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Agility evaluation using fuzzy logic

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Abstract

"Change" seems to be one of enterprises' major characteristics in this new competitive era. Agile enterprise whereby an organization can change and adapt quickly to changing circumstances is increasingly viewed as a winning strategy. However, in embracing agile enterprise, there are important questions to be asked: what precisely is agility and how can it be measured? How can one assist in achieving and enhancing agility effectively? Answers to such questions are critical to the practitioners and to the theory of agile enterprise design. The foundation of agile enterprise lies in the integration of information system/technologies, people, business processes and facilities. Due to the ill-defined and vague indicators which exist within agility assessment, most measures are described subjectively by linguistic terms which are characterized by ambiguity and multi-possibility, and the conventional assessment approaches cannot suitably nor effectively handle such measurement. However, fuzzy logic provides a useful tool for dealing with decisions in which the phenomena are imprecise and vague. Thus, the novelty in the paper is development of the absolute agility index, a unique and unprecedented attempt in agility measurement, using fuzzy logic to address the ambiguity in agility evaluation. Details of the approach and a framework of a fuzzy agility evaluation will be presented. An example is also used to illustrate the approach developed.

Keywords: Agile enterprise; Agility index; Agility measuring; Fuzzy logic

1. Introduction

Nowadays, many companies are facing constantly increasing competition stimulated by technological innovations, changing market environments and changing customer demands. This critical situation has led to a major revision in business priorities, strategic vision, and in the viability of conventional and even relatively contemporary models (Sharifi and Zhang, 1999). In an increasingly competitive market, there is a need to develop and improve organizational flexibility and responsiveness. In the past decade, most companies adopted restructuring and re-engineering in

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response to challenges and demands; however, these were not always successfully (Sutclife, 1999). Agile enterprise addresses new ways of running companies to react quickly and effectively to changing markets, driven by customized products and services. The foundation of agile enterprise is the integration of information system/technologies, people, business processes and facilities into a harmonious and flexible organization so as to respond quickly to changing circumstances. Indeed agile enterprise not only encompasses the whole spectrum of activities in the company but is also associated with the supply chain as well (Ren et al., 2001).

Agile enterprise in general can provide lower manufacturing costs, increase market share, satisfy customer requirements, facilitate the rapid introduction of new products, eliminate non-value added activities and increase company's competitiveness. Thus, agile enterprise has been advocated as the 21st century's enterprise paradigm, and is seen as the winning strategy to become national and international leaders in an ever increasing competitive market of fast changing customer requirements (Yusuf et al., 1999). However, the ability to build agile enterprise has not developed as rapidly as anticipated, because the development of technology to manage agile enterprise is still under way (Sharp et al., 1999). Thus, in embracing agile enterprise many important questions concerning agility need to be asked, such as: what precisely is agility and how can it be measured? How will companies know when they have it, as there are no simple metrics or indexes available? How and to what degree does the company's attributes affect companies' business performance? How to compare agility with competitiveness? If a company wants to improve agility, how can the company identify the principal obstacles to improvement? How to assist in achieving agility effectively (Sharp et al., 1999; James-Moore, 1997; Yusuf et al., 2001)? Answers to such questions are critical to the practitioners and to the theory of agile enterprise design. Therefore, the purpose of this research is to solve some of these problems, with particular focus upon agility measuring and identifying the principal obstacles to agility improvement.

To assist managers in better achieving an agile enterprise, there have been numerous studies dedicated to measure the agility of an enterprise. Some authors (Yusuf et al., 2001; Youssuf, 1993; Van Hoek et al., 2001) proposed integration agility index methods. They defined the agility index as a combination of measuring intensity levels of agility capabilities. Thus, the absolute agility level of company i is measured as

$$(\mathrm{AGILITY}_{\mathrm{index}})_i = \sum_{j=1}^{N} A_{ij},$$

where A_{ij} is the agility level of capability j of company i. Furthermore, the relative agility level can be obtained by standardizing all absolute agility levels of competitive companies.

Other measuring methods (Ren et al., 2000; Meade and Rogers, 1997) were developed on the basis of analytic hierarchical process (AHP) logical concept. Using these methods, the evaluators apply a pairwise comparison technique to evaluate the agility capabilities. Finally, this evaluation is synthesized across the entire capabilities to derive overall agility indexes for each company; distinguishing the superiority of different firms or different manufacturing operations can be done by comparing the agility of different firms or different manufacturing operations.

Furthermore, based on the characteristics of mass customization (MC) of product manufacturing and on the requirements of agile manufacturing, an MC product manufacturing agility evaluation index system was established by Yang and Li (2002). If R_i and W_i denote the agility index and the weight of each agility capability, respectively, they define the agility index as

$$(\mathrm{AGILITY}_{\mathrm{index}}) = \sum_{i=1}^{N} R_i \times W_i,$$

where $\sum_{i=1}^{N} W_i = 1.$

The above methods are easy to implement and focus attention on the most important issues. However, due to the imprecise and vague definition of agility indicators, and when a situation is characterized by either lack of evidence or the inability of the experts to make a significant assessment of an event, linguistic expressions are used to estimate ambiguous events (Karwowski and Mital, 1986). Most agility measurements are described subjectively by linguistic terms, which are characterized by ambiguity and multi-possibility. Thus, the scoring of the above techniques can always be criticized, because the scale used to score the agility capabilities has two limitations: (1) such techniques do not take into account the ambiguity and multi-possibility associated with the mapping of one's judgment to a number, and (2) the subjective judgment and the selection and preference of evaluators have a significant influence on those methods.

However, fuzzy logic provides a useful tool to deal with problems in which the phenomena are imprecise and vague (see Appendix A.1). Using fuzzy concepts, evaluators can use linguistic terms to assess the indicators in a natural language expression and each linguistic term can be associated with a membership function. Fuzzy logic by making no global assumption about the independence, exhaustiveness, or exclusiveness of facilitated evidence, tolerates a blurred boundary in definitions (Machacha and Bhattacharya, 2000). This brings hope of incorporating qualitative indicators into decision-making since it is often vaguely defined or has unclear boundaries. Furthermore, fuzzy logic has found large application in management decisions (Machacha and Bhattacharya, 2000; Lin and Chen, 2004; Basim and Imad, 2003; Büyüközkan and Feyzioglu, 2004; Beskese et al., 2004).

From this review, to assist managers in better achieving an agile enterprise, a model on the basis of fuzzy logic is purposed to provide a means of both measuring how agile an enterprise is and identifying the principal obstacles to improve the agility level. In this approach, the performance ratings and importance weights of different agility capabilities assessed by experts are expressed in linguistic terms. Then appropriate fuzzy numbers are used to present the linguistic values, and a simple fuzzy arithmetical operation is employed to synthesize these fuzzy numbers into one fuzzy number, which is called the fuzzy-agility-index (FAI). Also, the FAI is matched with appropriate linguistics, thereby enabling the agility level to be expressed in linguistic terms. After that the fuzzy performance-importance index (FPII) of each agility capability is devised to help managers identify the main adverse factors and calls for managers to institute an appropriate action plan to improve the agility level. As an illustration, the agility measuring of an MC product manufacturing is used to illustrate the approach developed, followed by a discussion on its effectiveness.

2. The conceptual model of agility enterprise

The purpose of agile enterprise is to enrich/satisfy customers and employees. An enterprise essentially possesses a set of capabilities so as to make appropriate responses to changes taking place in its business environment. However, the business conditions in which many companies find themselves are characterized by volatile and unpredictable demand; thus, the increasing urgency of pursuing agility. The agility might, therefore, be defined as the ability of an enterprise to rapidly respond to change in market and customers' demands (Sharp et al., 1999). To be truly agile, an enterprise should possess a number of distinguishing agile enablers. From a review of the normative literature, the authors have developed a conceptual model of agile enterprise, as shown in Fig. 1, culminating in many research propositions.

The main driving force behind agility is change. Even through change is nothing new, today's change is taking place at a much faster speed than ever before. Turbulence and uncertainty in the business environment have become the main causes of failure in the manufacturing industry. The number of changes and their type, specification or characteristic cannot be easily determined and are probably indefinite. Different enterprises with different characteristics and in different circumstances experience different changes that are specific and perhaps unique to themselves. But there are common characteristics in changes that occur, which can bring about a general consequence for every enterprise. Summarizing previous studies (Sharifi and Zhang, 1999; Ren et al., 2001;

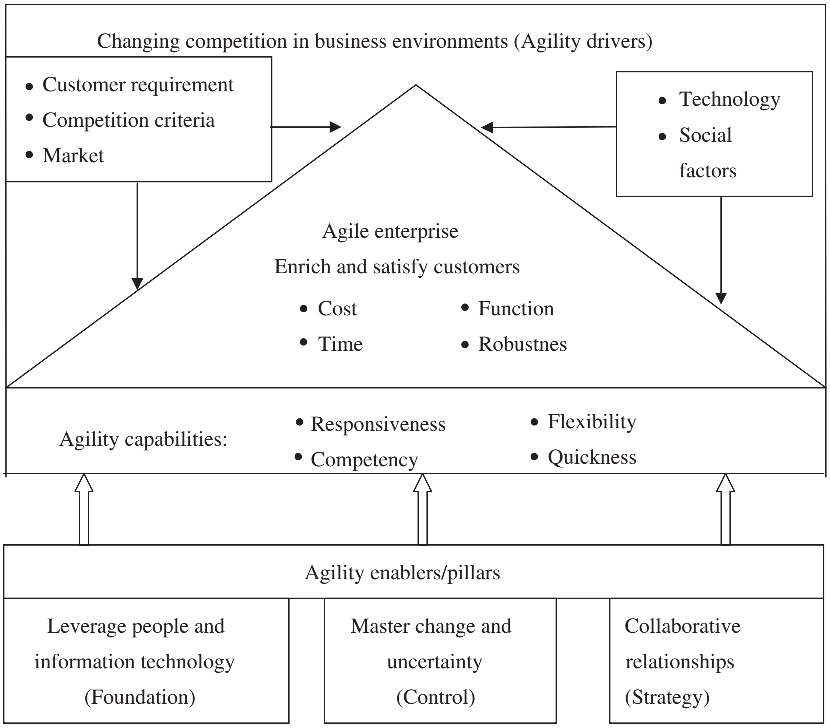

Fig. 1. Conceptual model for agile enterprise.

Yusuf et al., 1999), the general areas of change in business environment are categorized as follows: (1) market volatility caused by growth of the niche market, increasing new product introduction and product lifetime shrinkage; (2) intense competition caused by a rapidly changing market, increasing cost pressure, international competitiveness and short development of new products; (3) customer requirements' changes caused by demand for customization, quality expectation increase and quicker delivery time; (4) accelerating technological change caused by the introduction of new and efficient production facilities, and system integration (hardware and software); and (5) change in social factors caused by environmental protection, workforce/workplace expectations and legal pressures.

Agile enterprises are concerned about change, uncertainty and unpredictability within their business environment and make appropriate responses. Therefore, agile enterprises require a number of distinguishing capabilities or "fitness" to deal with the change, uncertainty and unpredictability within their business environment. These capabilities consist of four principle elements (Ren et al., 2001; Yusuf et al., 1999; Giachetti et al., 2003): (1) responsiveness which is the ability to identify changes and respond quickly to them, reactively or proactively, and recover from them; (2) competency which is the ability to efficiently and effectively reach enterprises' aims and goals; (3) flexibility/adaptability which is the ability to process different processes and achieve different goals with the same facilities; and (4) quickness/speed which is the ability to carry out activity in the shortest possible time. Furthermore, underpinning these fours principles is a methodology to integrate them into a coordinated, interdependent system, and to translate them into strategic competitive capabilities (Sharp et al., 1999). These must be taken into account if an organization is to carry out agile enterprise.

Achieving agile enterprise requires responsiveness in strategies, technologies, people, business processes and facilities. Thus all areas of the company need to have some agility providers to effectively respond to changing market requirements. In the past, to assist managers in achieving an agile enterprise, there have been numerous studies dedicated to identify agility providers from which organization leaders could select those items appropriate to their own strategies, organization business processes and information systems. For example, Goldman et al. (1991) suggested that agility has four underlying components of agility including delivering value to the customers, being ready for change, valuing human knowledge and skills, and forming virtual partnerships. The project ‘‘Next Generation Manufacturing’’ conducted by NGM Project Office (1997) indicates six attributes for agility: they are the customer, physical plant and equipment, human resources, global markets, core competency, and practices and cultures. Moreover, Yusuf et al. (1999) suggested a set of 32 agility providers as listed in Table 1, which include four dimensions: core management competency, virtual enterprise, capability for reconfiguration, and knowledge driven enterprise. These enablers are supposed to be the aspects of agility and to determine the entire behavior of the enterprise.

From this review we can see that different researchers provide some insights into different aspects of agility. There is a high probability that there is no single set of enablers, which reflect all aspects. However, the most important point is to understand the relationships of the enablers, to deploy and integrate them, and finally to transform them into strategic competitive capabilities. Even aspects of agility enablers listed in Table 1 are by no means exhaustive and therefore new factors may be added depending on the product, industry and market characteristics.

3. Fuzzy agility evaluation approach

The fuzzy agility evaluation (FAE) framework, shown in Fig. 2, is composed of two major parts. The first part is the business operation environments' evaluation and agility capabilities' identification. The purpose of the business environment survey is to collect and analyze the agility drivers which are the changes in the business environment that drive a company to reconsider the company's position, strategy and process, and in sequence maybe used to reset new strategies when running their business and building agility capabilities. The

Table 1
Agility enablers

Dimensions	Related attributes	Dimensions	Related attributes
Integration	Concurrent execution of activities	Change	Culture of change
	Enterprise integration		Continuous improvement
	Information accessible to employees	Partnership	Trust-based relationship with customers/suppliers
Competence	Business practice & structure are difficult to replicate		Rapid partnership formation
	Multi-venturing capabilities		Strategic relationship with customers
Team	Decentralized decision-making		Close relationship with suppliers
building	Empowered individuals working in teams	Market	Response to changing market requirements
	Cross-functional team		New product introduction
	Teams across company borders		Customer-driven innovations
Technology	Technology awareness		Customer satisfaction
	Leadership in the use of current technology	Education	Continuous training and development
	Skill and knowledge enhancing technologies		Learning organization
	Flexible production technology		Multi-skilled and flexible people
Quality	Quality over product life		Workforce skill upgrade
	Products with substantial added value	Welfare	Employee satisfaction
	First-time right design		
	Short development cycle times		

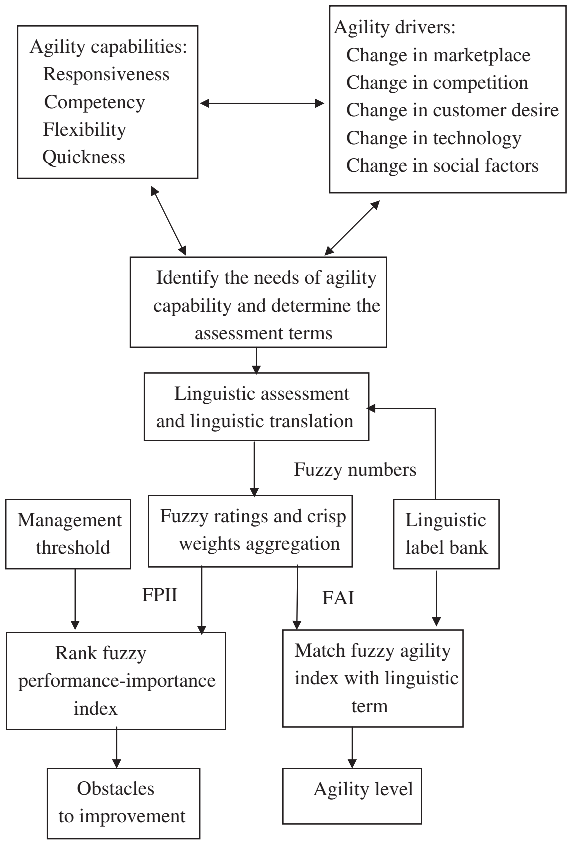

Fig. 2. Framework to measure enterprise' agility.

company's agility capabilities are the vital abilities that would provide the required strength to make appropriate responses to changes taking place in its business, so that agility capabilities will provide for agility measuring of a company.

The second part of the framework is to evaluate agility capabilities and synthesize the ratings and the weights to obtain an FAI of an agile enterprise and to match the FAI with an appropriate agility level and to make an improvement analysis. A stepwise description is given as follows:

1. Select criteria for evaluation.
2. Determine the appropriate linguistic scale to assess the performance ratings and importance weights of the agility capabilities.
3. Measure the performance and importance of agility capabilities using linguistic terms.
4. Approximate the linguistic terms by fuzzy numbers.
5. Aggregate fuzzy ratings with fuzzy weights to obtain an FAI of an enterprise.
6. Match the FAI with an appropriate level.
7. Analyze and identify the principal obstacles to improvement.

4. An illustrative example

In this section the FAE approach was employed to study and measure the agility of the MC product manufacturing company, Xi Dian Casting Limited Company (XDCLC) (Yang and Li, 2002).

Step 1: Select criteria for evaluation. MC is a kind of production model, which combines the advantages of mass-production with those of customized products to satisfy the customers' demand so that it supplies to the individual customer in random quantity, or to multi-variety small batch markets, based on mass-production with high efficiency. In a business environment that continues to vary very quickly, MC enterprise is required to enhance its ability to master change and uncertainty by improving its product manufacturing agility. Thus, MC's product manufacturing is aimed at enriching customers via agile response to customer demand, market change and market opportunities. MC enterprise uses a series of advanced information technology, modern management technology and advanced manufacturing technology. This makes components and technology universal and enables the rapid launch of products. Accordingly, MC enterprises are generally required to possess at least three general agility capabilities: organization management, product design and product manufacturing. According to Yang and Li (2002), the three grades of the three general agility capabilities (AC) for XDCLC are listed in Table 2.

Step 2: Determine the appropriate linguistic scale to assess the performance ratings and importance weights of the agility capabilities. In many cases it is virtually impractical for experts to directly determine the score of a vague indicator, such as the perfect degree of information systems, the way information demand was obtained,

Table 2
Agility capabilities for agility index evaluating in MC product manufacturing

1-Grade index	2-Grade index	3-Grade index
MC enterprise organization management agility (AC_1)	Information management agility (AC_{11})	Perfect degree of enterprise information system (AC_{111}), network connection extensiveness (AC_{112}), information and network utilization rate (AC_{113})
	Inter-organization cooperative extent (AC_{12})	The degree of cooperation with other enterprises (AC121), the application degree of the VE (AC_{122})
	Produce organizing agility (AC_{13})	The space organizational form of the production process (AC_{131}), the time organizational form of the production process (AC_{132})
	The agility of institutional framework (AC_{14})	The form of institutional framework (AC_{141}), the speed of the team building (AC_{142})
MC enterprise products design agility (AC_2)	Customer demand information agile to get (AC_{21})	The way of demand information got (AC_{211}), the proportion of information processing time in products period (AC_{212})
	The speed of products design (AC_{22})	The period products design (AC_{221}), the proportion of design period in products period (AC_{222})
	Products design flexibility (AC_{23})	The seriation degree of products (AC_{231}), the similar degree of products structure (AC_{232}), the universalization degree of the part (AC_{233})
MC enterprise processing manufacture agility (AC_3)	Re-configurable (AC_{31})	Packaging integrated unit modular (AC_{311}), supplement tool displacement (AC_{312}), displacement compatibility (AC_{313})
	The speed of manufacture (AC_{32})	The proportion of production and technology preparing time in products period (AC_{321}), the period of manufacture (AC_{322}), the proportion of manufacture period in products period (AC_{323})
	Manufacture flexibility (AC_{33})	The universalization degree of equipment (AC_{331}), the scalable degree of equipment (AC_{332})

displacement compatibility, etc. Therefore, in this approach, linguistic terms are used to assess the performance rating and importance weights of the agility capabilities.

The ad hoc usage of linguistic terms and corresponding membership functions is always criticized by 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 the sake of convenience, and instead of elicitation from the experts, linguistic terms and corresponding membership functions can be obtained directly from past data or used as a basis and modified to incorporate individual situations and the requirements of different users. Furthermore, it is in general suggested that linguistic levels not exceed nine levels, which represent the limits of human absolute discrimination.

On the basis of the original data of the study conducted by Yang and Li (2002) and considering the human way of perceiving differences, the linguistic variables {Excellent [E], Very Good [VG], Good [G], Fair [F], Poor [P], Very Poor [VP], Worst [W]}, are selected to assess the performance rating of the agility capabilities. Furthermore, the linguistic variables {Very High [VH], High [H], Fairly High [FH], Medium [M], Fairly Low [FL], Low [L], Very Low [VL]}, are selected to assess the importance weights of the agility capabilities.

Step 3: Measure the performance and importance of agility capabilities using linguistic terms. Once the linguistic variables for evaluating the performance ratings and the importance weights of the agility capabilities are defined, according to the company policy and strategy, company profile, company characteristics, business changes and practices, marketing competition information, and the experts' experience and knowledge, the experts can directly use the linguistic terms above to assess the rating which characterizes the degree of the performance of various agility capabilities. Concurrently, the experts can evaluate the relative importance of each agility capability by comparison, on the basis of the company's strategies and policies, marketing competition trend, technology development trend and experts' experience and knowledge.

This case study was adopted to sustain Yang and Li's (2002) data. Thus on the basis of their original assessment, five experts used the linguistic terms above to directly measure the performance rating and importance weight of the agility capabilities. Furthermore, median operation was used to aggregate the five experts' assessments (since median operation is more robust in a small sample). The results, integrated performance ratings and integrated importance weights of agility capabilities measured by linguistic variables, are shown in Table 3.

Step 4: Approximate the linguistic terms by fuzzy numbers. Applying the approximate reasoning of fuzzy sets theory (see the Appendix A.1), the linguistic value can be approximated by a fuzzy number. Using previous studies (Lin and Chen,

Table 3
Aggregated performance rating and aggregated importance weight of agility capabilities

AC_i	AC_{ij}	AC_{ijk}	W_i	W_{ij}	W_{ijk}	R_{ijk}
AC_1	AC_{11}	AC_{111}	H	VH	VH	G
		AC_{112}			VH	G
		AC_{113}			H	G
	AC_{12}	AC_{121}		H	VH	G
		AC_{122}			H	P
	AC_{13}	AC_{131}		VH	VH	G
		AC_{132}			VH	E
	AC_{14}	AC_{141}		H	VH	G
		AC_{142}			H	F
AC_2	AC_{21}	AC_{211}	H	H	H	VG
		AC_{212}			VH	VG
	AC_{22}	AC_{221}		VH	VH	VG
		AC_{222}			VH	VG
	AC_{23}	AC_{231}		H	H	VG
		AC_{232}			VH	VG
		AC_{233}			FH	G
AC_3	AC_{31}	AC_{311}	VH	FH	FH	G
		AC_{312}			FH	F
		AC_{313}			H	VG
	AC_{32}	AC_{321}		VH	H	G
		AC_{322}			VH	VG
		AC_{323}			VH	VG
	AC_{33}	AC_{331}		VH	VH	VG
		AC_{332}			H	G

Table 4
Fuzzy numbers for approximating linguistic variable values

Performance-rating		Importance-weighting	
Linguistic variable	Fuzzy number	Linguistic variable	Fuzzy number
Worst (W)	(0, 0.5, 1.5)	Very Low (VL)	(0, 0.05, 0.15)
Very Poor (VP)	(1, 2, 3)	Low (L)	(0.1, 0.2, 0.3)
Poor (P)	(2, 3.5, 5)	Fairly Low (FL)	(0.2, 0.35, 0.5)
Fair (F)	(3, 5, 7)	Medium (M)	(0.3, 0.5, 0.7)
Good (G)	(5, 6.5, 8)	Fairly High (FH)	(0.5, 0.65, 0.8)
Very Good (VG)	(7, 8, 9)	High (H)	(0.7, 0.8, 0.9)
Excellent (E)	(8.5, 9.5, 10)	Very High (VH)	(0.85, 0.95, 1.0)

2004; Chen and Hwang, 1992) as a basis and modifying to incorporate the MC product manufacturing XDCLCs situations, a set of fuzzy numbers for approximating linguistic variable values was developed as listed in Table 4. (Table 4 merely presents what we assessed to be most suitable for this case study. However, the competitive situations and requirements vary from company to company; hence, companies must establish their unique membership function appropriate to their specific environment and considerations.) Then, applying the relation between linguistic terms and fuzzy numbers, the linguistic terms shown in Table 3 are transferred into fuzzy numbers as shown in Table 5.

Step 5: Aggregate fuzzy ratings with fuzzy weights to obtain a FAI of the MC product manufacturing XDCLC. FAI is an information fusion, which consolidates the fuzzy ratings and fuzzy weights of all of the factors that influence agility. FAI represents overall enterprise agility. Enterprise agility increases with increasing FAI. Thus, the membership function of FAI is used to determine the agility level. According to fuzzy-weighted average definition, the fuzzy index of the agility 2-grade-capability AC_{ij} can be calculated as

$$\mathrm{AC}_{ij} = \sum_{k=1}^{n}(W_{ijk} \otimes \mathrm{AC}_{ijk}) \Big/ \sum_{k=1}^{n} W_{ijk}, \qquad (1)$$

where AC_{ijk} and W_{ijk}, respectively, represent the fuzzy performance rating and fuzzy importance weight of the agility element capability.

Then, by using the formulas in Eq. (1), the fuzzy index of the agility 2-grade-capability AC_{ij} is obtained. For example, the fuzzy index of the agility 2-grade capability, information management agility AC_{11}, is calculated as

$$\begin{aligned}\mathrm{AC}_{11} = {} & [(5, 6.5, 8) \otimes (0.85, 0.95, 1.0) \oplus (5, 6.5, 8) \\ & \otimes (0.85, 0.95, 1.0) \oplus (5, 6.5, 8) \\ & \otimes (0.7, 0.8, 0.9)]/[(0.85, 0.95, 1.0) \\ & \oplus (0.85, 0.95, 1.0) \oplus (0.7, 0.8, 0.9)] \\ = {} & (5, 6.5, 8).\end{aligned}$$

Applying the same equation, other fuzzy indexes of agility 2-grade-capabilities AC_{ij} and the agility 1-grade-capabilities AC_i are obtained as listed in Table 6.

Finally, applying Eq. (1) again, the FAI of MC product manufacturing XDCLC is calculated as

$$\begin{aligned}\mathrm{FAI}_{\mathrm{XDCLC}} = {} & \\ & [(4.85, 6.44, 7.91) \otimes (0.7, 0.8, 0.9) \\ & \oplus (6.75, 7.87, 8.94) \otimes (0.7, 0.8, 0.9) \\ & \oplus (5.79, 7.22, 8.54) \\ & \otimes (0.85, 0.95, 1.0)]/[(0.7, 0.8, 0.9) \\ & \oplus (0.7, 0.8, 0.9) \oplus (0.85, 0.95, 1.0)] \\ & = (5.72, 7.18, 8.52).\end{aligned}$$

Step 6: Match the FAI with an appropriate agility level. Once the FAI has been obtained, to identify the level of agility, the FAI can be further matched with the linguistic label whose membership function is the same as (or closest to)

Table 5
Linguistic terms approximated by fuzzy numbers

AC_i	AC_{ij}	AC_{ijk}	W_i	W_{ij}	W_{ijk}	R_{ijk}
AC_1	AC_{11}	AC_{111}	(0.7, 0.8, 0.9)	(0.85, 0.95, 1.0)	(0.85, 0.95, 1.0)	(5, 6.5, 8)
		AC_{112}			(0.85, 0.95, 1.0)	(5, 6.5, 8)
		AC_{113}			(0.7, 0.8, 0.9)	(5, 6.5, 8)
	AC_{12}	AC_{121}		(0.7, 0.8, 0.9)	(0.85, 0.95, 1.0)	(5, 6.5, 8)
		AC_{122}			(0.7, 0.8, 0.9)	(2, 3.5, 5)
	AC_{13}	AC_{131}		(0.85, 0.95, 1.0)	(0.85, 0.95, 1.0)	(5, 6.5, 8)
		AC_{132}			(0.85, 0.95, 1.0)	(8.5, 9.5, 10)
	AC_{14}	AC_{141}		(0.7, 0.8, 0.9)	(0.85, 0.95, 1.0)	(5, 6.5, 8)
		AC_{142}			(0.7, 0.8, 0.9)	(3, 5, 7)
AC_2	AC_{21}	AC_{211}	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(7, 8, 9)
		AC_{212}			(0.85, 0.95, 1.0)	(7, 8, 9)
	AC_{22}	AC_{221}		(0.85, 0.95, 1.0)	(0.85, 0.95, 1.0)	(7, 8, 9)
		AC_{222}			(0.85, 0.95, 1.0)	(7, 8, 9)
	AC_{23}	AC_{231}		(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(7, 8, 9)
		AC_{232}			(0.85, 0.95, 1.0)	(7, 8, 9)
		AC_{233}			(0.5, 0.65, 0.8)	(5, 6.5, 8)
AC_3	AC_{31}	AC_{311}	(0.85, 0.95, 1.0)	(0.5, 0.65, 0.8)	(0.5, 0.65, 0.8)	(5, 6.5, 8)
		AC_{312}			(0.5, 0.65, 0.8)	(3, 5, 7)
		AC_{313}			(0.7, 0.8, 0.9)	(7, 8, 9)
	AC_{32}	AC_{321}		(0.85, 0.95, 1.0)	(0.7, 0.8, 0.9)	(5, 6.5, 8)
		AC_{322}			(0.85, 0.95, 1.0)	(7, 8, 9)
		AC_{323}			(0.85, 0.95, 1.0)	(7, 8, 9)
	AC_{33}	AC_{331}		(0.85, 0.95, 1.0)	(0.85, 0.95, 1.0)	(7, 8, 9)
		AC_{332}			(0.7, 0.8, 0.9)	(5, 6.5, 8)

Table 6
Fuzzy index of each grade of agility capabilities

AC_i	AC_{ij}	R_i	R_{ij}
AC_1	AC_{11}	(4.85, 6.44, 7.91)	(5, 6.5, 8)
	AC_{12}		(3.65, 5.13, 6.58)
	AC_{13}		(6.75, 8, 9)
	AC_{14}		(4.1, 5.81, 7.53)
AC_2	AC_{21}	(6.75, 7.87, 8.94)	(7, 8, 9)
	AC_{22}		(7, 8, 9)
	AC_{23}		(6.32, 7.59, 8.79)
AC_3	AC_{31}	(5.79, 7.22, 8.54)	(4.9, 6.61, 8.21)
	AC_{32}		(6.31, 7.56, 8.74)
	AC_{33}		(6.1, 7.31, 8.53)

the membership function of the FAI from the natural-language expression set of agility label (AL).

Several methods for matching the membership function with linguistics terms have been proposed (Eshragh and Mandani, 1979; Schmucker, 1985). There are basically three techniques: (1) Euclidean distance method, (2) successive approximation, and (3) piecewise decomposition. It is recommended that the Euclidean distance method (see in Appendix A.2) be utilized because it is the most intuitive form of human perception of proximity (Guesgen and Albrecht, 2000).

In this case the natural-language expression set AL = {Extremely Agile [EA], Very Agile [VA], Agile [A], Fairly [F], Slowly [S]} is selected for labeling, and the linguistics and corresponding membership functions are shown in Fig. 3. Then, by using the Euclidean distance method, the Euclidean distance D from the FAI to each member in set AL is calculated:

$$D(\text{FAI}, \text{EA}) = 16984, \quad D(\text{FAI}, \text{VA}) = 0.0645,$$
$$D(\text{FAI}, \text{A}) = 1.9519, \quad D(\text{FAI}, \text{F}) = 1.9841,$$
$$D(\text{FAI}, \text{S}) = 1.9841.$$

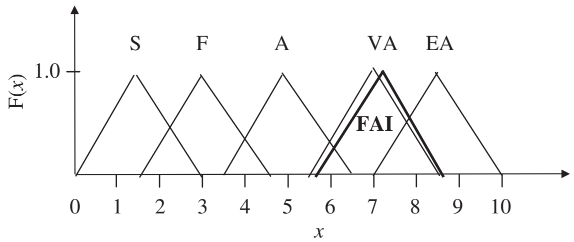

Fig. 3. Linguistic levels to match fuzzy-agility-index. [(S (0, 1.5, 3); F (1.5, 3, 4.5); A (3.5, 5, 6.5); VA (5.5, 7, 8.5); EA (7, 8.5, 10)].

Thus, by matching a linguistic label with the minimum D, the agility index level of the MC product manufacturing XDCLC can be identified as "very agile", as shown in Fig. 3.

Step 7: Analyze and identify the principal obstacles to improvement. An agility evaluation not only measures how agilze an enterprise is but also, most importantly, helps managers assess distinctive competencies and identify the principal obstacles for implementing appropriate improvement measures. Although the agility index level of MC product manufacturing XDCLC is "very agile" (according to the evaluation), there were obstacles within the organization which could have impacted the agility of the MC product manufacturing XDCLC.

In order to identify the principal obstacles for improving agility level, a fuzzy performance-importance index (FPII) of agility element capability, which combines the performance rating and importance weight of each agility element capability, represents an effect which will contribute to the agility level of an organization. The lower the FPII of a factor is, the lower the degree of contribution for this factor. Thus, the score of the FPII of a factor is used for identifying the principal obstacles.

If used directly to calculate the FPII, the importance weights W_{ijk} 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_{ijk} is high, then the transformation $[(1,1,1)) \ominus W_{ijk}]$ is low. Consequently, for each agility element capability *ijk,* the fuzzy performance-importance index FPII_{ijk}, is defined as

$$\mathrm{FPII}_{ijk} = W'_{ijk} \otimes \mathrm{AC}_{ijk}, \qquad (2)$$

where $W'_{ijk} = (1,1,1) \ominus W'_{ijk}$, W_{ijk} is the fuzzy importance weight of the agility element capability ijk.

Then, by using the formulas in Eq. (2), the FPIIs of each agility element capability are obtained as listed in Table 7. For example, the FPII of the perfect degree enterprise information system AC_{111}, is calculated as

$$\begin{aligned}\mathrm{FPII}_{111} &= [(1,1,1) \ominus (0.85, 0.95, 1.0)] \otimes (5, 6.5, 8) \\ &= (0, 0.325, 1.2).\end{aligned}$$

Since fuzzy numbers do not always yield a totally ordered set as real numbers do, all the FPIIs must be ranked. Many methods have been developed to rank fuzzy numbers (Chen and Hwang, 1992; Lee-Kwang and Lee, 1999). Here, the ranking of the fuzzy number is based on Chen and Hwang's left-and-right fuzzy-ranking method (see in Appendix A.3), since it not only preserves the ranking order but also considers the absolute location of each fuzzy number (Chen and Hwang, 1992). By using Chen and Hwang's left-and-right fuzzy-ranking method, the total scoring values of the 24 FPIIs of the agility element capabilities are obtained as shown in Table 7.

As mentioned in the Pareto principle, resources should be used in the improvement of critical obstacles. To identify the few critical obstacles, scale 0.8 was set as the management threshold to distinguish which critical obstacles need to be improved. Subsequently, as shown in Table 7, four capabilities have a lower performance than the threshold, namely: (1) perfect degree of enterprise information system, (2) network connection extensiveness, (3) the degree of cooperation with other enterprises, and (4) the space organizational form of the production process. These capabilities represent the most significant contributions to enhance the MC product manufacturing XDCLC and to achieve agility. Furthermore, according to this identification, managers can select appropriate agility providers from Table 1 to implement better agility level.

Table 7
Fuzzy performance—importance indexes of 24 agility capabilities

Agility capability	Aggregated fuzzy performance rating	$(1, 1, 1) \ominus W'_{ijk}$	Fuzzy performance—importance index	Ranking score
AC_{111}	(5, 6.5, 8)	(0, 0.05, 0.15)	(0, 0.325, 1.2)	0.709
AC_{112}	(5, 6.5, 8)	(0, 0.05, 0.15)	(0, 0.325, 1.2)	0.709
AC_{113}	(5, 6.5, 8)	(0.1, 0.2, 0.3)	(0.5, 1.3, 2.4)	1.703
AC_{121}	(5, 6.5, 8)	(0, 0.05, 0.15)	(0, 0.325, 1.2)	0.709
AC_{122}	(2, 3.5, 5)	(0.1, 0.2, 0.3)	(0.2, 0.7, 1.5)	1.028
AC_{131}	(5, 6.5, 8)	(0, 0.05, 0.15)	(0, 0.325, 1.2)	0.709
AC_{132}	(8.5, 9.5, 10)	(0, 0.05, 0.15)	(0, 0.475, 1.5)	0.907
AC_{141}	(5, 6.5, 8)	(0, 0.05, 0.15)	(0, 0.325, 1.2)	0.709
AC_{142}	(3, 5, 7)	(0.1, 0.2, 0.3)	(0.3, 1.0, 2.1)	1.413
AC_{211}	(7, 8, 9)	(0.1, 0.2, 0.3)	(0.7, 1.6, 2.7)	1.95
AC_{212}	(7, 8, 9)	(0, 0.05, 0.15)	(0, 0.4, 1.35)	0.809
AC_{221}	(7, 8, 9)	(0, 0.05, 0.15)	(0, 0.4, 1.35)	0.809
AC_{222}	(7, 8, 9)	(0, 0.05, 0.15)	(0, 0.4, 1.35)	0.809
AC_{231}	(7, 8, 9)	(0.1, 0.2, 0.3)	(0.7, 1.6, 2.7)	1.95
AC_{232}	(7, 8, 9)	(0, 0.05, 0.15)	(0, 0.4, 1.35)	0.809
AC_{233}	(5, 6.5, 8)	(0.2, 0.35, 0.5)	(1.0, 2.275, 4.0)	2.715
AC_{311}	(5, 6.5, 8)	(0.2, 0.35, 0.5)	(1.0, 2.275, 4.0)	2.715
AC_{312}	(3, 5, 7)	(0.2, 0.35, 0.5)	(0.6, 1.75, 3.5)	2.274
AC_{313}	(7, 8, 9)	(0.1, 0.2, 0.3)	(0.7, 1.6, 2.7)	1.95
AC_{321}	(5, 6.5, 8)	(0.1, 0.2, 0.3)	(0.5, 1.3, 2.4)	1.703
AC_{322}	(7, 8, 9)	(0, 0.05, 0.15)	(0, 0.4, 1.35)	0.809
AC_{323}	(7, 8, 9)	(0, 0.05, 0.15)	(0, 0.4, 1.35)	0.809
AC_{331}	(7, 8, 9)	(0, 0.05, 0.15)	(0, 0.4, 1.35)	0.809
AC_{332}	(5, 6.5, 8)	(0.1, 0.2, 0.3)	(0.5, 1.3, 2.4)	1.703

5. Discussion and conclusions

This paper has highlighted the question: how far toward becoming agile is an organization? How can an organization improve its agility effectively? Also, limited by the nature of agility definition, agility measurement is associated with vagueness and complexity and the conventional (crisp) assessment approaches are unsuitable and ineffective for handling such evaluation. To compensate for these limitations, an FAI which concentrates on the application of linguistic approximating and fuzzy arithmetic has been developed to address agility measuring, stressing the multi-possibility and ambiguity of agility capability measurement. Three aspects, including organization management, product design and product manufacturing, form the agility index of MC product manufacturing. The evaluation procedures include: identifying agility capabilities, selecting linguistic variables for assessing and interpreting the values of the linguistic variables, fuzzy rating and fuzzy weights integrating, fuzzy index labeling, and defuzzifying FPII in order to identify the main adverse factors which can influence agility achievement.

This model was developed from the concept of MCDM (Multi Criteria Decision Making) and fuzzy logic, and adopted the MC product manufacturing XDCLC (Yang and Li, 2002) as an initial case study to validate the model and approach. With regard to the efficiency of the method to measure agility index, the result generated by both approaches seemingly leads to similar conclusions as shown in Table 8. However, the FAI generated by the fuzzy logic approach is expressed in terms of ranges of value. This rating can provide an overall picture of the pertinent possibility and ensure that the decision made in the subsequent selection process is not biased. Furthermore, it gives the decision-makers a high degree of flexibility in decision-making. As an example in this study, the agility index had a fuzzy

Table 8
Comparison of fuzzy logic approach and crisp approach

Approach	Agility index	Range	Linguistic labeling
Fuzzy logic	(5.72, 7.18, 8.52)	2.8	Very agile
Crisp approach	7.26		Very agile

value (5.72, 7.18, 8.52). Qualitatively, this suggests that the agility level of MC product manufacturing XDCLC approaches "very agile" while being far from "extremely agile".

In comparison with the original study, seven linguistic levels and a range value are designated to represent the linguistic ambiguity range. Actually, on the basis of the needs of cognitive perspectives and available data characteristics, the number of linguistic levels and its membership functions can be adjusted correspondingly. In general, it is suggested that one not exceed the human discrimination capacity consisting of nine levels.

Finally, there are some limitations to this fuzzy logic approach. The membership functions of linguistic variables depend on the managerial perception of the decision-maker. Thus, the decision-maker must be at a strategic level in the company in order to realize the importance, possibility and trends of all aspects, such as strategy, marketing and technology. Furthermore, competitive situations and requirements vary from company to company; hence, companies have to establish their unique membership function by fitting in with their specific environment and considerations. In addition, the computation of a fuzzy-weighted average is still complicated and not easily appreciated by managers. Fortunately, this calculation has been computerized to increase accuracy while reducing both time and possibility of errors.

Furthermore, the contribution of this work has provided potential value to practitioners by offering a rational structure to reflect the imprecise phenomena in agility evaluation and has taken into account the ambiguity of each agility capability to ensure relatively realistic and informative information, and to researchers by demonstrating an unprecedented application of fuzzy logic. In addition, from the example, this approach has several advantages when compared to previous methods:

(1) This method can give the analyst relatively realistic and informative information. The FAI is expressed in a range of values. This provides an overall picture about the possible agility of an organization and ensures that the decision made in selection will not be biased. As an example of this study, the agility index has a fuzzy value (5.72, 7.18, 8.52).
(2) This method can systematically identify the weak factors within an organization and provide the means for a manager to formulate a comprehensive plan for improvement. Therefore, the method can be further used in self-assessment.
(3) It provides an appropriate function structure to reflect the imprecise phenomena in many business environments and takes into account the uncertainty effect of each factor to ensure a more convincing and reliable evaluation.

Moreover, algorithm of the proposed method can be computerized. Thus, by the decision-makers' providing linguistic assessments through a menu-driven interface design, the agility level of an enterprise and its agility obstacles can be obtained easily.

Appendix A

A.1. Basic concept of fuzzy set theory

For the purpose of application, the basic properties of fuzzy set theory needed in this study are introduced. Additional discussion can be found in books by Klir and Yuan (1995).

A.1.1. Fuzzy numbers

Let X be a collection of objects, called the universe, whose elements are denoted by x. A fuzzy subset A in X is characterized by a membership function $f_A(X)$ which is associated with each element x in X and a real number in the interval [0,1]. The function value $f_A(X)$ represents the grade of membership of x in A.

A fuzzy subset A is called a fuzzy (real) number if A is convex and there exists exactly one real number a with $f_A(a) = 1$. There are many forms of fuzzy numbers to represent imprecise information. As used here, triangular fuzzy numbers are applied.

Let $x, a, b, c \in R$ (real line); hence, a triangular fuzzy number is a fuzzy number A in R, if its membership function $f_A : R \to [0,1]$ is

$$f_A(x) = \begin{cases} (x-a)/(b-a), & a \leqslant x \leqslant b, \\ (x-c)/(c-b), & b \leqslant x \leqslant c, \\ 0, & \text{otherwise.} \end{cases}$$

The triangular fuzzy number is parameterized by the triplet $A = (a, b, c)$. The parameter "b" gives the maximal grade of $f_A(x)$, i.e., $f_A(b) = 1$, which is the most probable value of the evaluation data. The parameters "a" and "c" are the lower and upper bounds of the available area for the evaluation data. For example, the triangular fuzzy number to represent "close to 5" can be parameterized by $A = (3, 5, 7)$. Triangular fuzzy numbers are mostly used because they are easily specified by experts. Furthermore, under some weak assumptions, such use immediately complies with the relevant optimization criteria.

A.1.2. Linguistic variables

The concept of a linguistic variable is very useful in dealing with situations which are too complex or too ill-defined to be reasonably described in conventional quantitative expressions. A linguistic variable is a variable whose values are words or sentences in natural or artificial language. For example, "low" is a linguistic variable if its value is linguistic rather than numerical. Furthermore, by the approximate reasoning of fuzzy sets theory, the linguistic value can be represented by a fuzzy number. For example, for the linguistic variables, {Excellent [E], Very Good [VG], Good [G], Fair [F], Poor [P], Very Poor [VP], Worst [W]}, the fuzzy numbers approximate to these linguistic values are shown in Table 4.

A.1.3. Fuzzy number arithmetic operations

Let A_1 and A_2 be two triangular fuzzy numbers, where $A_1 = (a_1, b_1, c_1)$ and $A_2 = (a_2, b_2, c_2)$. According to the extension principle, the triangular fuzzy-number addition, subtraction and multiplication operations of A_1 and A_2 are defined as follows:

Fuzzy-number addition $\oplus$:

$$\begin{aligned} A_1 \oplus A_2 &= (a_1, b_1, c_1) \oplus (a_2, b_2, c_2) \\ &= (a_1 + a_2, b_1 + b_2, c_1 + c_2). \end{aligned}$$

Fuzzy-number subtraction $\ominus$:

$$\begin{aligned} A_1 \ominus A_2 &= (a_1, b_1, c_1) \ominus (a_2, b_2, c_2) \\ &= (a_1 - c_2, b_1 - b_2, c_1 - a_2). \end{aligned}$$

Fuzzy-number multiplication $\otimes$:

$$\begin{aligned} A_1 \otimes A_2 &= (a_1, b_1, c_1) \otimes (a_2, b_2, c_2) \\ &= (a_1 \times a_2, b_1 \times b_2, c_1 \times c_2). \end{aligned}$$

A.2. Euclidean distance method

The Euclidean distance method consists of calculating the Euclidean distance from the given fuzzy number to each of the fuzzy numbers representing the natural-language expressions set. Suppose the natural-language expression set is agility level (AL). Then the distance between the fuzzy number fuzzy-agility-index (FAI) and each fuzzy number member $\text{AL}_i \in \text{AL}$ can be calculated as below:

$$d(\text{FAI}, \text{AL}_i) = \left\{ \sum_{x \in p} (f_{\text{FAI}}(x) - f_{\text{AL}_i}(x))^2 \right\}^{1/2},$$

where $p = \{x_0, x_1, \ldots, x_m\} \subset [0, 10]$ so that $0 = x_0 < x_1 < \cdots < x_m = 10$. To simplify, let $p = \{0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10\}$. Then, the distance from the FAI to each of the members in the set AL can be calculated.

A.3. Chen and Hwang's left-and-right fuzzy-ranking method

In the Chen and Hwang's left-and-right fuzzy-ranking method, for defuzzifying a fuzzy number, the fuzzy maximizing and minimizing set are, respectively, defined as:

$$f_{\max}(x) = \begin{cases} x, & 0 \leqslant x \leqslant 10, \\ 0, & \text{otherwise}, \end{cases}$$

$$f_{\min}(x) = \begin{cases} 10 - x, & 0 \leqslant x \leqslant 10, \\ 0, & \text{otherwise}, \end{cases}$$

When given a triangular fuzzy number FPII defined as f_{FPII}: $R \to [0, 10]$, with a triangular membership function, the right-and-left scores of FPII can be obtained, respectively, as

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

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

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

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

Using the total score, the fuzzy numbers can be ranked. For example, the total scoring value of a fuzzy number $\mathrm{FPII}_{111} = (0,\ 0.325,\ 1.2)$ is calculated as

$$U_{\mathrm{R}}(\mathrm{FPII}_{111}) = \sup_x \lfloor f_{\mathrm{FPII}_{111}}(x) \wedge f_{\max}(x) \rfloor = 1.103,$$

$$U_{\mathrm{L}}(\mathrm{FPII}_{111}) = \sup_x \lfloor f_{\mathrm{FPII}_{111}}(x) \wedge f_{\min}(x) \rfloor = 9.685,$$

$$U_{\mathrm{T}}(\mathrm{FPII}_{111}) = [U_{\mathrm{R}}(\mathrm{FPII}_{111}) + 10 - U_{\mathrm{L}}(\mathrm{FPII}_{111})]/2 = 0.709.$$

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