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Agility index in the supply chain

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Abstract

To achieve a competitive edge in the rapidly changing business environment, companies must align with suppliers and customers to streamline operations, as well as working together to achieve a level of agility beyond individual companies. Consequently, agile supply chains are the dominant competitive vehicles. Embracing agile supply chain requires asking some important questions, namely: what exactly is agility and how can it be measured? Moreover, how can agility be effectively achieved and enhanced? Due to the ambiguity of agility assessment, most measures are described subjectively using linguistic terms. Thus, this study develops a fuzzy agility index (FAI) based on agility providers using fuzzy logic. The FAI comprises attribute' ratings and corresponding weights, and is aggregated by a fuzzy weighted average. To illustrate the efficacy of the method, this study also evaluates the supply chain agility of a Taiwanese company. This evaluation demonstrates that the method can provide analysts with more informative and reliable information for decision.

Keywords: Agile supply chain; Agility index; Agility measuring; Fuzzy logic; Supply chain management

1. Introduction

At the beginning of the 21st Century, the world faces significant changes in almost all aspects, especially marketing competition, technological innovations and customer demands. Mass markets are continuing to fragment as customers become increasing demanding and their expectations rise. These developments have caused a major revision of business priorities and strategic vision (Sharifi and Zhang, 1999). Companies have realized that agility is essential for their survival and competitiveness. This study further recognizes that no company possesses all of the resources required to meet every opportunity. Therefore, to achieve a competitive edge in the global market, companies must align with suppliers and customers to streamline operations and work together to achieve a level of agility beyond the reach of

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individual companies, which has come to be termed agility supply chain (ASC). ASC forges legally separate but operationally interdependent companies such as suppliers, designers, manufacturers, distribution services, etc. linked via a feedforward flow of materials and feedback flow of information; ASC focuses on promoting adaptability, flexibility, and has the ability to respond and react quickly and effectively to changing markets. ASC has been advocated as the 21st century supply paradigm, and is seen as a winning strategy for companies wishing to become national and international leaders (Yusuf et al., 1999).

A supply chain is a loosely related group of companies formed to enable collaboration to achieve mutually agreed on goals (Christopher, 2000). However, the ability to build agile relationships has developed more slowly than anticipated, because technology for managing agile relationships is still being developed (Sharp et al., 1999). Thus, in embracing ASC numerous important questions must be asked regarding agility, including: What exactly is agility and how can it be measured? How will companies know when they have agility, as no simple metrics or indices are available? If a company wishes to improve its agility, how can that company identify the principal obstacles to improvement? How can one assist in achieving agility effectively (Sharp et al., 1999; Ren et al., 2001; Yusuf et al., 2001)? Therefore, this study attempts to solve some of these problems, with a particular focus on measuring agility and identifying the main obstacles to agility enhancement.

2. Related literature

To assist managers in better achieving an ASC, numerous studies have attempted to measure organization' agility. Some authors (Yusuf et al., 2001; Youssuf, 1993) defined the agility index as a combination of measuring the intensity levels of agility enable-attributes, while other measuring methods (Ren et al., 2000; Meade and Rogers, 1997) were developed based on the logical concept of analytic hierarchical process (AHP); furthermore, a mass customization product manufacturing agility evaluation index system was devised by Yang and Li (2002). These methods are easy to implement and focus attention on the key issues. However, the foundation of the agile supply chain lies in the integration of customer sensitivity, organization, processes, networks and information systems. Based on previous research (Karwowski and Mital, 1986), in situations where assessors are unable to make significant assessment, linguistic expressions are used to estimate ambiguous events. Owing to the either "imprecise" or "vague" definition of agility enable-attributes, agility measurements are described subjectively using linguistic terms, which are characterized by multi-possibility. Thus, the scoring of the above approaches can always be criticized, because the scale used for scoring agility enable-attributes suffers two limitations: (1) such approaches do not consider the ambiguity and multi-possibility associated with the mapping of individual judgment to a number, and (2) subjective judgment of evaluators significantly influence those methods.

To overcome the vagueness of the agility assessment, Tsourveloudis and Valavanis (2002) designed some IF–THEN rules for measuring enterprise agility based on fuzzy logic. The disadvantage of this framework is its inflexibility since the IF–THEN rules must be redesigned to fit the new situation as more levels of linguistic terms or different membership functions are used.

To be truly agile, a supply chain must possess a number of distinguishing enable-attributes such as marketing/customer sensitivity, cooperative relationships, process integration, and information integration (Christopher, 2000; Goldman et al., 1995; Van Hoek et al., 2001). Due to the qualitative and ambiguous attributes linked to agility assessment, most measures are described subjectively using linguistic terms, and cannot be handled effectively using conventional assessment approaches. However, fuzzy logic provides an effective means of dealing with problems involving imprecise and vague phenomena. Fuzzy logic, by making no global assumptions regarding independence, exhaustiveness, and exclusiveness, can tolerate a blurred boundary in definitions (Lin and Chen, 2004). Fuzzy concepts enable assessors to use linguistic terms to assess indicators in natural language expressions, and each linguistic term can be associated with a membership function. Furthermore, fuzzy logic has found significant applications in management decisions (Lin and Chen, 2004; Machacha and Bhattacharya, 2000).

From the above literature review, to assist managers in better achieving an ASC, a supply chain agility evaluation model based on fuzzy logic and the multi-criteria decision-making (MCDM) is proposed to provide a means for both measuring supply chain agility and also identifying the major obstacles to improving agility levels.

3. Routes to agility

An agile supply chain aims to enrich/satisfy customers and employees. An agile supply chain thus should possess the ability to respond appropriately to changes occurring in its business environment. Agility thus might be defined as the ability of a supply chain to rapidly respond to changes in market and customer demands (Sharp et al., 1999). Agile supply chain can be considered to be structure under the goals of satisfying customers and employees within which every organization can design its own business strategies, organization, processes and information systems. The structure is supported by four principles: mastering change and uncertainty, innovative management structures and virtual organization, cooperative relationships, and flexible and intelligent technologies (Sharp et al., 1999; Youssuf, 1993). These fours principles are underpinned by a methodology to integrate them into a coordinated, interdependent system, and for translating them into strategic competitive capabilities. Based on a review of the normative literature (Sharifi and Zhang, 1999; Yusuf et al., 1999; Christopher, 2000; Sharp et al., 1999; Yusuf et al., 2001; Ren et al., 2000; Weber, 2002), the authors have designed a conceptual model of agile supply chain, as shown in Fig. 1, culminating in many research propositions.

The driver of agility is change. Although not new, change is occurring faster than previously. Turbulence and uncertainty in the business environment have become the main causes of supply chain failure (Stratton and Warburton, 2003). Different companies with different characteristics and in different circumstances experience different specific changes that may be unique to them. However, common characteristics exist which can have general consequences for all companies. Summarizing previous studies (Sharifi and Zhang, 1999; Yusuf et al., 1999; Christopher, 2000), the general areas of business environment change are categorized as (1) market volatility, (2) intense competition, (3) changes in customer requirements, (4) accelerating technological change, and (5) change in social factors. Based on the business environment assessment, the level of supply chain agility required can be set by the organization.

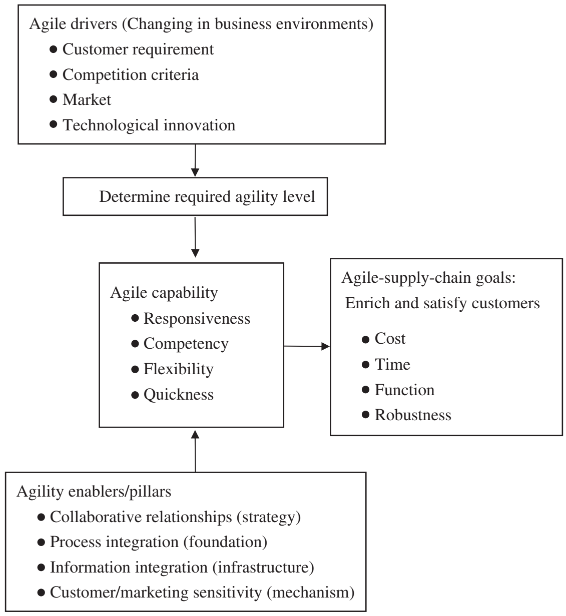

Fig. 1. Conceptual model of agile supply chain.

Agile supply chain concerns change, uncertainty and unpredictability within its business environment and makes appropriate responses to changes. Therefore, an agile supply chain requires various distinguishing capabilities, or "fitnesses". These capabilities include four main elements (Christopher, 2000; Sharp et al., 1999; Giachetti et al., 2003): (1) responsiveness, which is the ability to identify changes and respond to them quickly, reactively or proactively, and also to recover from them; (2) competency, which is the ability to efficiently and effectively realize enterprise objectives; (3) flexibility/adaptability, which is the ability to implement different processes and apply different facilities to achieve the same goals; and (4) quickness/speed, which is the ability to complete an activity as quickly as possible.

Agility-enabled attributes are supposed to be the aspects of agility content and to determine the entire supply chain behavior, so that agility-enabled attributes enable the measuring of supply chain agility. To be truly agile, Goldman et al. (1991) created a demand for identifying the menu of agility-enabled attributes required for an organization to become an agile supply chain and from which organization leaders could select required items. Hence, based on other related works (Sharifi and Zhang, 1999; Yusuf et al., 1999; Christopher, 2000; Sharp et al., 1999; Ren et al., 2001; Ren et al., 2000; Weber, 2002) and the finding of this study, key enablers/pillars are classified into four categories.

(1) Collaborative relationship: this supply chain strategy is the ability to attract the buyers and suppliers to work collaboratively, jointly develop products and share information.
(2) Process integration: as the foundation of the supply chain, process integration means that the supply chain is a confederation of partners linked into a network.
(3) Information integration: as the infrastructure of the supply chain, it includes the ability to use information technology to share data between buyers and supplies, thus effectively creating a virtual supply chain. Virtual supply chains are information-based rather than inventory-based.
(4) Customer/marketing sensitivity: as the mechanism of the supply chain, it includes the ability to read and respond to real customer requirements, and also to master change and uncertainty.

4. Method and algorithm

The framework of the fuzzy agility evaluation method (FAEM), as shown in Fig. 2, comprises three main parts. The first part involves examining business operation environments, measuring agility drivers and identifying of agile supply chain capabilities. Through this evaluation, the agility level needed by a supply chain can be determined and the agile-enabled attributes can be identified for measuring agility. The second part of the framework assesses the agile-enabled attributes and synthesizes fuzzy ratings and weights to obtain the fuzzy agility index (FAI) of a supply chain and the fuzzy performance importance index for each agile supply chain attribute (ASCA). Moreover,

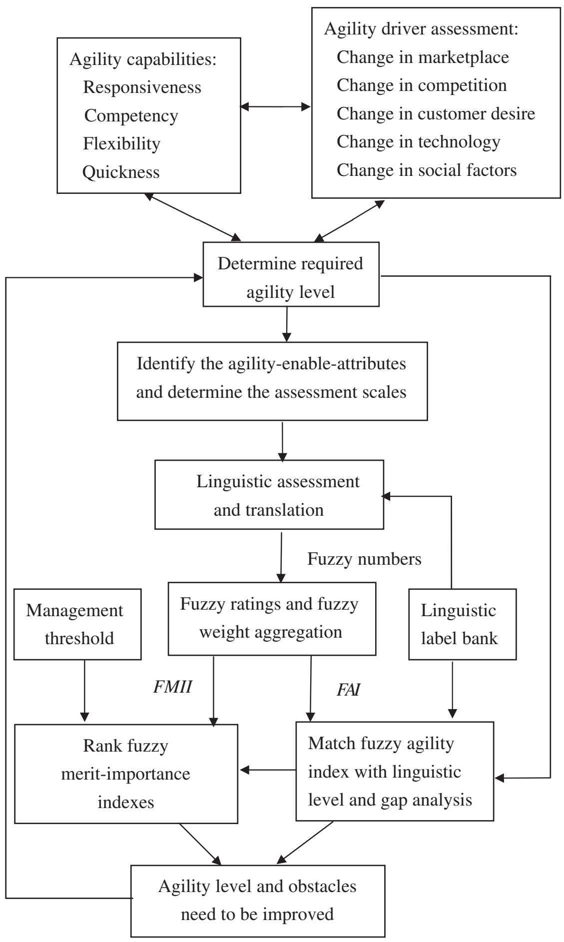

Fig. 2. Framework for evaluating supply chain agility.

the third part of the framework matches the FAI with an appropriate linguistic term to identify the supply chain agility level, and selects major barriers to enable managers may proactively implement appropriate improving measures. A stepwise description is presented below:

1. Form a self-assessment committee, determine the required agility level and select agile-enabled attributes for assessment.
2. Collect and survey data or information.
3. Determine the appropriate preference scale for assessing the ratings and weights of the agile-enable-attributes.
4. Measure the agile-enabled-attributes' ratings and weight using linguistic terms.
5. Approximate the linguistic ratings and weights with fuzzy numbers.
6. Aggregate fuzzy ratings and fuzzy weights into the FAI of a supply chain.
7. Translate the FAI into an appropriate linguistic level.
8. Analyze gaps and identify barriers to agility.

4.1. Form a self-assessment committee, determine the required agility level and select agile-enable-attributes for assessment

For successful knowledge acquisition, various experts must be chosen from different departments. This approach not only ensures complete domain coverage, but also encourages that all areas of business will receive equal emphasis in the final system.

Preliminary assessment: the committee must examine the business operation environments, determine the level of agility required by the agile supply chain and determine the capabilities of the agile supply chain in response to unpredictable changes. Based on the external environment survey and internal capability assessment, a supply chain can identify the agile-enabling-attributes that enable the achievement of the so-called capabilities and provide for agility measurement. In summing up previous studies, agility-enabling-attributes can be broadly classified into four categories: collaborative relationship, process integration, information integration and customer/marketing sensitivity. Based on this framework, companies can develop sub-attributes that affect agility achievement.

4.2. Collecting survey data or information

To prepare for agility assessment, the assessors must survey and study the related data or information on agility implementation, focusing particularly on challenges in the business environment and on company performance. The survey aims to understand the information that will be considered in assessing agility-enable-attributes.

4.3. Preference scale system

Due to imprecise and ambiguous criteria in agility evaluation, a precision-based evaluation may be impractical. Assessments thus are frequently measured linguistically rather than numerically. Ad hoc usage of linguistic terms and corresponding membership functions is characteristic of fuzzy logic. Notably, many popular linguistic terms and corresponding membership functions have been proposed for linguistic assessment (Karwowski and Mital, 1986; Chen and Hwang, 1992). For convenience, as a substitute for assessor elicitation, linguistic terms and corresponding membership functions were obtained directly from previous studies, or based on the needs of cognitive perspectives, and available data characteristics used data from previous studies as a basis for modifying linguistic terms to meet individual situations and requirements.

4.4. Aggregate fuzzy ratings and weights into the FAI of a supply chain

Many methods can be adopted to aggregate the assessments of multiple decision-makers, such as arithmetic mean, median, and mode. Since the average operation is the most widespread aggregation method, this study uses the arithmetic mean to pool the opinions of experts.

Assume that a committee of m evaluators, i.e., E_t, $t = 1, 2, \ldots, m$, conducts the agility evaluation. Let $F_j, j = 1, 2, \ldots, n$, be factors for measuring agility; let $R_{tj}=(a_{jt},b_{jt},c_{jt})$ be the fuzzy numbers approximating the linguistic ratings given to F_t by assessor E_t, and let $W_{tj}=(x_{jt},y_{jt},z_{jt})$ be the fuzzy numbers approximating the linguistic importance weights assigned to F_t by assessor E_t. The average fuzzy rating R_j and average fuzzy weight W_j, the aggregation of the opinions of experts then are calculated as

$$R_j=(a_j,b_j,c_j)=(R_{j1}(+)R_{j2}(+)\cdots(+)R_{jm})/m, \tag{1}$$

$$W_j=(x_j,y_j,z_j)=(W_{j1}(+)W_{j2}(+)\cdots(+)W_{jm})/m. \tag{2}$$

Fuzzy agility index (FAI) is an information fusion, which consolidates the fuzzy ratings and fuzzy weights of all of the factors that influence agility. FAI represents overall supply chain agility. Supply chain agility increases with increasing FAI. Thus, the membership function of FAI is used to determine the agility level.

Let R_j and W_j, $j=1,2,\ldots,n$, respectively, denote the average fuzzy rating and average fuzzy weight given to factor j by the evaluation committee. The fuzzy agility index, FAI, then is defined as

$$\mathrm{FAI}=\sum_{j=1}^{n}(W_j(\cdot)R_j)\bigg/\sum_{j=1}^{n}W_j. \tag{3}$$

The membership function of FAI can be calculated using the fuzzy weighted average operation; the calculation can be found in Kao and Liu (2001).

4.5. Match the fuzzy attractiveness rating with an appropriate linguistic level

Once the FAI is obtained, to identify the agility level, the FAI can be further matched with the linguistic label, the membership function of which is the same as (or closest to) the membership function of the FAI from the membership function of the natural-language expression set of agility label (AL).

Several methods have been proposed for matching the membership function with linguistic terms, of which include (1) Euclidean distance, (2) successive approximation, and (3) piecewise decomposition. This study recommends utilizing the Euclidean distance method since it is the most intuitive method for humans to use in perceiving proximity (Guesgen and Albrecht, 2000).

The Euclidean method calculates the Euclidean distance from the given fuzzy number to each of the fuzzy numbers representing the natural-language agility level expression set. Assuming the natural-language agility level expression set is AL, then U_{FAI} and U_{AL_i} represent the membership functions of the FAI and natural-language agility i, respectively. The distance between U_{FAI} and U_{AL_i} then can be calculated as

$$d(\mathrm{FAI},\mathrm{AL}_i)=\left\{\sum_{x\in p}(U_{\mathrm{FAI}}(x)-U_{\mathrm{AL}_i}(x))^2\right\}^{1/2} \tag{4}$$

where $p=\{x_0,x_1,\ldots,x_m\}\subset[0,1]$ so that $0=x_0<x_1<\cdots<x_m=1.0$. To simplify, let $p=\{0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1\}$. The distance from the FAI to natural-language agility i can then be calculated, and the closest natural expression with the smallest distance U_{FAI} to U_{AL_i} can be identified.

4.6. Rank fuzzy merit-importance indexes of agility provider

As mentioned above, agility evaluation not only determines supply chain agility, but also helps managers identify the main adverse factors involved in implementing an appropriate action plan to improve the agility level.

To identify the main obstacles to improving the agility level, a fuzzy performance-importance index (FPII) is defined, which combines the performance rating and weighting of each agile-enable-attribute. FPII represents an effect which influences supply chain agility level. The degree of contribution of supply chain agility for a factor decreases with decreasing FPII. Thus, the score of the FPII of a factor is used for identifying the principal obstacles of supply chain agility.

If used directly to calculate the FPII, the importance weights W_i will neutralize the performance ratings in calculating FPII; in this case, it will become impossible to identify the actual main obstacles (low performance rating and high importance). If W_i is high, then the transformation [(1,1,1) (−) W_i] is low. Consequently, to elicit a factor with low performance rating and high importance, for each agile-enable-attribute i, the fuzzy performance-importance index FPII_i, indicating the effect of each agile-enable-attribute that contributes to supply chain agility which, is defined as

$$\text{FMII}_i = R_i(\cdot)[(1,1,1)(-)W_i]. \tag{5}$$

Since fuzzy numbers do not always yield a totally ordered set in the manner of real numbers, the FPIIs must be ranked. Numerous methods have been devised for ranking fuzzy numbers (Chen and Hwang, 1992; Lee-Kwang and Lee, 1999). Here, the fuzzy numbers are ranked based on the left-and-right fuzzy-ranking method of Chen and Hwang Chen and Hwang (1992), since this method not only preserves the ranking order but also considers the absolute location of each fuzzy number. The disadvantage of this method is that the ranking score will be different as different fuzzy maximizing and minimizing sets be used.

In the proposed ranking method, the fuzzy maximizing and minimizing sets are, respectively, defined as

$$U_{\max}(x) = \begin{cases} x, & 0 \leqslant x \leqslant 1, \\ 0, & \text{otherwise}, \end{cases} \tag{6}$$

$$U_{\min}(x) = \begin{cases} 1-x, & 0 \leqslant x \leqslant 1, \\ 0, & \text{otherwise}. \end{cases} \tag{7}$$

Given a triangular fuzzy number FPII defined as $U_{\text{FPII}} : R \to [0,1]$ which has a triangular membership function, the right-and-left scores of FPII can be obtained, respectively, as

$$U_{\text{R}}(\text{FPII}) = \sup_x [U_{\text{FPII}}(x) \wedge U_{\max}(x)], \tag{8}$$

$$U_{\text{L}}(\text{FPII}) = \sup_x [U_{\text{FPII}}(x) \wedge U_{\min}(x)], \tag{9}$$

where $\wedge$ denotes the Min operator.

Finally, the total score of FPII can be calculated by combining the left-and-right scores. The total score is defined as

$$U_{\text{T}}(\text{FPII}) = [U_{\text{R}}(\text{FPII}) + 1 - U_{\text{L}}(\text{FPII})]/2. \tag{10}$$

For example: Given a fuzzy number FPII = (0.025, 0.081, 0.181), the right-and-left scores of FPII are:

$$U_{\text{R}}(\text{FPII}) = \sup_x [U_{\text{FPII}}(x) \wedge U_{\max}(x)] = 0.1645,$$

$$U_{\text{L}}(\text{FPII}) = \sup_x [U_{\text{FPII}}(x) \wedge U_{\min}(x)] = 0.9233.$$

Thus, the total score of FPII is calculated as

$$\begin{aligned} U_{\text{T}}(\text{FPII}) &= [U_{\text{R}}(\text{FPII}) + 1 - U_{\text{L}}(\text{FPII})]/2 \\ &= 0.1206. \end{aligned}$$

5. Case study

This section cites the supply chain agility evaluation of a Taiwan based international IT products company to demonstrate that the FAEM procedure can be applied to measure supply chain agility.

5.1. Subject of case study

As an internationally recognized IT products and services company with a good reputation among PC vendors, AW has an annual turnover of around US$3.5 billion. Involved in marketing and service operations across the Asia-Pacific, Europe, the Middle East, and the Americas, AW supports dealers and distributors in over 100 countries. When IT product markets matured during the late 1990s, large multinational firms endeavored to simultaneously provide local responsiveness and global integration in response to an uncertain business environment. Furthermore, due to the downturn in the global IT products market in 2000 and the entry of low cost suppliers who from new development Asian countries, particularly China, companies found it increasingly difficult to ensure/

achieve growth and success. These changes have presented AW with significant challenges. To achieve and sustain global success and satisfy based on its experience of globalization, AW strove to become a major global supplier to satisfy its customers, reduce its time to market, lower its total ownership costs, and boost its overall competitiveness.

The IT product supply chain is characterized by poor dynamics and volatile product demand. Since ASC has been advocated as the 21st century business paradigm and is perceived as the optimum strategy for companies seeking to become international leaders, the corporate management team (the executive team) set the goal of achieving an extremely agile supply chain through continuous improvement; an assessment team thus was organized and led by the executive vice president to achieve this. This assessment team comprised key personnel with good knowledge of agile supply chain and an excellent understanding of problems specific to the company, and the team then was assigned the task of investigating and correcting these problems. The team members included the global manufacturing manager, information center manager, marketing vice president, general auditor, and a senior project manager. Each of these members brought specific perspectives to the decision-making, and decisions were made based on consensus, since all parties would share responsibility for the decision success or failure.

5.2. Commitments of the assessment

Top-level commitment is critical for achieving supply chain agility. To demonstrate top-level "commitment", the CEO agreed to specific self-assessment objectives, as follows:

- To conduct a supply chain-wide self-assessment and establish an assessment criteria.
- To identify supply chain strengths and areas for improvement, and also to feed these back to the corporate management team.
- To feed improvement opportunities into the business planning cycle, including corporate objectives.
- To devise a process of self-assessment using the ASC model as an annual part of the business planning cycle.

5.3. Measuring supply chain agility using fuzzy logic

When the concept of the agile supply chain first emerged, AW had several questions, including: What exactly is agility and how can it be measured? How can AW develop both analytical and intuitive understandings of "agility" in an ever-changing demand market? Answering these questions requires knowledge of what to measure, how to measure it and how to assess the results. Owing to ill-defined and ambiguous agile-enable-attributes, most measures are described subjectively using linguistic terms, and conventional assessment approaches are ineffective for such measurement. Furthermore, fuzzy logic is useful for dealing with such decisions. The assessors endeavored to apply a fuzzy logic approach in their assessment. To achieve a large-scale global and extremely agile supply chain, the following supply chain agility evaluation procedure was used:

Step 1: Identify the agile-enabling attributes: The first task in successfully analyzing and measuring supply chain agility is to identify agility-enablers. To accurately elicit assessment criteria that reflected the complete set of attributes of an agile supply chain, the committee proceeded through a series of discussion activities, the content of which mainly included changes in marketplace, competition circumstances and criteria, technological innovation, changes in customer requirements, company strategy and the agility capability needs. Finally, based on the general areas of agility enablers, collaborative relationship, process integration, information integration and customer/marketing sensitivity, the supply chain capability requirements were translated into corresponding agility-enable-attributes to determine the hierarchical ASCA structure, as listed in Table 1.

Step 2: Hold review meetings: To facilitate assessor holistic understanding of the perfor-

Table 1
Agility attributes for measuring agility index in the supply chain

Agile supply chain	Main attributes	Sub-attributes
Responsiveness Competency Flexibility Quickness	Collaborative relationships (Strategy) ($ASCA_1$)	Trust-based relationships with customers/suppliers ($ASCA_{11}$) Focused on developing core competencies' through process excellence ($ASCA_{12}$) Organized along functional lines ($ASCA_{13}$) Team-based goals and measures ($ASCA_{14}$) First choice partner ($ASCA_{15}$) Actively share intellectual property with partners ($ASCA_{16}$) Marketing information fluid cluster of network associate ($ASCA_{17}$) Concurrent execution of activities throughout the supply chain ($ASCA_{18}$)
	Process integration (Foundation) ($ASCA_2$)	Facilitate rapid decision making ($ASCA_{21}$) Infrastructure in place to encourage innovation within shortening time-frames ($ASCA_{22}$) Pro-actively update the mix of available manufacturing processes in the SC network ($ASCA_{23}$) Organizational walls do not exist ($ASCA_{23}$) Vertical integration ($ASCA_{25}$)
	Information integration (Infrastructure) ($ASCA_3$)	Capture demand information immediately ($ASCA_{31}$) Prefer to keep information on file ($ASCA_{32}$) Information accessible supply chain-wide ($ASCA_{33}$) Virtual connection ($ASCA_{34}$)
	Customer/marketing sensitivity (Mechanism) ($ASCA_4$)	Customer-based measures ($ASCA_{41}$) Product ready for use by individual customers ($ASCA_{42}$) See opportunities to increase customer value ($ASCA_{43}$) Customer-driven products ($ASCA_{44}$) Retain and grow customer relationships ($ASCA_{45}$) Products with substantial added value for customers ($ASCA_{46}$) Fast introduction of new products ($ASCA_{47}$)

mance, plans and strategies, the business development manager was asked to conduct a briefing session for introducing the business development plan. Furthermore, a series of side discussion activities, and a range of assessment material were collected and evaluated, the content of which mainly included:

- *Policy and strategy:* company policies, plans and strategies, quality documents, monitoring information and feedback reports.
- *Characteristics:* company priorities (quality, cost, time, customers' satisfaction and so on), perceived quickness, responsiveness, core competencies, specific company problems.
- *Changes:* key causes of firm change, and strategies take to response the change.
- *Business structure:* organization, business process, human resources, information system and innovation structures which facilitate supply chain agility.
- *Practices:* responses to change.

Step 3: Devise preference evaluation terms: Since the needs of cognitive perspectives, the available data characteristics and differences in learning or experience connect the assessment terms, managers initially were unable to reach a consensus. For convenience and instead of extended debate and argument, the linguistic terms

Table 2
Linguistic variables and their corresponding fuzzy numbers for assessing

Performance ratings		Importance weights	
Linguistic variables	Fuzzy numbers	Linguistic variables	Fuzzy numbers
Worst	(0, 0.05, 0.15)	Very Low	(0, 0.05, 0.15)
Very Poor	(0.1, 0.2, 0.3)	Low	(0.1, 0.2, 0.3)
Poor	(0.2, 0.35, 0.5)	Fairly Low	(0.2, 0.35, 0.5)
Fair	(0.3, 0.5, 0.7)	Medium	(0.3, 0.5, 0.7)
Good	(0.5, 0.65, 0.8)	Fairly High	(0.5, 0.65, 0.8)
Very Good	(0.7, 0.8, 0.9)	High	(0.7, 0.8, 0.9)
Excellent	(0.85, 0.95, 1.0)	Very High	(0.85, 0.95, 1.0)

and corresponding membership functions used in previous studies were adopted as a basis of evaluation terms and modified to incorporate the specific requirements of AW. Finally, the committee set the rating scale (i.e., Worst [W], Very Poor [VP], Poor [P], Fair [F], Good [G], Very Good [VG], Excellent [E]) used to measure the ratings of the agile-enable-attributes; the weighting scale (i.e., Very Low [VL], Low [L], Fairly Low [FL], Medium [M], Fairly High [FH], High [H], Very High [VH]) used to measure the weighting of agile-enable-attributes. Furthermore, based on its long-standing recognition of the meaning of linguistic value, the committee selected the fuzzy numbers, as listed in Table 2, to approximate linguistic ratings and weights for performance and importance, respectively.

Step 4: Measure the agile-enable-attributes using linguistic terms, and approximate the linguistic terms using fuzzy numbers: Based on the collected data and their personal experience/knowledge, committee members applied the rating terms to assess the performance of the different criteria and to evaluate the relative importance of both main criteria and sub-criteria. The results are listed in Tables 3 and 4, respectively. Furthermore, based on the corresponding relation between the linguistic terms and fuzzy numbers, as listed in Table 2, the linguistic terms of rating and weight were approximated with fuzzy numbers.

Step 5: Aggregate the fuzzy ratings and fuzzy weights into a FAI of a supply chain: Eqs. (1) and (2) can be used to aggregate the rating and weight fuzzy numbers under the same criterion. For example, the average fuzzy rating of the trust-based relationships with customers/suppliers (ASCA_{11}) was calculated as

$$\begin{aligned}\mathrm{ASCA}_{11} = {} & [(0.5, 0.65, 0.8)(+)(0.7, 0.8, 0.9)(+)\\ & (0.7, 0.8, 0.9)(+)(0.5, 0.65, 0.8)(+)\\ & (0.7, 0.8, 0.9)]/5 = (0.62, 0.74, 0.86).\end{aligned}$$

Applying the same equation, Table 5 lists other average fuzzy ratings and average fuzzy weights of main criteria ASCA_i and sub-criteria ASCA_{ij}.

Furthermore, using Eq. (3), the integrated fuzzy rating of the main criteria ASCA_3 was calculated as

$$\begin{aligned}\mathrm{ASCA}_3 = {} & [(0.66, 0.77, 0.88)(\cdot)(0.79, 0.89, 0.96)\\ & (+)(0.38, 0.56, 0.74)(\cdot)(0.46, 0.62, 0.78)\\ & (+)(0.42, 0.59, 0.76)(\cdot)(0.82, 0.92, 0.98)\\ & (+)(0.46, 0.62, 0.78)(.)(0.73, 0.83, 0.92)]/\\ & [(0.79, 0.89, 0.96)(+)(0.46, 0.62, 0.78)\\ & (+)(0.82, 0.92, 0.98)(+)(0.73, 0.83, 0.92)]\\ \cong {} & (0.477, 0.641, 0.801).\end{aligned}$$

Applying the same equation, other integrated fuzzy ratings were obtained as

$$\mathrm{ASCA}_1 \cong (0.572, 0.722, 0.857),$$
$$\mathrm{ASCA}_2 \cong (0.433, 0.607, 0.771),$$
$$\mathrm{ASCA}_4 \cong (0.55, 0.70, 0.84).$$

Finally, applying Eq. (3) again, the FAI of the AW supply chain was obtained as

$$\mathrm{FAI} \cong (0.564, 0.669, 0.821).$$

Table 3
Ratings of sub-criteria assigned by assessors using linguistic terms

$ASCA_i$	$ASCA_{ij}$	Assessors				
		E_1	E_2	E_3	E_4	E_5
$ASCA_1$						
	$ASCA_{11}$	G	VG	VG	G	VG
	$ASCA_{12}$	G	G	F	VG	G
	$ASCA_{13}$	VG	G	G	G	VG
	$ASCA_{14}$	VG	G	G	VG	G
	$ASCA_{15}$	G	F	G	G	F
	$ASCA_{16}$	F	G	F	F	G
	$ASCA_{17}$	VG	E	VG	E	VG
	$ASCA_{18}$	E	VG	E	VG	E
$ASCA_2$						
	$ASCA_{21}$	F	P	G	F	F
	$ASCA_{22}$	G	VG	G	VG	VG
	$ASCA_{23}$	F	F	G	F	G
	$ASCA_{24}$	P	F	F	P	F
	$ASCA_{25}$	VG	G	E	VG	VG
$ASCA_3$						
	$ASCA_{31}$	VG	VG	VG	G	VG
	$ASCA_{32}$	G	F	F	G	F
	$ASCA_{33}$	G	F	G	F	G
	$ASCA_{34}$	F	G	F	G	VG
$ASCA_4$						
	$ASCA_{41}$	VG	E	E	G	VG
	$ASCA_{42}$	G	VG	VG	G	F
	$ASCA_{43}$	F	F	F	G	F
	$ASCA_{44}$	G	G	VG	F	F
	$ASCA_{45}$	G	F	G	VG	G
	$ASCA_{46}$	VG	G	VG	VG	E
	$ASCA_{47}$	G	VG	VG	E	G

Table 4
Weights of main criteria and sub-criteria assigned by assessors using linguistic terms

$ASCA_i$	$ASCA_{ij}$	Assessors				
		E_1	E_2	E_3	E_4	E_5
$ASCA_1$		H	VH	VH	H	**H**
	$ASCA_{11}$	VH	H	VH	VH	H
	$ASCA_{12}$	FH	H	FH	FH	M
	$ASCA_{13}$	H	VH	H	H	VH
	$ASCA_{14}$	H	H	FH	VH	H
	$ASCA_{15}$	FH	H	FH	M	M
	$ASCA_{16}$	H	FH	FH	VH	H
	$ASCA_{17}$	H	FH	H	H	FH
	$ASCA_{18}$	VH	VH	H	VH	VH
$ASCA_2$		H	VH	H	H	H
	$ASCA_{21}$	VH	H	VH	VH	H
	$ASCA_{22}$	H	VH	FH	VH	H
	$ASCA_{23}$	FH	H	FH	M	FH
	$ASCA_{24}$	H	H	H	H	VH
	$ASCA_{25}$	H	VH	H	H	FH
$ASCA_3$		H	VH	H	H	VH
	$ASCA_{31}$	VH	H	VH	VH	H
	$ASCA_{32}$	FH	M	FH	H	M
	$ASCA_{33}$	VH	VH	VH	VH	H
	$ASCA_{34}$	H	VH	H	H	H
$ASCA_4$		VH	VH	H	VH	VH
	$ASCA_{41}$	VH	H	VH	H	VH
	$ASCA_{42}$	H	VH	VH	H	H
	$ASCA_{43}$	FH	VH	H	H	H
	$ASCA_{44}$	VH	H	H	VH	H
	$ASCA_{45}$	VH	VH	VH	H	VH
	$ASCA_{46}$	VH	VH	VH	VH	VH
	$ASCA_{47}$	H	H	VH	VH	H

Step 6: The FAI is translated into an appropriate linguistic term. After obtaining the FAI, to identify the agility level, the assessment committee further approximated a linguistic label with a meaning identical or close to the meaning of the FAI from the natural-language expression set of the agility level (AL). In this case, the agility level set AL = {Definitely Agile [DA], Extremely Agile [EA], Very Agile [VA], Highly Agile [HA], Agile [A], Fairly [F], Slightly Agile [SA], Low Agile [LA], Slowly [S]} was selected for labeling, and the linguistics and corresponding membership functions are shown in Fig. 3. Eq. (4) then was used to calculate the Euclidean distance d from the FAI to each member in set AL:

$$D(\text{FAI}, \text{DA}) = 1.8895, \quad D(\text{FAI}, \text{EA}) = 1.6813,$$
$$D(\text{FAI}, \text{VA}) = 0.7912, \quad D(\text{FAI}, \text{HA}) = 1.1149,$$
$$D(\text{FAI}, \text{A}) = 1.8142, \quad D(\text{FAI}, \text{F}) = 1.8895,$$
$$D(\text{FAI}, \text{SA}) = 1.8895, \quad D(\text{FAI}, \text{LA}) = 1.8895,$$
$$D(\text{FAI}, \text{S}) = 1.8895.$$

Thus, by matching a linguistic label with the minimum D, the AW supply chain can be labeled "Very Agile".

Step 7: Perform gap analysis and identify the barriers to agility: Although the agility index of the

Table 5
Average fuzzy ratings and average fuzzy weights of main criteria and sub-criteria

$ASCA_i$	$ASCA_{ij}$	Fuzzy average ratings	Fuzzy average weights
$ASCA_1$			(0.76, 0.86, 0.94)
	$ASCA_{11}$	(0.62, 0.74, 0.86)	(0.79, 0.89, 0.96)
	$ASCA_{12}$	(0.5, 0.65, 0.8)	(0.5, 0.65 0.8)
	$ASCA_{13}$	(0.58, 0.71, 0.84)	(0.76, 0.86, 0.94)
	$ASCA_{14}$	(0.58, 0.71, 0.84)	(0.69, 0.8, 0.9)
	$ASCA_{15}$	(0.42, 0.59, 0.76)	(0.46, 0.62, 0.78)
	$ASCA_{16}$	(0.38, 0.56, 0.74)	(0.65, 0.77, 0.88)
	$ASCA_{17}$	(0.76, 0.86, 0.94)	(0.62, 0.74, 0.86)
	$ASCA_{18}$	(0.79, 0.89, 0.96)	(0.82, 0.92, 0.98)
$ASCA_2$			(0.73, 0.83, 0.92)
	$ASCA_{21}$	(0.32, 0.5, 0.68)	(0.79, 0.89, 0.96)
	$ASCA_{22}$	(0.62, 0.74, 0.86)	(0.72, 0.83, 0.92)
	$ASCA_{23}$	(0.38, 0.56, 0.74)	(0.5, 0.65 0.8)
	$ASCA_{24}$	(0.26, 0.44, 0.62)	(0.73, 0.83, 0.92)
	$ASCA_{25}$	(0.69, 0.8, 0.9)	(0.69, 0.8, 0.9)
$ASCA_3$			(0.76, 0.86, 0.94)
	$ASCA_{31}$	(0.66, 0.77, 0.88)	(0.79, 0.89, 0.96)
	$ASCA_{32}$	(0.38, 0.56, 0.74)	(0.46, 0.62, 0.78)
	$ASCA_{33}$	(0.42, 0.59, 0.76)	(0.82, 0.92, 0.98)
	$ASCA_{34}$	(0.46, 0.62, 0.78)	(0.73, 0.83, 0.92)
$ASCA_4$			(0.82, 0.92, 0.98)
	$ASCA_{41}$	(0.72, 0.83, 0.92)	(0.79, 0.89, 0.96)
	$ASCA_{42}$	(0.54, 0.68, 0.82)	(0.76, 0.86, 0.94)
	$ASCA_{43}$	(0.34, 0.53, 0.72)	(0.69, 0.8, 0.9)
	$ASCA_{44}$	(0.46, 0.62, 0.78)	(0.76, 0.86, 0.94)
	$ASCA_{45}$	(0.5, 0.65, 0.8)	(0.82, 0.92, 0.98)
	$ASCA_{46}$	(0.69, 0.8, 0.9)	(0.85, 0.95, 1.0)
	$ASCA_{47}$	(0.65, 0.77, 0.88)	(0.76, 0.86, 0.94)

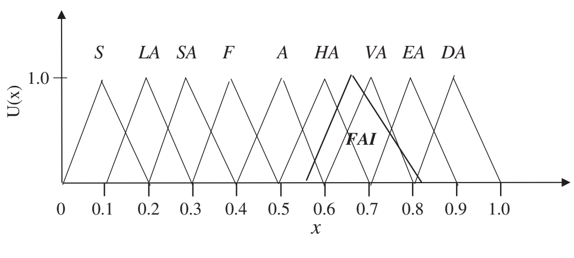

Fig. 3. Linguistic levels for matching the FAI. [(*S* (0.0, 0.1, 0.2); LA (0.1, 0.2, 0.3); SA (0.2, 0.3, 0.4); F (0.3, 0.4, 0.5); A (0.4, 0.5, 0.6); HA (0.5, 0.6, 0.7); VA (0.6, 0.7, 0.8); EA (0.7, 0.8, 0.9); DA (0.8, 0.9, 1.0)].

AW supply chain approaches "Very Agile" (according to the evaluation) while being far from "Extremely Agile" (the agility level required by AW), obstacles existed within the organization that could block agility achievement. Applying Eq. (5) could obtain the 24 FPIIs of the agile-enable-attributes, as listed in Table 6.

Furthermore, Eqs. (6)–(10) were applied to defuzzify the FPIIs, as listed in Table 6. The scores represent the effect of each agile-enabler, which contributes to supply chain agility. Based on the Pareto principle, the committee focused resources on the critical few factors (10%) and set a scale of 0.10 as the management threshold for identifying the factors requiring most urgent improvement. Subsequently, Table 6 indicates that two factors performed below the threshold, namely: (1) facilitate rapid decision-making, (2) immediately capture demand

Table 6
Fuzzy merit-importance indexes of sub-criteria

Criterion	R_i	(1.0, 1.0, 1.0) Θ W_i	Fuzzy merit-importance indexes	Ranking score
$ASCA_{11}$	(0.62, 0.74, 0.86)	(0.04, 0.11, 0.21)	(0.025, 0.081, 0.181)	0.1206
$ASCA_{12}$	(0.5, 0.65 0.8)	(0.2, 0.35, 0.5)	(0.1, 0.228, 0.4)	0.2717
$ASCA_{13}$	(0.58, 0.71, 0.84)	(0.06, 0.14, 0.24)	(0.035, 0.099, 0.202)	0.1381
$ASCA_{14}$	(0.58, 0.71, 0.84)	(0.1, 0.2, 0.31)	(0.058, 0.142, 0.26)	0.1818
$ASCA_{15}$	(0.42, 0.59, 0.76)	(0.22, 0.38, 0.54)	(0.092, 0.224, 0.41)	0.2718
$ASCA_{16}$	(0.38, 0.56, 0.74)	(0.12, 0.23, 0.35)	(0.046, 0.129, 0.259)	0.1742
$ASCA_{17}$	(0.76, 0.86, 0.94)	(0.14, 0.26, 0.38)	(0.106, 0224, 0.357)	0.2577
$ASCA_{18}$	(0.79, 0.89, 0.96)	(0.02, 0.08, 0.18)	(0.016, 0.071, 0.173)	0.1121
$ASCA_{21}$	(0.32, 0.5, 0.68)	(0.04, 0.11, 0.21)	(0.013, 0.055, 0.143)	0.0921
$ASCA_{22}$	(0.62, 0.74, 0.86)	(0.08, 0.17, 0.28)	(0.05, 0.126, 0.241)	0.1666
$ASCA_{23}$	(0.38, 0.56, 0.74)	(0.2, 0.35, 0.5)	(0.076, 0.196, 0.37)	0.2438
$ASCA_{24}$	(0.26, 0.44, 0.62)	(0.08, 0.17, 0.27)	(0.021, 0.075, 0.167)	0.112
$ASCA_{25}$	(0.69, 0.8, 0.9)	(0.1, 0.2, 0.31)	(0.069, 0.16, 0.279)	0.198
$ASCA_{31}$	(0.66, 0.77, 0.88)	(0.04, 0.11, 0.21)	(0.026, 0.085, 0.185)	0.1242
$ASCA_{32}$	(0.38, 0.56, 0.74)	(0.22, 0.38, 0.54)	(0.084, 0.213, 0.4)	0.2628
$ASCA_{33}$	(0.42, 0.59, 0.76)	(0.02, 0.08, 0.18)	(0.008, 0.047, 0.137)	0.0855
$ASCA_{34}$	(0.46, 0.62, 0.78)	(0.08, 0.17, 0.27)	(0.037, 0.105, 0.211)	0.1446
$ASCA_{41}$	(0.72, 0.83, 0.92)	(0.04, 0.11, 0.21)	(0.029, 0.091, 0.193)	0.1304
$ASCA_{42}$	(0.54, 0.68, 0.82)	(0.06, 0.14, 0.24)	(0.032, 0.095, 0.197)	0.1341
$ASCA_{43}$	(0.34, 0.53, 0.72)	(0.1, 0.2, 0.31)	(0.034, 0.106, 0.223)	0.1492
$ASCA_{44}$	(0.46, 0.62, 0.78)	(0.22, 0.38, 0.54)	(0.101, 0.236, 0.421)	0.2816
$ASCA_{45}$	(0.5, 0.65, 0.8)	(0.2, 0.35, 0.5)	(0.1, 0.228, 0.4)	0.2717
$ASCA_{46}$	(0.69, 0.8, 0.9)	(0.1, 0.2, 0.31)	(0.069, 0.16, 0.279)	0.198
$ASCA_{47}$	(0.65, 0.77, 0.88)	(0.12, 0.23, 0.35)	(0.078, 0.177, 0.308)	0.2167

information. These factors represented the most significant contributions to allowing the AW supply chain to enhance agility. Combined with the weakest factors within the organization, these factors indicated that an action plan be conducted to improve the adverse factors and enhance AW supply chain agility.

Following 2 years and four cycles of continuous improvement, the supply chain agility index rose to approach the "Extremely Agile" level and managers were able to instantly capture demand information from all over the world to facilitate increasingly efficient, effective and timely responses to customers. The tangible benefits are as follows: mean lead-time for responding to customer demands was reduced by approximately 34% given the same inventory level, and sales increased by 23%, especially sales to the European market.

6. Discussion and conclusions

This study has addressed the questions of how to measure and improve supply chain agility. Also, conventional evaluation approaches, which are inappropriate and ineffective for handling situations that, by nature, are characterized by complexity and uncertainty, were evaluated. To compensate for these limitations of the conventional evaluation approaches, a fuzzy supply chain agility index which focuses on the application of linguistic approximation and fuzzy arithmetic was designed for addressing agility measurement, stressing the multiplicity of meaning and ambiguity of attribute measurement. This model was developed from the concept of MCDM and adapted for an IT product supply chain, which served as an initial case study for validating the model and approach. This work has potentially assisted practitioners by offering a rational structure for reflecting inaccuracies in many business environments, and has considered the uncertainty of each attribute for assuring realistic and informative assessment. To researchers, the proposed model demonstrates an unprecedented application of fuzzy logic. Furthermore, the proposed model has the following novel features:

(1) The model can provide more informative and reliable analytical results. The FAI of a supply chain is expressed in a range of values, which can provide a holistic picture of agility.
(2) The model can systematically identify supply chain weaknesses and provide the means for managers to devise a comprehensive improvement plan. The model thus facilitates systematic continuous quality improvement over the full range of activities and processes.

Although the case study demonstrated the usefulness of the model for supply chain agility evaluation, we believe that room still remains for future validation and improvement. Further research is necessary to fine tune the proposed model and to compare the efficiency of different models for measuring agility.

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