏈彈性評估之互動式群體決策模式

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Abstract

With rapidly intensifying global competition shifting to the supply chain level, the flexibility of supply chain has increased importance. However, the availability of the literature addressing supply chain flexibility is still limited to date. So the objective of this study is to build a group decision-making structure model of flexibility in a supply chain development. In this paper, a framework for evaluating supply chain flexibility is presented, which includes two parts, one is an evaluation hierarchy with flexibility dimensions and related metrics, the other an evaluation scheme with three stages to identify the evaluation results of supply chain flexibility. Then the paper proposes an algorithm for determining the degree of supply chain flexibility using a fuzzy linguistic approach. While evaluating the degree of supply chain flexibility, one may find the need for improving supply chain flexibility, and determine the dimensions of supply chain flexibility as the best direction to improvement. Additionally, an example using a case study is used to illustrate the availability of the proposed methods.

Keywords: Supply chain; Supply chain flexibility; Group decision-making; Fuzzy linguistic approach; Interactive consensus analysis

摘　要

快速白熱化的全球化競爭達到供應鏈層次，供應鏈彈性的策略性功能日益重要。然而，供應鏈彈性的相關文獻卻相當有限。本文提出一種供應鏈彈性的群體決策模式；其中，提出一個供應鏈彈性的評估架構，涵蓋有一個供應鏈彈性的評估層級，以及一個三階段的評估程序；同時，運用模糊語意法，提出一個演算法，來確認供應鏈彈性的程度，不僅可以發現供應鏈彈性的改善需求，更可以協助群體決策者確認最適合的供應鏈彈性的改善維度。在個案分析中，藉由個案研究來說明本法的應用過程，以及群體評估的合理性。

關鍵字： 供應鏈；供應鏈彈性；群體決策；模糊語意法；互動式共識分析

1. Introduction

Recently, the concept of supply chain (SC) has been receiving considerable attention from both practitioners and researchers. Generally, a SC is a network of suppliers, manufacturers, distributors, and retailers, through which raw materials are required, transformed, produced, and delivered to the end consumer [Ahn *et al.,* 2003]. Thus a SC involves the complex flow of materials, products, services, information, and money across multiple functional areas within and among the complex hierarchies of all the participating enterprises. As competition intensified and markets became global, organizations began to realize that it is not enough to improve efficiencies within an organization, but their whole SC has to be made competitive [Agarwal *et al.,* 2006; Ahn *et al.,* 2003; Gong, 2008; Li *et al.,* 2005; Pujawan, 2004]. It has been pointed out that the flexibility often viewed as a reaction to environmental uncertainty [Gupta and Goyal, 1989; Swamidass and Newell, 1987]. Enterprises with the desirability of certain system properties, such as flexibility, agility, etc., are more able to cope with increased environmental uncertainty, adapt to the fast pace of change of today's markets, and react with the smaller windows of opportunity for decision-making [Giachetti *et al.,* 2003]. The flexibility is required for SC to meet continuously changing, unpredictable requirements in global marketplace, and enhance organizational competitiveness [Duclos *et al.,* 2003; Garavelli, 2003; Sanchez and Perez, 2005; Vickery *et al.,* 1999].

With rapidly intensifying global competition shifting to the supply chain level, the flexibility of supply chain has increased importance. As stated by Roa and Wadhwa [2002] and Vickery *et al.* [1999], the supply chain flexibility (SCF) is emerging as one of the key competitive priorities for the future. Lummus *et al.* [2003] identified that SCF is important for several reasons. First, recent trends, such as mass customization, require SC to meet individual customer requirements without adding significant cost. Companies are allowing customers to provide specific product information needs and are producing product for that specific customer. Mass production efficiencies are required quantities of one. Second, certain industries, particularly high-tech, require upside and downside flexibility. This generally refers to the ability to increase or decrease production (by 20% or more) in a minimal amount of time to a new unplanned level of production and then being able to sustain the new level. Third, in many innovative product categories, such as fashion apparel and electronic devices, uncertainty of demand is a fact of life and creating a responsive SC is one method of avoiding uncertainty. And last, the ever-changing environment in which companies find themselves requires new product introduction, quick response to customer requirements in all parts of the world, and fast turn-around on customer orders. Lummus et al. [2005] also proposed SCF is important in today's global market place; companies compete globally and are networked globally. Some empirical studies have showed a positive relation between a superior performance on SCF and firm performance, although flexibility dimensions are not equally important for firm performance [Sanchez and Perez, 2005; Vickery *et al.,* 1999]. Practicing managers must evaluate SCF when making capital investment decisions and measuring performance level. Despite its importance, the availability of the literature addressing SCF is still limited to date [Gong, 2008; Lummus *et al.,* 2003; Pujawan, 2004; Roa and Wadhwa, 2002], and so the needs of management have not yet been met.

Many reviews on flexibility have been from the viewpoint of a manufacturing system as a single entity in a SC [Beach *et al.,* 2000; De Toni and Tonchia, 1998; Sarker *et al.,* 1994; Sethi and Sethi, 1990; Vokurka and O'Leary-Kelly, 2000]. Only several researchers paid their attention on flexibility in the context supply chains [Garavelli, 2003; Gong, 2008; Lummus *et al.,* 2003, 2005; Pujawan, 2004; Roa and Wadhwa, 2002; Sanchez and Perez, 2005; Vickery *et al.,* 1999]. Vickery *et al.* [1999] proposed five supply chain flexibilities obtained from an integrative, customer-oriented perspective: product, volume, launch (or new product introduction), access (or distribution), and target market (or responsiveness to target market) flexibility. Roa and Wadhwa [2002] proposed a conceptual framework for SCF based on the interdependencies between products, transformations, processes, and resources. In an attempt to develop a model of SCF, Lummus *et al.* [2003, 2005] focused on the cross-functional, cross-enterprise nature of SCF, and identified five dimensions of SCF include operations systems, logistics process, supply network, organizational design, and information systems flexibility. Garavelli [2003] provided two dimension of SCF, and considered nine configurations of SC network resulted from the combination of the degrees of supplier and assembler flexibility, i.e., no flexibility, limited flexibility and total flexibility, respectively. Pujawan [2004] presented a framework for assessing flexibility of a SC, and identified four flexibility dimensions: product delivery system, production system, product development, and supply system flexibility. Sanchez and Perez [2005] provided a framework of SCF dimensions that includes ten dimensions: product, volume, routing, delivery, trans-shipment, postponement, sourcing, launch, response, and access flexibility. Gong [2008] proposed that a SCF model is developed comprising labor, machine, routing, and information technology flexibility, with total system flexibility measured by an economic index. However, these researches are tried theoretically or objectively to quantify SCF. The subjective assessment for both grade of importance and rating of performance for SCF dimensions and related metrics have seldom been addressed.

Most managers (or experts) cannot provide exact numerical values to express opinions, based on perception, on flexibility metrics, more realistic evaluation uses linguistic assessments instead of numerical values [Beach *et al.,* 2000; Herrera and Herrera-Viedma, 2000; Lummus *et al.,* 2005; Sanchez and Perez, 2005]. In fact the metrics can be measured as linguistic labels (terms), such as high, middle, and low, etc. After Zadeh [1965] introduced fuzzy set theory to deal vague problems, linguistic terms have been used in approximate reasoning within the framework of fuzzy set theory to handle the ambiguity in evaluating data and the vagueness of linguistic expression [Zadeh, 1975]. This work applies a modified linguistic ordered weighted geometric averaging (*LOWGA*) operator, which uses the maximum entropy weights, to the direct computation on the indexes of the terms, that is, the independence of the fuzzy numbers that support the semantics of the linguistic terms [Delgado *et al.,* 1993; Herrera *et al.,* 1995; Xu, 2004].

Therefore, the purpose of this study was to build an evaluation framework for evaluating the flexibility in a SC. An algorithm is proposed to assess the degree of SCF in a fuzzy environment using a fuzzy linguistic approach. Section 2 presents a fuzzy linguistic approach to evaluating the flexibility in a SC development. Section 3 then proposes an evaluation framework of SCF for organizations, in which, the both dimensions and metrics of SCF are introduced and an evaluation scheme is presented. This paper considers a situation in which the various experts are equally important, i.e., a homogeneous group of experts problem, since the weights of experts are still not widely accepted, and assume that a group of K experts $(E_1, E_2, \cdots, E_K)$ has been formed to conduct further evaluation of SCF to making capital investment decisions. A three-stage algorithm is then proposed to evaluate degree of SCF development in Section 4. In Section 5, an example using a case of leading Taiwanese bicycle manufacturers is used to illustrate the proposed method. Finally, the last section summarizes this research.

2. Fuzzy linguistic approach

2.1. Linguistic assessments

The linguistic assessment is an approximate method based on linguistic variables. The concept of linguistic variables is extremely useful in dealing with decision situations, which are too complex or ill-defined to be reasonably described using conventional quantitative expressions [Zadeh, 1975]. A linguistic variable is one whose values are not numbers but rather words or sentences in a natural or artificial language [Zimmermann, 1996]. In the real world, the linguistic approach is appropriate for many evaluation problems in which information may be qualitative, or quantitative information may not be stated precisely, since it is unavailable or the cost of its determination is excessive, such that an ‘*approximate value*’ suffices [Herrera and Herrera-Viedma, 2000]. Therefore, the approach allows the representation of expert information more directly and adequately [Herrera *et al.,* 1996].

Generally, most experts cannot provide exact numerical values to express their opinions on flexibility metrics. More appropriately, experts will give the evaluations in form of linguistic terms in the presence of qualitative flexibility metrics. The information should include both the importance grade and performance rating of each flexibility metric, and the importance grade of each flexibility dimension, based on the SC strategy. Therefore, the degree of SCF can be evaluated with the importance and performance of each flexibility dimension and related metrics.

As mentioned above, the importance grade and performance rating should be rated for each flexibility metric. Therefore, both were scored on a linguistic term set (or linguistic scale). The strongest assessment is assigned the highest (or lowest) term *‘Definitely high’* (or *‘Definitely low’*) on a linguistic scale. The elements of the term set determine the granularity of the uncertainty. Furthermore, let $S=\{s_1, s_2, \cdots, s_T\}$ be a finite and totally ordered term set with an odd cardinal, where the middle term represents ‘*average*’, i.e., a probability of ‘*approximately 0.5*’, and the remaining terms are ordered symmetrically around it, and exhibit the following properties [Herrera *et al.,* 1995].

1. The set is ordered: $s_i \geqq s_j$ if $i \geqq j$.
2. The negation operator is defined as Neg(s_i) = s_j such that $j = T+1- i$.
3. The maximization operator is Max (s_i, s_j) = s_i if $s_i \geqq s_j$.
4. The minimization operator is Min (s_i, s_j) = s_j if $s_i \geqq s_j$.

2.2. Fusion of linguistic information

In the aggregation process of linguistic information, some results may not exactly match any linguistic terms in S [Xu, 2008]. To preserve all the given information, Xu [2004, 2005, 2008] extended the discrete linguistic term set S to a continuous linguistic term set $\overline{S} = \{s_\alpha / s_1 \le s_\alpha \le s_T, \alpha \in [1, T]\}$. If $s_\alpha \in S$, then s_α is termed an original linguistic term, otherwise, s_α is termed a virtual linguistic term. In general, the decision maker (or expert) used the original linguistic terms to evaluate alternatives, and the virtual linguistic terms can only appear in operation. Consider any two linguistic terms s_α, $s_\beta \in \overline{S}$, and μ, μ_1 and $\mu_2 \in [0, 1]$, Xu [2004] defined some operational laws as follows:

1. $(s_\alpha)^\mu = s_{\alpha^\mu}$, *(1)*
2. $(s_\alpha)^{\mu_1} \otimes (s_\alpha)^{\mu_2} = (s_\alpha)^{\mu_1 + \mu_2}$, *(2)*
3. $(s_\alpha \otimes s_\beta)^\mu = (s_\alpha)^\mu \otimes (s_\beta)^\mu$, *(3)*
4. $s_\alpha \otimes s_\beta = s_\beta \otimes s_\alpha = s_{\alpha\beta}$. *(4)*

The linguistic information (importance grade and performance rating) provided by a group of experts for each flexibility metric with respect to each flexibility dimension are defined as the original linguistic terms on the continuous linguistic scale $\overline{S}$. In order to preserve all the given information, with respect to a situation of group decision-making, this paper considers the *LOWGA* operator based on maximum entropy weights as the aggregation operator. It is elicited as follows.

The *LOWGA* operator is defined by Xu [2004] The *LOWGA* operator weights the ordered position of the linguistic argument instead of weighting the argument itself. Some desirable properties of the *LOWGA* operator can be obtained from the research of Xu [2004]. With respect to the ordered position weights of *LOWGA* operators, Yager [1988] provided two measures, namely *'orness'* and *'dispersion (or entropy)'*. The orness is a value that lies in *[0, 1]*, and measure the degree to which the aggregation resembles an *'or'* operation, and can be considered a gauge of decision-maker optimism. The more closely the orness of an *LOWGA* operator approaches the *'or'* operator, the more the optimistic decision-maker is about obtaining the best solution. The dispersion measures the degree to which all the aggregates are equally used. In the framework of multiple attribute group decision-making under uncertainty, the *LOWGA* operators can be provided for aggregating the attributes (experts) associated with some fuzzy linguistic quantifiers, such as *'as many as possible'*, *'most'*, *'average'*, *'at least half'*, etc., used to determine the weights. Therefore, in the group decision-making, fuzzy linguistic quantifiers are used to indicate a fusion strategy for guiding the process of aggregating expert opinions.

To determine the argument's ordered position weights, O'Hagan [1988] developed a maximum entropy approach, which formulates the problem as a constraint nonlinear optimization model with a predefined degree of orness as its constraint and the entropy as its objective function. The resultant weights are termed the maximum entropy weights. Filev and Yager [1995] explored a two-step process for obtaining the maximum entropy weights that generate some prescribed orness without having to solve the constraint nonlinear optimization problem. Chuu [2005] developed a modified linguistic ordered weighted averaging (*LOWA*) operator based on maximum entropy weights, and proposed a fuzzy multi-attribute decision-making using the modified *LOWA* operator for evaluating manufacturing flexibility. Mitchell and Estrakh [1997] presented an application of maximum entropy ordered weighted averaging (*MEOWA*) operators to lossless image compression, and found maximum entropy weights to be effective.

Let $S = \{s_{\alpha_1}, s_{\alpha_2}, \cdots, s_{\alpha_n}\}$ be a set of linguistic terms to be aggregated. Then the modified *LOWGA* operator of dimension n is a mapping

$$\Phi_Q : \overline{S}^n \rightarrow \overline{S}$$

which has associated with the non-decreasing proportional fuzzy linguistic quantifier Q, is defined as:

$$\Phi_Q(s_{\alpha_1}, s_{\alpha_2}, \cdots, s_{\alpha_n}) = (s_{\beta_1})^{w_1^*} \otimes (s_{\beta_2})^{w_2^*} \otimes \cdots \otimes (s_{\beta_n})^{w_n^*} = s_\beta \qquad (7)$$

where $\beta = \prod_{j=1}^{n} \beta_{j,}^{w_j^*}$ s_{β_j} is the jth largest of the s_{α_i}, $W^* = (w_1^*, w_2^*, \cdots, w_n^*)^T$ is an exponential maximum entropy weighting vector, obtained from Q , with $w_i^* \in [\ 0,\ 1]$ and $\sum_{i=1}^{n} w_i^* = 1$, and $s_{\alpha_i} \in \overline{S}$.

An algorithm for calculating the exponential maximum entropy weighting vector is as follows [Chuu, 2005; Filev and Yager, 1995; Herrera *et al.,* 1995; Kacprzyk, 1986; Yager, 1988]:

Step1: Determine the non-decreasing proportional linguistic fuzzy quantifier Q, used to represent the fuzzy majority over dimensions or metrics, as follows:

$$Q(r) = \begin{cases} 0 & \text{if } r < a, \\ (r-a)/(b-a) & \text{if } a \leqq r \leqq b, \\ 1 & \text{if } r > b, \end{cases} \tag{6}$$

with $a, b, r \in [0, 1]$. Some non-decreasing proportional linguistic fuzzy quantifiers are typified by terms *'most'*, *'at least half'*, *'average'*, and *'as many as possible'*, the respective parameters (a, b) of which are $(0.3, 0.8), (0, 0.5), (0, 1),$ and $(0.5, 1)$, respectively.

Step 2: Compute the exponential weighting vector W,

$$w_i = Q(i/n) - Q((i-1)/n), \text{ for } i = 1, 2, \ldots, n. \tag{7}$$

Step 3: Compute the *orness* value α ,

$$\alpha = (\sum_{i=1}^{n}(n-i)w_i)/(n-1). \tag{8}$$

Step 4: Compute the exponential maximum entropy weighting vector W^*, which is used in modified *LOWGA* operator, according to the two-step process.

4-1: Find a positive solution h^* of the algebraic equation,

$$\sum_{i=1}^{n}((n-i)/(n-1)-\alpha)h^{(n-i)} = 0. \tag{9}$$

4-2: Obtain W^* from the following equation, using $\beta^* = (n-1)\ln h^*$,

$$w_i^* = \frac{e^{\beta^* \times ((n-i)/(n-1))}}{\sum_{j=1}^{n} e^{\beta^* \times ((n-j)/(n-1))}}, \text{ for } i = 1, 2, \ldots, n. \tag{10}$$

Table 1. Linguistic terms of performance rating and importance grade

Nine ranks of performance rating	Nine ranks of importance grade
S_1 = DL : Definitely low	S_1 = DL : Definitely low
S_2 = VL : Very low	S_2 = VL : Very low
S_3 = L : Low	S_3 = L : Low
S_4 = ML :More or less low	S_4 = ML :More or less low
S_5 = M : Middle	S_5 = M : Middle
S_6 = MH : More or less high	S_6 = MH : More or less high

S_7 = H : High	S_7 = H : High
S_8 = VH : Very high	S_8 = VH : Very high
S_9 = DH : Definitely high	S_9 = DH : Definitely high

3. An evaluation framework for SCF

In this section, we will present an evaluation framework for SCF. The framework consists of two parts, an evaluation hierarchy and an evaluation scheme for SCF. In the hierarch, the dimensions (or metrics) for evaluating SCF are presented through limited literature review on SCF. Based on the evaluation hierarchy, an evaluation scheme is convenient for managers to identify the need for improving SCF, and determine the dimensions of SCF as the best direction to improvement.

3.1. An evaluation hierarchy for SCF

Some studies on SCF provide implicitly or explicitly stated definitions of SCF [Garavelli, 2003; Gong, 2008; Lummus et al., 2003; Vickery et al., 1999]. Generally, supply chain flexibility (SCF) is considered as the ability of a supply chain to cope with environmental uncertainties effectively and efficiently, which able to provide a variety of quality products at low cost. For example, Tinchell and Radcliffe [1996] emphasized that a system is flexible if it is able to cope with the uncertainty of change effectively and efficiently. The effectiveness of the response is determined by whether the effect of uncertainty is counteracted. The responsive efficiency is determined by the time, cost and effort that are required. This is consistent with Upton's [1994] definition that flexibility is defined as the ability to change or react with little penalty in time, effort, cost or performance. Therefore, the degree of SCF relates to the uncertainties imposed upon the SC, and to the penalty of response that are required.

With respect to the limited reviews on SCF, Lummus's [2003] conceptual model of SCF proposes that the flexibility of the entire SC is a result of the characteristics of the operations systems, the logistic processes, and the supply network at each location in the SC. It is suggested that determining whether these characteristics actually result in a flexible SC is affected by the organizational design and information systems of each SC partner. They identified five components of SCF include operations systems, logistic processes, supply network, organizational design, and information systems. Slack [1987] suggested that evaluation of a flexibility dimension requires consideration of three elements: the ranges of states a system can change, the time and the cost required by a system to change a state. Whereas there is a negative correlation between the cost and the time, it means a trade-off as only two elements may be considered for each of the flexibility dimension: the range of states and the time for change. Upton [1994] reinforced this notion that each of flexibility dimensions is specified by three elements: range, mobility, and uniformity. Thus the greater the range of possible options the greater the flexibility; the higher the mobility the greater the flexibility; the more uniformity across the range the greater the flexibility. Golden and Powell [2000] proposed an inclusive definition of flexibility in which flexibility can be evaluated by four metrics: efficiency, responsiveness, versatility, and robustness. These metrics derived from the three flexibility elements can be used to assess each flexibility dimension.

As mentioned above, a systematic approach is proposed to evaluate the degree of SCF, using a fuzzy linguistic approach and hierarchical structure analysis. This method is suited to decision- making in a fuzzy environment. In this model, the dimensions of SCF presented by Lummus [2003, 2005] were expressed with five dimensions, including operations systems flexibility, logistic processes flexibility, supply network flexibility, organizational design flexibility, and information systems flexibility. These were based on the literature review on manufacturing flexibility, strategic flexibility and the limited empirical literature on SCF. A more formal definition for each of the five dimensions of SCF is presented in Table 2. Furthermore, the extent of each dimension of SCF can be assessed by four flexibility metrics: efficiency, responsiveness, versatility, and robustness [Golden and Powell, 2000]. In order to facilitate experts to provide precise judgments, the detail on the metrics are also described in Table 3. For convenience, the dimension operations systems flexibility is represented as X_1, logistic processes flexibility as X_2, and so on. The metrics on the *i*th flexibility dimension are represented as in Fig. 1; for example, efficiency is denoted by X_{i1}, responsiveness by X_{i2}, and so on.

Table 2. The definitions of supply chain flexibility dimensions [Lummus *et al.,* 2003, 2005]

Dimensions	Definitions
Supply network flexibility	The ability to reconfigure the supply chain, altering the supply of product in line with customer demand at each participating company of the supply chain
Operations systems flexibility	The ability to configure assets and operations to react to emerging customer trends (product changes, volume, mix) at each participating company of the supply chain
Logistics processes flexibility	The ability to cost effectively receive and deliver product as sources of supply and customers change (customer location changes, globalization, postponement) within and between each participating company of the supply chain
Information systems flexibility	The ability to align information system architectures and systems with the changing information needs of the organization as it responds to changing customer demand within and between each participating company of the supply chain
Organizational design flexibility	The ability to align labor force skill to the needs of the supply chain to meet customer service/demand requirements at each participating company of the supply chain

Table 3. The four metrics of flexibility [Golden and Powell, 2000; Chuu, 2005]

Metrics	Definitions
Efficiency	The rating to which a system meet new circumstances within the time constraints imposed, and can be assessed by the suitability rating within time limit
Responsiveness	The rating at which a system react to new circumstances, and can be assessed by the suitability rating with a speedy response
Versatility	The rating of a system to accommodate foreseen environmental uncertainties effectively, and can be assessed for its suitability rating with a range of planned options
Robustness	The rating of a system to cope with unforeseen environmental uncertainties effectively, and can be assessed by the suitability rating with a range of unplanned options

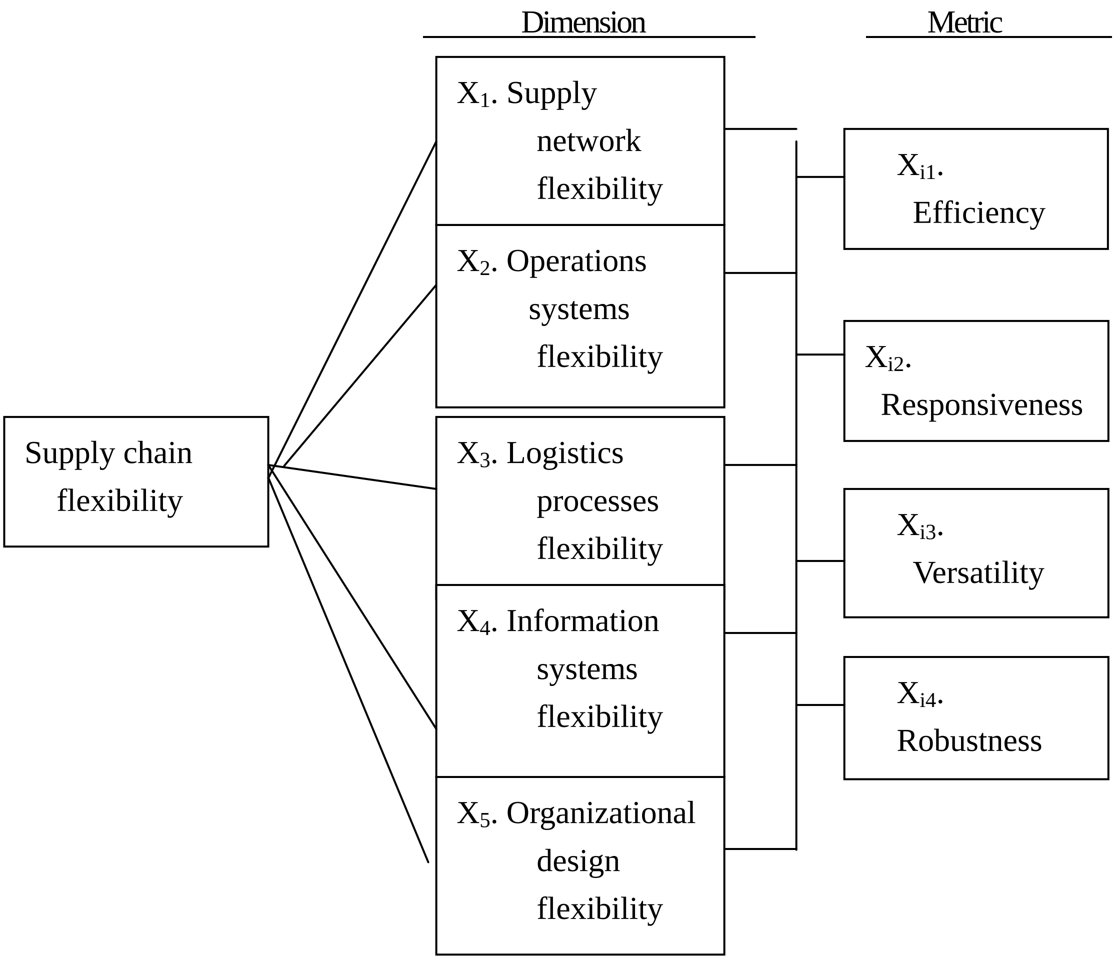

Fig. 1. The evaluation hierarchy of supply chain flexibility

3.2. An evaluation scheme for SCF

From the above, it is easy to see that the flexibility of the SC depends on the five dimensions. All of them are very important and any one cannot be missing. More specific, these dimensions must be balanced and improved, depend on the industry to which a SC belongs and the strategy that the SC implements. If we only consider the collective evaluation result of SCF, then the information of one dimension may be submerged by that of the other. So an evaluation scheme for SCF is proposed to provide a means for both measuring SCF and also identifying the major obstacles to improving flexibility levels.

Furthermore, the evaluation of SCF can be identified by an evaluation scheme, which is shown as Fig. 2. In Fig. 2, the assessment scheme will be developed in the three main stages. The first-stage assessment evaluates the improvement degrees with respect to each flexibility dimension. The second-stage assessment comprises evaluating the improvement degree with respect to SCF. Finally, three-stage of the scheme involves the interactive consensus analysis used to making a consistent decision.

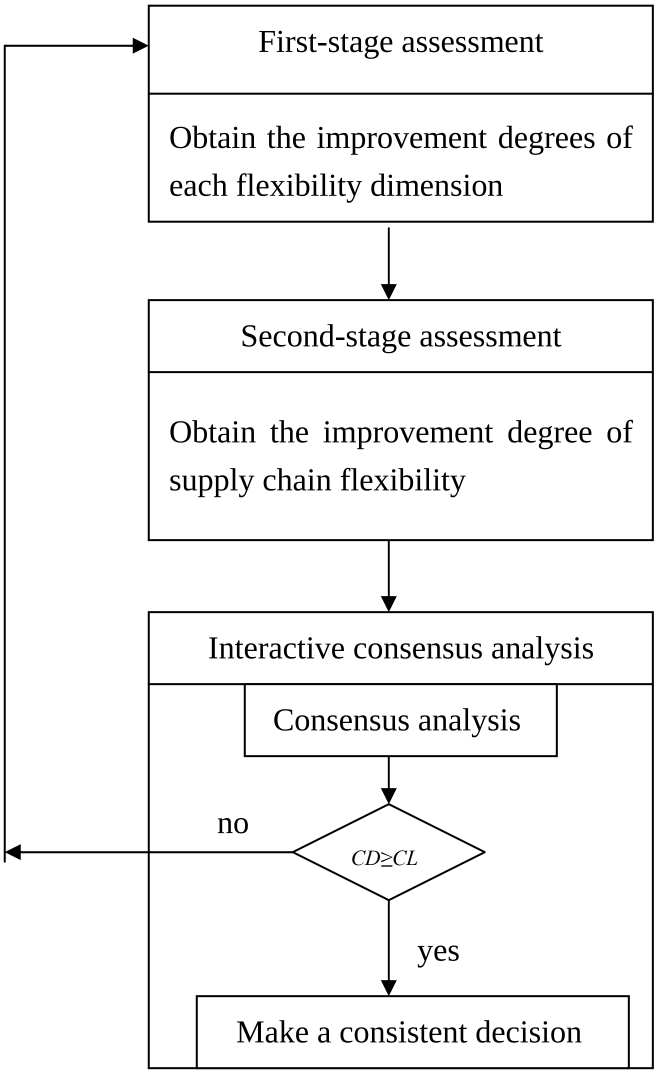

Fig. 2. The evaluation scheme for supply chain flexibility

Owing to the evaluation of SCF requires group opinions from a group of experts. The consensus reaching process used in the interactive consensus analysis is a necessity of group decision-making, because to achieve a general consensus about selected options is a desirable goal [16:Herrera et al., 1996]. In the consensus analysis, group decision-makers determine the consensus level *(CL)* required for the solution in advance. When the consensus degree obtained in consensus analysis reaches *CL*, the evaluation results are accurate and reliable enough to make a consistent decision. If that is not the case, the process has to go back to the initial stage in order to gather additional information of the evaluation problem. When making a consistent decision, according to the consistent assessment results obtained from previous stages, if the improvement degree of SCF is a positive value, then decision-makers should be improving SCF. On the other hand, comparing the improvement degrees of each flexibility dimension may identify maximum positive values and then determine which dimensions of SCF as the best directions to improvement.

As mentioned above, the model proposed in this study to evaluate the degree of SCF involves group decision-making, and therefore the assessment of SCF are more objective and unbiased than those individually assessed. The decision-makers (experts) are responsible for providing assessment information, and consider the importance grade and related performance rating both as $S=\{s_1, s_2, \cdots, s_9\}$, as shown in Table 1. Suppose a group of K experts $(E_1, E_2, \cdots, E_K)$ are responsible for assessing the degree of SCF. The symbol I_i^k is used denote the importance grade of SCF dimension X_i ;

I_{ij}^{k} and P_{ij}^{k} are used to the importance grade and related performance rating for flexibility metric X_{ij}, respectively, according to expert E_k's assessing data *(i=1, 2,⋯, 5; j=1, 2, 3, 4; k=1, 2,⋯, K)*. Table 4 represents the above given the data assessed by expert E_k *(k=1, 2,⋯, K)*. The data assessed by all *K* experts are combined to evaluate the degree of SCF. Therefore, the following section proposes an approach for evaluating the degree of SCF for use by a group of experts.

Table 4. The contents of evaluation hierarchy of SCF for expert E_k

Flexibility dimension	X_1	X_2	X_3	X_4	X_5
Importance grade	I_1^k	I_2^k	I_3^k	I_4^k	I_5^k
Flexibility metric	$X_{11}X_{12}X_{13}X_{14}$	$X_{21}X_{22}X_{23}X_{24}$	$X_{31}X_{32}X_{33}X_{34}$	$X_{41}X_{42}X_{43}X_{44}$	$X_{51}X_{52}X_{53}X_{54}$
Performance rating	$P_{11}^kP_{12}^kP_{13}^kP_{14}^k$	$P_{21}^kP_{22}^kP_{23}^kP_{24}^k$	$P_{31}^kP_{32}^kP_{33}^kP_{34}^k$	$P_{41}^kP_{42}^kP_{43}^kP_{44}^k$	$P_{51}^kP_{52}^kP_{53}^kP_{54}^k$
Importance grade	$I_{11}^kI_{12}^kI_{13}^kI_{14}^k$	$I_{21}^kI_{22}^kI_{23}^kI_{24}^k$	$I_{31}^kI_{32}^kI_{33}^kI_{34}^k$	$I_{41}^kI_{42}^kI_{43}^kI_{44}^k$	$I_{51}^kI_{52}^kI_{53}^kI_{54}^k$

4. An approach for evaluating the degree of SCF

In this section, according to the evaluation hierarchy of SCF, as shown in Fig. 1, and the details shown in Table 2 and Table 3, an algorithm for evaluating the degree of SCF is proposed by using the modified *LOWGA* operator. The algorithm is developed in three main stages, as shown in Fig. 2, as follow:

1. First-stage assessment.
2. Second-stage assessment.
3. Interactive consensus analysis.

The first-stage assessment evaluates the improvement degrees with respect to each flexibility dimension. With respect to SCF, the second-stage assessment assesses the improvement degree of SCF. The last stage involves the interactive consensus analysis used to making a consistent decision. Using this algorithm, the group of experts' linguistic assessments with the evaluation hierarchy of SCF can be taken into account in the aggregation process to ensure more convincing and accurate decision-making. In order to establish the decision matrix for each expert, experts use the linguistic term from the set $S=\{s_1, s_2, \cdots, s_9\}$, as shown in Table 1, to express their opinions for evaluation hierarchy of SCF. The first level evaluates the importance grade with respect to each flexibility dimension, and the second level identifies importance grade and performance rating with respect to each flexibility metric under each flexibility dimension. This can be carried out by questionnaires, which are used for soliciting expert opinions.

4.1. First-stage assessment

This stage aims to obtain the improvement degree of each flexibility dimension. In the fuzzy linguistic assessment, let *S* be an appropriate linguistic scale chosen by experts to be used for the assessment versus flexibility metrics. The symbols P_{ij}^{k} and I_{ij}^{k} are linguistic terms belonging to *S*, presented in Table 1, and used to denote the performance rating and related importance grade for flexibility metric X_{ij}, respectively, according to the assessment data of expert E_k *(i=1, 2,⋯, 5; j=1, 2,* *3, 4; k=1, 2,⋯, K)*. To preserve all the given information, this work applies the *LOWGA* operator with some operational laws, defined by Xu [2004], of two linguistic terms through direct computation. Consequently, using Eqs. (1) and (4), the weighted rating IP_{ij}^{k} is also a linguistic term belonging to a continuous linguistic scale $\overline{S}$, obtained from *S*, can be formed as follows:

$$IP_{ij}^{k} = C^{2}(I_{ij}^{k}, P_{ij}^{k}) = (s_a)^{\mu} \otimes (s_b)^{(1-\mu)} = s_{a^{\mu}} \otimes s_{b^{(1-\mu)}} = s_c, \qquad (11)$$

$s_a, s_b \in S$, $s_c \in \overline{S}$ for $i=1, 2, \cdots, 5; j=1, 2, 3, 4; k=1, 2, \cdots, K$,

such that $c = a^{\mu} b^{(1-\mu)}$,

where operator $\otimes$ denotes the general product of linguistic terms, and $\mu \in [0, 1]$.

According to the multiple expert opinions obtained, both direct and indirect approaches can be employed to derive solutions [15:Herrera et al., 1995; 18:Kacprzyk, 1986]. This study considers the indirect approach for a heterogeneous group of experts. For handling the multiple expert information, the degree of importance of expert ε_k, should be considered in the aggregation procedure. This work applies a modified *LOWGA* operator with the maximum entropy weighing vector. Since the aggregation is based upon individual flexibility metric, the maximum entropy weighing vector obtained from a fuzzy linguistic quantifier represents the fuzzy majority over the *K* experts. The fuzzy linguistic quantifier can be used to measure the degree of decision-maker optimism. The aggregation algorithm for a group of experts is presented as follows:

(1) Aggregate IP_{ij}^{k} and I_{i}^{k} to yield the aggregated weighted rating $(X_{(ij)}^{A})$ and aggregated importance $(I_{(i)}^{A})$, respectively. The aggregated parameters obtained from the assessment data of *K* experts can be obtained by

$$X_{(ij)}^{A} = \Phi_{Q_1}(IP_{ij}^{1}, IP_{ij}^{2}, \cdots, IP_{ij}^{K}) \text{ for } i=1, 2, \cdots, 5; j=1, 2, 3, 4, \qquad (12)$$

$$I_{(i)}^{A} = \Phi_{Q_1}(I_{i}^{1}, I_{i}^{2}, \cdots, I_{i}^{K}) \text{ for } i=1, 2, \cdots, 5, \qquad (13)$$

where Φ_{Q_1} denotes the *LOWGA* operator with the exponential maximum entropy weighing vector W_1^{*}, obtained from a fuzzy linguistic quantifier Q_1, which represents the fuzzy majority over the *K* experts, and the exponential weighing vector *W*, used to denote the degree of importance of experts' opinions.

(2) Aggregate $X_{(ij)}^{A}$ to yield the first-stage aggregated rating $(X_{(i)}^{A})$. Using the concept of fuzzy majority over the flexibility metrics specified by a fuzzy linguistic quantifier Q_2, and using the *LOWGA* operator associated with the exponential maximum entropy weighing vector W_2^{*}, yields the first-stage aggregated rating on flexibility dimension X_i, as follows:

$$X_{(i)}^{A} = \Phi_{Q_2}(X_{(i1)}^{A}, X_{(i2)}^{A}, X_{(i3)}^{A}, X_{(i4)}^{A}) \text{ for } i=1, 2, \cdots, 5. \qquad (14)$$

(3) Calculate the improvement degree of each flexibility dimension $(\gamma(X_i))$. Computing the difference between the ranks of linguistic terms, $I_{(i)}^{A}$ and $X_{(i)}^{A}$ with respect to each flexibility dimension is obtained. If $X_{(2)}^{A} = s_m$ and $I_{(2)}^{A} = s_n$, then the difference between the ranks of linguistic terms for X_2, i.e., the improvement degree of X_2 $(\gamma(X_2))$, is defined as

$$\gamma(X_2) = n - m. \qquad (15)$$

Similarly, $\gamma(X_1), \gamma(X_3), \gamma(X_4)$ and $\gamma(X_5)$ are associated with flexibility dimensions X_1, X_3, X_4 and X_5, respectively. Comparing the improvement degree of each flexibility dimension may yield maximum positive values and then determine which dimensions of SCF represent the best direction for improvement.

4.2. Second-stage assessment

This stage aims to obtain the improvement degree of SCF. Both the aggregated importance and first-stage aggregated rating on each flexibility dimension should be evaluated to determine the degree of SCF. Let $I_{(i)}^{A}$ and $X_{(i)}^{A}$, $i=1, 2, \cdots, 5$, are linguistic terms belonging to $\overline{S}$, used to denote the aggregated importance and the first-stage aggregated rating for each X_i, respectively. The algorithm for second-stage assessment is presented as follows.

(1) Aggregate $X_{(i)}^{A}$ and $I_{(i)}^{A}$ to yield the first-stage aggregated weighted rating $(IX_{(i)}^{A})$. As mentioned in first-stage assessment, using Eqs. (1) and (4), the first-stage aggregated weighted rating $IX_{(i)}^{A}$ can be formed as follows:

$$IX_{(i)}^{A} = C^2(I_{(i)}^{A}, X_{(i)}^{A}) = (s_a)^{\mu} \otimes (s_b)^{(1-\mu)} = s_{a^{\mu}} \otimes s_{b^{(1-\mu)}} = s_c, \qquad (16)$$

s_a , s_b and $s_c \in \overline{S}$ for $i=1, 2, \cdots, 5$,

such that $c = a^{\mu}b^{(1-\mu)}$,

where operator $\otimes$ denotes the general product of linguistic terms, and $\mu \in [0, 1]$.

(2) Aggregate $IX_{(i)}^{A}$ and $I_{(i)}^{A}$ to yield the degree of SCF $(D(SCF))$ and importance of SCF $(I(SCF))$, respectively. Based on the *LOWGA* operator with the exponential maximum entropy weighing vector W_3^*, is used. It is obtained from a fuzzy linguistic quantifier Q_3, representing the fuzzy majority over the *flexibility* dimensions, as follows:

$$I(SCF) = \Phi_{Q_3}(I_{(1)}^{A}, I_{(2)}^{A}, \cdots, I_{(5)}^{A}), \qquad (17)$$

$$D(SCF) = \Phi_{Q_3}(IX_{(1)}^{A}, IX_{(2)}^{A}, \cdots, IX_{(5)}^{A}). \qquad (18)$$

(3) Calculate the improvement degree of SCF $(\gamma(SCF))$. The linguistic terms, $I(SCF)$ and $D(SCF)$, represent the importance of SCF and degree of SCF, respectively, according to the assessment of K experts. Thus, the difference between the rank of $I(SCF)$ and $D(SCF)$, i.e., the improvement degree $\gamma(SCF)$ is also computed. If $I(SCF) = s_n$ and $D(SCF) = s_m$, then $\gamma(SCF)$ is defined as

$$\gamma(SCF) = n - m. \qquad (19)$$

If $\gamma(SCF)$ is a positive value, then decision-makers should be improving SCF.

4.3. Interactive consensus analysis

This analysis aims to make a consistent decision. Owing to the evaluation of SCF requires opinions from a group of experts. With respect to the assessment results obtained in the former two stages assessment, the consensus reaching process used in this stage is a necessity of group decision-making, because to achieve a general consensus about selected options is a desirable goal [16:Herrera *et al.,* 1996]. In the consensus analysis, group decision-makers determine the consensus level *(CL)* required for the solution in advance when the consensus degree obtained in the analysis reaches *CL*, the evaluation result are accurate and reliable enough to make a consistent decision. If that is not the case, the process has to go back to the initial stage in order to gather additional information of the evaluation problem. The steps of interactive consensus analysis are presented as follows.

(1) Aggregate P_{ij}^{k} and I_{ij}^{k} to yield the aggregated rating (P_{ij}^{A}) and the aggregated importance (I_{ij}^{A}), respectively. As in first-stage assessment with the Q_1, P_{ij}^{A} and I_{ij}^{A} for each X_{ij} can be obtained as follows.

$$P_{ij}^{A} = \Phi_{Q_1}(P_{ij}^{1}, P_{ij}^{2}, \cdots, P_{ij}^{K}) \text{ for } i=1, 2, \cdots, 5; j=1, 2, 3, 4, \qquad (20)$$

$$I_{ij}^{A} = \Phi_{Q_1}(I_{ij}^{1}, I_{ij}^{2}, \cdots, I_{ij}^{K}) \text{ for } i=1, 2, \cdots, 5; j=1, 2, 3, 4. \qquad (21)$$

(2) Calculate the three major consensus degrees $(CD_h^k, h=1, 2, 3)$ for each E_k with respect to P_{ij}^{A}, I_{ij}^{A} and $I_{(i)}^{A}$, respectively. A method proposed by Xu [37:2005] is used for measuring the degree of similarity between linguistic terms. According to this approach, let s_α and s_β be two linguistic terms, and s_α , $s_\beta \in \overline{S}$. Then the similarity degree between s_α and s_β can be measured by the similarity function ρ as follows:

$$\rho(s_\alpha, s_\beta) = 1 - \frac{|\alpha - \beta|}{T-1}, \qquad (22)$$

where $\rho(s_\alpha, s_\beta) \in [0, 1]$, and T denotes the number of linguistic terms in the linguistic term set S. Obviously, the larger the value of $\rho(s_\alpha, s_\beta)$, the greater the similarity between s_α and s_β. It should be noted that $\rho(s_\alpha, s_\beta) = \rho(s_\beta, s_\alpha)$. Similarly, let $A=\{a_{ij}\}_{n\times m}$ and $B=\{b_{ij}\}_{n\times m}$ be two linguistic terms, then the consensus degree between A and B as follows:

$$\rho(A, B) = \frac{1}{n\times m}\sum_{i=1}^{n}\sum_{j=1}^{m}\rho(a_{ij}, b_{ij}), \qquad (23)$$

where $\rho(A, B) \in [0, 1]$.

Also, the larger the value of $\rho(A, B)$, the greater the consensus between s_α and s_β. It should be noted that $\rho(A, B) = \rho(B, A)$. Thus using Eqs. (22) and (23), the three consensus degrees for each E_k with respect to P_{ij}^A, I_{ij}^A and $I_{(i)}^A$, respectively, can be calculated by Eqs. (24)－(26), as follows:

$$CD_1^k = \frac{1}{5\times 4}\sum_{i=1}^{5}\sum_{j=1}^{4}\rho(P_{ij}^k, P_{ij}^A) \text{ for } k = 1, 2, \cdots, K, \qquad (24)$$

$$CD_2^k = \frac{1}{5\times 4}\sum_{i=1}^{5}\sum_{j=1}^{4}\rho(I_{ij}^k, I_{ij}^A) \text{ for } k = 1, 2, \cdots, K, \qquad (25)$$

$$CD_3^k = \frac{1}{5}\sum_{i=1}^{5}\rho(I_i^k, I_{(i)}^A) \text{ for } k = 1, 2, \cdots, K. \qquad (26)$$

(3) According to CD_h^k, $h=1, 2, 3$, related to each E_k, if $CD_h^k \geq CL$ for $h=1, 2, 3$; $k=1, 2, \cdots, K$, then make a consistent decision for SCF. Otherwise, comparing the consensus degree of each E_k may find minimum values, then identify which experts may find the need to change their opinions, and go back to the initial stage, in order to gather additional information of the evaluation problem. When making a consistent decision, based on the assessment results obtained in second-stage assessment, if the improvement degree of SCF $(\gamma(SCF))$ is a positive value, then decision-makers should be improving SCF. On the other hand, according to the assessment results obtained in first-stage assessment, comparing the improvement degrees of each flexibility dimension, $\gamma(X_i)$ for $i = 1, 2, \cdots, 5$, may yield maximum positive values and then determine which dimensions of SCF as the best direction to improvement.

5. Illustrative example

This section cites SCF evaluation of a leading Taiwan company in the bicycle industry to demonstrate the proposed evaluation method can be applied to measure SCF. For reasons of confidentiality the name of the company is not revealed, we have labeled with fictitious name: *G*-company. Generally, a bike product consists of eleven subsystems including a frame, suspension fork, derailleur shifters, brokers, hubs and rims, tires, pedals, handle bar, stem, saddle, and seat post. Each subsystem has several models that can be selected by customer. Thus a bicycle supply chain comprises bicycle parts suppliers, a bicycle assembly company, distributors and dealers (or retailers), and customers. The bicycle assembly company, i.e., *G*-company purchases parts such as derailleur gears, brokers, etc., obtained from over 270 firms, such as *Shimano, Rockshox, Honour wheel, Answer,* etc., and assembles bike products. The bikes are delivered to distributors and dealers that sell complete products to customers. The distributors and dealers comprise *Specialized USA, Trek, Scoot, Hodata,* and *Giant* etc. In 2005, *G*-company has an annual sales of around US＄304 million. It consists of four manufacturers and eight marketing companies. The former includes *G-Taiwan, G-Europe, Kun-sian, G-Phoenix* manufacturers. The latter includes *G-Taiwan, G-Europe, G-United States, G-Australia, G-Japan, G-China, G-Canada,* and *G-New Zealand,* etc.

Lately, due to increasing customization, consumer demands of global bicycle product markets have changed so fast in recent decades that the flexibility of SC had become increasingly important. *G*-company endeavored to simultaneously provide local responsiveness and global integration in response to an uncertain business environment, and used to satisfy its customers, reduce its time to market, and improve its overall competitiveness. *G*-company aims to build a new SC which would make it the leader in the market for bicycles. In order to evaluate the competitiveness of SC and before making investment decisions, the flexibility of SC would be studied. To implement the evaluation task of SCF, a heterogeneous group of three experts, E_1, E_2, E_3, has been formed to conduct further evaluation of SCF. Based on the evaluation hierarchy of SCF, as shown in Fig. 1, five flexibility dimensions were used: operations systems flexibility, logistics processes flexibility, supply network flexibility, organizational design flexibility, and information systems flexibility, as presented in Table 2. The assessment for each flexibility dimension was assessed by four flexibility metrics: efficiency, responsiveness, versatility, and robustness, as presented in Table 3, and the nine-rank linguistic scale used for assessment as shown in Table 1. Consequently, group members use the linguistic terms to evaluate the importance grades of dimensions and related metrics, and use to assess the performance ratings of four metrics under each of the flexibility dimensions. The assessing data identified by experts are presented in Table 5.

Table 5. The assessing data of fuzzy linguistic quantifiers, importance grades and performance ratings of SC for three experts

Flexibility dimension	Flexibility metric	Importance grade						performance rating		
(most)	(most)		E_1		E_2		E_3	E_1	E_2	E_3
x_1	x_{11}	V	V	D	H	H	M	H	H	VH
	x_{12}		H		M		M	M	H	H
	x_{13}		M		H		V	H	M	MH
	x_{14}		V		V		V	M	M	MH
x_2	x_{21}	H	H	H	V	H	V	V	V	DH
	x_{22}		V		V		H	H	V	DH
	x_{23}		H		M		V	V	H	VH
	x_{24}		H		M		M	D	H	H
x_3	x_{31}	D	V	V	H	D	D	M	H	MH
	x_{32}		V		H		D	H	M	H
	x_{33}		H		V		V	M	M	MH
	x_{34}		D		V		V	M	M	H

X_4	X_{41}	M	V	H	V	M	H	H	M	ML
	X_{42}		H		H		D	M	M	M
	X_{43}		V		M		H	M	M	ML
	X_{44}		D		M		V	M	M	L
X_5	X_{51}	M	H	M	M	M	H	L	M	L
	X_{52}		V		M		H	V	M	ML
	X_{53}		M		H		V	M	L	ML
	X_{54}		M		H		D	D	L	L

Table 6. The weighted ratings for four flexibility metrics under each flexibility dimension

Flexibility dimension	Flexibility metric	Weighted rating		
		E_1	E_2	E_3
X_1	X_{11}	$S_{7.4833}$	S_7	$S_{6.9282}$
	X_{12}	$S_{6.4807}$	$S_{5.9161}$	$S_{6.4807}$
	X_{13}	$S_{5.9161}$	$S_{6.4807}$	$S_{6.9282}$
	X_{14}	$S_{6.4807}$	$S_{6.9282}$	$S_{6.9282}$
X_2	X_{21}	$S_{7.4833}$	S_8	$S_{8.4853}$
	X_{22}	$S_{7.4833}$	S_8	$S_{7.9373}$
	X_{23}	$S_{7.4833}$	$S_{5.9161}$	S_8
	X_{24}	$S_{7.9373}$	$S_{5.9161}$	$S_{6.4807}$
X_3	X_{31}	$S_{6.9282}$	S_7	$S_{7.3485}$
	X_{32}	$S_{7.4833}$	$S_{6.4807}$	$S_{7.9373}$
	X_{33}	$S_{6.4807}$	$S_{6.3246}$	$S_{6.9282}$
	X_{34}	$S_{7.3485}$	$S_{6.3246}$	$S_{7.4833}$
X_4	X_{41}	$S_{7.4833}$	$S_{6.9282}$	$S_{5.2915}$
	X_{42}	$S_{6.4807}$	$S_{5.9161}$	$S_{6.7082}$
	X_{43}	$S_{6.3246}$	$S_{5.4772}$	$S_{5.2915}$
	X_{44}	$S_{7.3485}$	$S_{5.4772}$	$S_{4.899}$
X_5	X_{51}	$S_{4.5826}$	$S_{4.899}$	$S_{4.5826}$
	X_{52}	S_4	$S_{4.899}$	$S_{5.2915}$
	X_{53}	$S_{4.899}$	$S_{4.5826}$	$S_{5.6569}$
	X_{54}	$S_{2.4495}$	$S_{4.5826}$	$S_{5.1962}$

5.1 First-stage assessment calculations (Steps 4-7)

Using Eq. (11) and letting μ= 0.5, the weighted rating (IP_{ij}^{k}) for each flexibility metric versus flexibility dimensions can be obtained, as presented in Table 6. All the weighted ratings for a group of experts are aggregated to form a group opinion for each metric as follows:

(1) Aggregate IP_{ij}^{k} and I_{i}^{k} to yield the aggregated weighted rating ($X_{(ij)}^{A}$) and aggregated importance ($I_{(i)}^{A}$), respectively. Using Eqs. (12) and (13), respectively, the decision-makers of the decision problem assigns a fuzzy linguistic quantifier *'most'* to the corresponding experts; i.e., the modified *LOWGA* operator Φ_{Q_1} guided by *'most'* with its parameters (0.3. 0.8), and the algorithm for calculating the exponential maximum entropy weighing vector yields the exponential weighing vector $W_1 = (0.0667, 0.6667, 0.2667)^T$, orness value $\alpha_1 = 0.4$, and the exponential maximum entropy weighing vector $W_1^* = (0.2384, 0.3233, 0.4383)^T$. The aggregated results are obtained and they are shown in Table 7.

(2) Aggregate $X_{(ij)}^{A}$ to yield the first-stage aggregated rating ($X_{(i)}^{A}$). Using Eq. (14), the modified *LOWGA* operator Φ_{Q_2} guided by *'most'* with its parameters (0.3. 0.8), and the algorithm for calculating the W_2^* yields $W_2 = (0, 0.4, 0.5, 0.1)^T$, $\alpha_2 = 0.4333$, and $W_2^* = (0.1932, 0.2269, 0.2666, 0.3133)^T$. The following results are thus obtained:

$X_{(1)}^{A} = \mathbf{s_{6.5241}}$, $X_{(2)}^{A} = s_{7.1343}$, $X_{(3)}^{A} = s_{6.8552}$, $X_{(4)}^{A} = s_{5.8668}$, $X_{(5)}^{A} = s_{4.3151}$,

where, for example, the term $X_{(1)}^{A}$ is obtained by Eq. (14):

$$X_{(1)}^{A} = \Phi_{'most'}(s_{7.0802}, s_{6.2269}, s_{6.3268}, s_{6.7284})$$
$$= (s_{7.0802})^{0.1932} \otimes (s_{6.7284})^{0.2269} \otimes (s_{6.3268})^{0.2666} \otimes (s_{6.2269})^{0.3133} = s_{6.5241}.$$

(3) Calculate the improvement degree ($\gamma(X_i)$). The difference of each dimension can be calculated by Eq. (15), as shown in Table 8, thus dimension X_3 has a maximum positive value, and then X_3 is determined as the best direction for improvement, while dimensions X_1 and X_5 are rank second and third, respectively.

Table 7. Aggregated weighted ratings and aggregated importance for four flexibility metrics under each flexibility dimension

Flexibility dimension	Flexibility metric	Aggregated importance	Aggregated weighted rating
X_1	X_{11}	$s_{7.7601}$	$s_{7.0802}$
	X_{12}		$s_{6.2269}$
	X_{13}		$s_{6.3268}$
	X_{14}		$s_{6.7284}$
X_2	X_{21}	s_7	$s_{7.8791}$
	X_{22}		$s_{7.7495}$
	X_{23}		$s_{6.8592}$
	X_{24}		$s_{6.5353}$
X_3	X_{31}	$s_{8.5472}$	$s_{7.0496}$
	X_{32}		$s_{7.1254}$
	X_{33}		$s_{6.5147}$

	X_{34}		$s_{6.9106}$
X_4	X_{41}	$s_{5.5392}$	$s_{6.2705}$
	X_{42}		$s_{6.2783}$
	X_{43}		$s_{5.5832}$
	X_{44}		$s_{5.5944}$
X_5	X_{51}	$s_{5.5392}$	$s_{4.6561}$
	X_{52}		$s_{4.5656}$
	X_{53}		$s_{4.9237}$
	X_{54}		$s_{3.5883}$

Table 8. The result of first-stage assessment

Flexibility dimension	X_1	X_2	X_3	X_4	X_5
(1) Aggregated importance	7.7601	7	8.5472	5.5392	5.5392
(2) First-stage aggregated weighted rating	6.5241	7.1343	6.8552	5.8668	4.3151
Improvement degree (1)－ (2)	＋1.2360	－0.1343	＋1.6920	－0.3276	＋1.2241

5.2 Second-stage assessment calculations (Steps 8-10)

(1) Aggregate $X^A_{(i)}$ and $I^A_{(i)}$ to yield first-stage aggregated weighted rating $(IX^A_{(i)})$. Using Eq. (16) and letting μ= 0.5, the following results are thus obtained:

$IX^A_{(1)} = s_{7.1153}$, $IX^A_{(2)} = s_{7.0668}$, $IX^A_{(3)} = s_{7.6546}$, $IX^A_{(4)} = s_{5.7006}$, $IX^A_{(5)} = s_{4.889}$,

where, for example, the term $IX^A_{(1)}$ is obtained by Eq. (16):

$IX^A_{(1)} = C^2(s_{7.7601}, s_{6.5241}) = (s_{7.7601})^{0.5} \otimes (s_{6.5241})^{1-0.5} = s_{7.1153}$.

(2) Aggregate $IX^A_{(i)}$ and $I^A_{(i)}$ to yield the degree of SCF *(D(SCF))* and the importance of SCF *(I(SCF))*, respectively. Using Eq. (17) and (18), the modified *LOWGA* operator Φ_{Q_3} guided by *'most'* with its parameters (0.3. 0.8), and the algorithm for calculating the W^*_3 yields $W_3 = (0, 0.2, 0.4, 0.4, 0)^T$, $\alpha_3 = 0.45$, and $W^*_3 = (0.1620, 0.1791, 0.1980, 0.2189, 0.2420)^T$. Then it results in the following assessment:

$D(SCF) = \Phi_{'most'}(s_{7.1153}, s_{7.0668}, s_{7.6546}, s_{5.7006}, s_{4.889}) = s_{6.2551}$,

$I(SCF) = \Phi_{'most'}(s_{7.7601}, s_7, s_{8.5472}, s_{5.5392}, s_{5.5392}) = s_{6.6117}$.

Therefore, $s_{6.6117}$ and $s_{6.2551}$ are the linguistic assessment for the importance and the degree of SCF, respectively.

(3) Calculate the improvement degree of SCF $(\gamma(SCF))$. Such as Eq. (19) the difference of rank for SCF is obtained:

$\gamma(SCF) = 6.6117 - 6.2551 = +0.3566.$

Thus the decision-makers should be improving SCF. However, owing to the evaluation of SCF requires opinions for a group of experts. The interactive consensus analysis is a necessity of group decision-making

5.3 Interactive consensus analysis calculations (Steps 11-13)

With respect to the consensus analysis of evaluation results, the decision-makers of decision problem assigns a consensus level *(CL)* is 0.75. The steps of interactive consensus analysis are presented as follows:

(1) Aggregate P_{ij}^k and I_{ij}^k to yield the aggregated rating (P_{ij}^A) and the aggregated importance (I_{ij}^A), respectively. As in step 5 and the *'most'* in first-stage assessment, using Eqs. (20) and (21), the aggregated results are obtained.

(2) Calculate the three consensus degrees $(CD_h^k,\ h=1,2,3;\ k=1,2,3)$ for each expert (E_k) with respect to P_{ij}^A, I_{ij}^A and $I_{(i)}^A$, respectively. Using Eq. (22), the similarity degrees (ρ) for each E_k with respect to P_{ij}^A, I_{ij}^A and $I_{(i)}^A$, respectively. Then using Eqs. (24)-(26), CD_h^k, $h=1, 2, 3;\ k=1, 2, 3,$ are thus given in Table 9.

(3) Since the consensus degrees for each expert, as shown in Table 9, are above the consensus level, i.e., CL = 0.75. So, the consensus reaching process would be completed if experts accept the evaluation results. When making a consistent decision for SCF, according to evaluation results obtained in both first-stage and second-stage assessment, the decision-makers should be improving SCF, and then identifying dimension X_3 (logistics processes flexibility) to represent the best direction for improvement, while dimension X_1 (supply network flexibility) and dimension X_5 (organizational design flexibility) are ranked second and third, respectively.

Table 9. The result of consensus analysis

	CD_1^k	CD_2^k	CD_3^k
E_1	0.9234	0.8909	0.9596
E_2	0.9193	0.9205	0.9303
E_3	0.9136	0.8901	0.9447

6. Conclusion

The proposed fuzzy method based on modified *LOWGA* operator in this paper has the advantages of directly acting on linguistic terms, computing results as linguistic terms, and preserving no loss of experts' assessment information. The proposed method is independent of the type of membership functions being used. It is appropriate for the situations in which assessment information may be qualitative, or the precise quantitative information is unavailable or the cost of its computation is too high. However, the method is limited in that it uses approximate reasoning, experts must perfectly distinguish the set of terms under a similar conception, and must use linguistic terms to express their opinions.

The above method with the group decision-making structure in the presence of multiple dimensions and related multiple metrics, used to evaluate the degree of SCF, is very useful in supply chain development. The importance grades or performance ratings must be improved until acceptable when evaluating the degree of SCF. If the degree of SCF is too low, it may have to be improved. The dimensions of SCF on which improvements must best be made should be determined by the assessment scheme. The model described in this study to evaluate the degree of

SCF involves group of experts and interactive consensus analysis. Therefore, the evaluation results are more objective and unbiased than those individually assessed. A case study of SCF evaluation has been conducted to exemplify the feasibility of the proposed method.

References

[1] Agarwal, A., Shankar, R., Tiwari, M. K., Modeling the metrics of lean, agile and leagile supple chain: An ANP-based approach, International Journal of Advanced Manufacturing Technology 173 (2006) 211-225.
[2] Ahn, H. J., Lee, H., Park, S. J., A flexible agent system for change adaptation in supple chains, Expert Systems with Applications 25 (2003) 603-618.
[3] Beach, R., Muhlemann, A. P., Price, D. H. R., Paterson, A., Sharp, J. A., A review of manufacturing flexibility, European Journal of Operational Research 122 (2000) 41-57.
[4] Chuu, S.J., Fuzzy multi-attribute decision-making for evaluating manufacturing flexibility, Production Planning and Control 16(3) (2005) 323-335.
[5] Delgado, M., Verdegay, J. L., Vila, M. A., On aggregation operations of linguistic labels, International Journal of Intelligent Systems 8 (1993) 351-370.
[6] De Toni, A., Tonchia, S., Manufacturing flexibility: a literature review, International Journal of Production Research 36(6) (1998) 1587-1617.
[7] Duclos, L. K., Vokurka, R. J., Lummus, R. R., A conceptual model of supple chain flexibility, Industrial Management and Data Systems 103(6) (2003) 446-456.
[8] Filev, D., Yager, R. R., Analytic properties of maximum entropy OWA operators, Information Sciences 85 (1995) 11-27.
[9] Garavelli, A. C., Flexibility configurations for the supple chain management, International Journal of Production Economics 85 (2003) 141-153.
[10] Giachetti, R. E., Martinez, L. D., Saenz, O. A., Chen, C. S., Analysis of the structural measures of flexibility and agility using a measurement theoretical framework, International Journal of Production Economics 86 (2003) 47-62.
[11] Golden, W., Powell, P., Towards a definition of flexibility: In search of the Holy Grail, Omega 28 (2000) 373-384.
[12] Gong, Z., An economic evaluation model of supple chain flexibility, European Journal of Operational Research 184 (2008) 745-758.
[13] Gupta, Y. P., Goyal, S., Flexibility of the manufacturing system: Concepts and measurement, European Journal of Operational Research 43 (1989) 119-135.
[14] Herrera, F., Herrera-Viedma, E., Linguistic decision analysis: steps for solving decision problems under linguistic information, Fuzzy Sets and Systems 115 (2000) 67-82.
[15] Herrera, F., Herrera-Viedma, E., Verdegay, J. L., A sequential selection process in group decision making with a linguistic assessment approach, Information Sciences 85 (1995) 223-239.
[16] Herrera, F., Herrera-Viedma, E., Verdegay, J. L., A model of consensus in group decision-making under linguistic assessment, Fuzzy Sets and Systems 78 (1996) 73-87.
[17] Herrera, F., Martinez, L., A 2-tuple fuzzy linguistic representation model for computing with words, IEEE Transactions on Fuzzy Systems 8(6) (2000) 746-752.
[18] Kacprzyk, J., Group decision making with a fuzzy linguistic majority, Fuzzy Sets and Systems 18 (1986) 105-118.
[19] Li, S., Rao, S. S., Ragu-Nathan, T. S., Ragu-Nathan, B., Development and validation of a measurement instrument for studying supple chain management practices, Journal of Operations Management 23 (2005) 618-641.
[20] Lummus, R. R., Duclos, L. K., Vokurka, R. J., Supple chain flexibility: Building a new model, Global Journal of Flexible Systems Management 4(4) (2003) 1-13.
[21] Lummus, R. R., Vokurka, R. J., Duclos, L. K., Delphi study on supple chain flexibility, International Journal of Production Research 43(13) (2005) 2687-2708.
[22] Mitchell, H.B., Estrakh, D.D., A modified OWA operator and its use in lossless DPCM image compression, International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems 5(4)

(1997) 429-436.
[23] O’Hagan, M., Aggregating template rule antecedents in real-time expert systems with fuzzy set logic, In: Proceedings 22nd Annual IEEE Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA (1988) 681-689.
[24] Olcer, A.I., Odabasi, A.Y., A new fuzzy multiple attributive group decision making methodology and its application to propulsion/manoeuvring system selection problem, European Journal of Operational Research 166 (2005) 93-114.
[25] Pujawa, N., Assessing supple chain flexibility: A conceptual framework and case study, International Journal of Integrated Supply Management 1(1) (2004) 79-97.
[26] Roa, K. M., Wadhwa, S., Understanding flexibility in supply chains: A conceptual framework and models, Global Journal of Flexible Systems Management 3(4) (2002) 1-12.
[27] Sanchez, A. M., Perez, M. P., Supply chain flexibility and firm performance: A conceptual model and empirical study in the automotive industry, International Journal of Operations and Production Management 25(7) (2005) 681-700.
[28] Sarker, B. R., Krishnamurthy, S., Kuthethur, S. G., A survey and critical review of flexibility measures in manufacturing systems, Production Planning and Control 5(6) (1994) 512-523.
[29] Sethi, A.K., Sethi, S.P., Flexibility in manufacturing: A surrey, International Journal of Flexible Manufacturing Systems 2(4) (1990) 289-328.
[30] Slack, N., Flexibility as a manufacturing objective, International Journal of Operations and Production Management 3(3) (1983) 4-13.
[31] Swamidass, P. M., Newell, W. T., Manufacturing strategy, environmental uncertainty and performance: A path analytic model, Management Science 33(4) (1987) 509-524.
[32] Tinchell, D. J., Radecliffe, D. F., A generic model of manufacturing flexibility based on system control hierarchies, International Journal of Production Research 34(1) (1996) 19-32.
[33] Upton, D.M., The management of manufacturing flexibility, California Management Review 36(2) (1994) 72-89.
[34] Vickery, S., Calantone, R., Droge, C., Supple chain flexibility: An empirical study,” Journal of Supple Chain Management 35(3) (1999) 16-24.
[35] Vokurka, R.J., O’Leary-Kelly, S.W., A review of empirical research on manufacturing flexibility, Journal of Operations Management 18 (2000) 485-501.
[36] Xu, Z. S., A method based on linguistic aggregation operators for group decision making with linguistic preference relations, Information Sciences 166 (2004) 19-30.
[37] Xu, Z. S., Deviation measures of linguistic preference relations in group decision making, Omega 33 (2005) 249-254.
[38] Xu, Z. S., Group decision making based on multiple types of linguistic preference relations, Information Sciences 178 (2008) 452-467.
[39] Yager, R. R., On ordered weighted averaging aggregation operators in multicriteria decision making, IEEE Transactions on Systems, Man, and Cybernetics 18(1) (1988) 183-190.
[40] Zadeh, L. A., Fuzzy set, Information and Control 8 (1965) 338-353.
[41] Zadeh, L. A., The concept of a linguistic variable and its application to approximate reasoning, Information Sciences 8 (1975) 199-249 (I); 301-357 (II); 9, 43-80 (III).
[42] Zimmermann, H.J., Fuzzy Set Theory and Its Applications, Kluwer Academic Publishers, Boston (1996).