Chapter 8
Prioritization of Supply Chain Performance Measurement Factors by a Fuzzy Multi-criteria Approach

I. U. Sari, S. Ugurlu and C. Kahraman

Abstract Measurement of supply chain performance is an important issue to identify success, to understand processes, to figure out problems and where improvements are possible as well as provide facts for decision-making. Using classical performance measurement techniques, it may not be possible to incorporate judgments of decision makers comprehensively. Hence, we propose a fuzzy multi-criteria evaluation method for this purpose in the framework of supply chain performance measurement. Fuzzy DEMATEL is used to prioritize the performance measurement criteria of supply chain. We also present a sensitivity analysis using different linguistic scales.

Keywords Supply chain · Performance measurement · Fuzzy sets · DEMATEL method · Linguistic scale

8.1 Introduction

Globalization and the new market environment in which customer is ruling have evolved business drastically. Product life cycles have shortened significantly, agility has gained importance and outsourcing has become an option offering competitive advantage. In order to survive, collaboration among companies became inevitable. Rigid boundaries between companies have turned out to be a countercheck for performance. The ability for collaboration is encouraged through new techniques and technologies, which link a chain of companies working together as a single unit in order to satisfy customer needs. The new organization,

I. U. Sari · S. Ugurlu · C. Kahraman (✉)
Department of Industrial Engineering, Istanbul Technical University,
34367 İstanbul, Turkey
e-mail: kahramanc@itu.edu.tr

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named as supply chain (SC), is formed to achieve higher performance in the new era. In order to measure the performance of the SC, we need to combine a new perspective and novel tools with the existing performance measures. The traditional performance measures such as productivity, customer satisfaction need to be redefined in an integrated manner. On the other side, the performance factors of flexibility and risk management are considered as the ultimate purpose of a SC needed to respond to changes in the market environment.

Organizational performance measurement serves various purposes: (i) identifying success, (ii) specifying whether customer needs are met; (iii) helping to understand processes and confirming what is known or not known; (iv) identifying problems, bottlenecks, waste and where improvements are possible; (v) providing facts for decision-making; (vi) enabling and tracking improvements; and (vii) facilitating communication and cooperation (Parker 2000). In summary, a performance measurement system plays an important role in maintaining continuous improvement and decision-making.

The new organization named as SC consists of different companies with contradicting goals, technologies, and work procedures. Moreover, applications of SC aims to integrate not only various enterprises along the value chain but also various functions such as marketing, operations, sales, technology, procurement, etc., within these companies. Developing an integrated performance measurement system that would support an integrated SC development and operations is essential. The performance measures and metrics should facilitate the integration of various functional areas and also so-called extended enterprises or partnering firms along the value chain (Gunasekaran and Kobu 2007). Measuring the performance of the key functional activities of a SC is a multi-criteria decision problem. Various aspects of performance of a SC include quality, flexibility, cost (i.e., inventory turnover), customer satisfaction (i.e., responsiveness), risk (i.e., SC uncertainty), delivery (i.e., proximity to suppliers and markets).

There is a body of literature investigating SC performance measurement systems as a multi-criteria decision-making problem. Among these studies, analytical hierarchy method (AHP) and analytical network method have been used commonly. A stream of studies which employ balance scorecard is presented in order to identify the balance between external-internal focus, long-short term using the four dimensions of the scorecard. The multi-criteria nature of the problem has also been handled by operations research techniques such as mixed integer programming and data envelopment analysis. There have also been attempts to incorporate the dynamic nature of the SC in performance measurement using system dynamics and classical control theory.

In this chapter, we make use of a multi-criteria decision-making approach, which is called fuzzy decision-making trial and evaluation laboratory (DEMATEL) to prioritize the SC performance measures. We first attempt to prioritize the key performance indicators of the performance measurement system using fuzzy DEMATEL and then investigate the effect of fuzzy linguistic scale in the prioritization of the criteria.

The rest of the chapter is organized as follows: SC types and their association with performance measures are discussed in Sect. 8.2.1. Then, the scope of performance measurement in SC is reviewed in Sect. 8.2.2. In Sect. 8.3, a literature review on performance measurement systems in SC is presented. In Sect. 8.4, fuzzy set theory and linguistic variables are described. In Sect. 8.5, fuzzy DEMATEL method is reviewed. We applied fuzzy DEMATEL method for prioritization of SC performance criteria in Sect. 8.6. We then investigate the effect of the fuzzy linguistic scale on the results in Sect. 8.7. Finally, Sect. 8.7 concludes with the discussion of findings and future research.

8.2 Supply Chain Performance Measurement

In this section, we present types of SCs and performance measures as well as the scope of performance measurement in SCs.

8.2.1 Types of Supply Chains and Performance Measures

Designing a performance measurement system for a SC, performance measures and metrics should be prioritized with respect to the type of SC. In the literature, various types of SCs are identified based on the type of product manufactured. A classification of the SCs in relation to the type of products is given in Table 8.1.

Functional products are typically manufactured in high volumes so the emphasis is mainly on productivity together with quality, customer service, and cost. Demand of functional products is fairly stable. Some examples of these types of products are grocery, automobiles, etc.

However, SCs through which innovative products are manufactured, need to adapt to a volatile market. Demand is difficult to forecast. Besides, the design of

Table 8.1 Types of supply chains in the literature

Product type	Type of supply chain	Reference
Functional products	Efficient supply chain	Fisher (1997)
	Lean supply chain	Turkett (2001) Christopher and Towill (2000)
Innovative products	Quick supply chain	Fischer (1997); Huang and Uppal (2002); Selldin and Olhager (2007)
	Agile supply chain	Christopher and Towill (2000)
Functional and innovative products	Hybrid supply chain	Naylor et al. (1999); Huang and Uppal (2002)

the products changes quickly. Thus, performance of the SC depends mainly on flexibility, responsiveness and risk management. Some examples of products manufactured in quick or agile SCs are mobile phones requiring changes due to technical developments and fashion goods requiring design changes frequently.

A recent type, hybrid SC has been introduced which is a combination of a lean SC and agile SC. In hybrid SC, leanness which focuses on elimination of waste through the value stream and innovativeness are combined. For example, manufacturers of automobiles, computers, etc., need to operate in a competitive market where price is important as well as introduce innovative features in their products. Another aim for hybrid SCs is to achieve flexibility together with productivity to maintain a customer-driven approach.

Based on the focus of the SC, importance given to different performance measures and metrics may differ. For an efficient SC, productivity improvements for cost reduction and quality are vital. Cost reduction is achieved in connection to the suppliers and internal process improvements. Some of the metrics related to costs may be purchasing costs, handling costs, storage costs, supplier handling costs, etc. Similarly, quality is another important measure which is defined with many sub-dimensions such as conformance to the product specifications, performance of a product, and reliability. Some metrics related to quality are defects per million opportunities, perfect order fulfillment which calculates the error-free rate of each stage of a purchase order.

Customer satisfaction is a multidimensional performance measure for which measurements can vary greatly. For the performance measurement of SCs, delivery metrics gain importance to verify customer satisfaction. Some metrics are on time delivery, performance to promise dates or fill rate which expresses shipping performance as a percentage of the total order.

For SCs of innovative products, measurement of SC risk gains importance due to rapid change and uncertainty of markets. Risk is typically measured using the probability of an event occurring and impact of the event on the SC, and subsequently the overall business. Performance measurement systems of SCs should ensure that evaluation and redesign is made in response to market changes, including new product launches, global sourcing, new acquisitions, credit availability, the need to protect intellectual property, and the ability to maintain asset and shipment security.

Similarly, flexibility is vital for quick and agile SCs. Flexibility is needed to respond to marketplace changes to gain or maintain competitive advantage. In the literature, four types of flexibility are identified Slack (1991): (i) volume flexibility (the ability to change the output level of products produced), (ii) delivery flexibility (the ability to change planned delivery dates), (iii) mix flexibility (the ability to change the variety of products produced), and (iv) new product flexibility (the ability to introduce and produce new products). Some metrics used are SC response time and production flexibility.

8.2.2 Scope of Performance Measurement in Supply Chains

Supply chain is viewed as a new organization aiming to integrate various enterprises along the value chain. Since enterprises are building blocks of a SC, the performance of each enterprise influences the performance of its SC. Performance measurement within each enterprise is an element of the SC performance measurement system. An enterprise consists of various functions related to the SC performance. For example sourcing, production and delivery are different functions of an enterprise having different performance levels. In this perspective, the scope of the within-enterprise performance measurement may be limited to the performance of only one of the function of an enterprise named as functional performance. On the other side, within-enterprise performance measurement may be extended to cross-functional measurements along many functions of the enterprise, named as integrated performance.

From another perspective, scope of the performance measurement may be enlarged on the boundaries of an enterprise and handled together with its suppliers or customers. These types of measures are known as one-sided integrated measures and depict performance across organizational boundaries as well as measuring chain performance across supplier or customer boundaries, for example, total cost, total lead-time, and delivery speed, SC response time (Chibba 2007). However, the most complementary approach to performance measurement of SCs is depicted with the performance across organizational boundaries including links both to the suppliers and the end customers. Total chain measures are used to assess the performance of the entire SC and provide an opportunity to minimize the total cost. Stewart (1995) identified the following measures of delivery performance as total chain measures: delivery-to request date, delivery-to-commit date, and order fill lead-time.

The content of the performance measurement of SC systems is mainly related to the five phases of the SC systems: (i) plan; (ii) source; (iii) make; (iv) deliver; and (v) return. The Supply-Chain Operations Reference (SCOR) model developed by the SC Council illustrated in Fig. 8.1 summarizes the processes of a SC system.

The “plan” processes describe the planning activities associated with operating a SC, including information gathering customer requirements, resources, and balancing requirements and resources to determine planned capabilities and resource gaps. The “source” processes describe the ordering and receipt of goods and services.

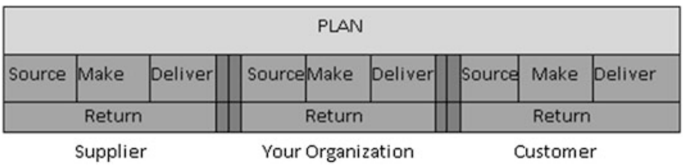

Fig. 8.1 SCOR model of the supply chain council

The "make" processes describe the activities associated with the conversion of materials or creation of the content for services which include not only production and manufacturing because but also assembly, chemical processing, maintenance, repair, overhaul, recycling, remanufacturing, and other material conversion processes. The "deliver" processes describe the activities associated with the creation, maintenance, and fulfillment of customer orders. Finally, the "return" processes describe the activities associated with the reverse flow of goods back from the customer. As is understood from the definitions of the processes of SC systems, each phase may be related to only one function of an enterprise, cross-functional in an enterprise or related to the suppliers or customers of an enterprise. Based on the level of SC performance we need to assess, the focus will be the processes of the SC in an enterprise or on the integrated performance of the whole or a part of the SC including customers or suppliers.

8.3 Literature Review

There exists a vast literature on the performance measurement systems of SCs. In the literature, seven different performance measurement systems have been proposed: function-based measurement system, dimension-based measurement system, SC operations reference model, SC balanced scorecard, hierarchical-based measurement system, interface-based measurement system, and perspective-based measurement system (Ramaa 2009). In Table 8.2, different performance measurement systems have been compared with respect to the measurement aspects and drawbacks of the system.

Performance measurement of SCs has a multidimensional nature which may be identified with the processes of the SC, management levels, performance dimensions, integration levels, or perspectives. Operations research perspective in SC performance measurement have been recently studied in the literature using data envelopment analysis, which is a nonparametric method in operations research to empirically measure productive efficiency of decision-making units. Wong and Wong (2007) developed two DEA models for the technical efficiency and the cost efficiency of internal SC performance measurement.

Talluri et al. (2006) attempted to develop a vendor evaluation model by presenting a chance-constrained data envelopment analysis approach in the presence of multiple uncertain performance measures that allow considering variability in vendor attributes. Supply chain performance is exposed to many uncertainties due to the stochastic nature of demand and supply processes. Besides, SC performance also includes many imprecise qualitative dimensions. For example, collaboration is one of the main drivers of success in SC processes. Angerhofer and Angelides (2006) developed a system dynamics model in order to reveal the constituents of a collaborative SC, key parameters they influence and pinpoint areas where the actual SC can be improved.

Table 8.2 Comparison of supply chain performance measurement systems

Performance measurement system	References	Measurement aspects	Specification of measurement	Drawback
Function based (FBMS)	Christopher (1992)	Processes of the SC	Measurement of functional processes of SC in isolation with company strategy	It does not provide the top level measures to cover the entire supply chain
Dimension based (DBMS)	Beamon (1999) Hausman (2004)	Resources, output and flexibility Service, assets and speed	Measurement based on various dimensions of performance	Dimensions should coincide with an organization's strategic goals
Supply chain operations reference model (SCOR)	Supply chain council	Reliability, responsiveness, flexibility, cost, and asset	Measurement of cross-functional processes of SC based on metrics related to processes and benchmarks	An exhaustive system requiring dedicated resources, a well-defined infrastructure, and project-based completion approach
SC balanced scorecard (SCBS)	Kaplan and Norton (1992)	Customer, internal processes, innovation and financial	Measurement based on the customers, internal business processes, learning and growth and the financial indicators	Limited to the balance scorecard dimensions
Hierarchical based (HBMS)	Gunasekaran et al. (2001)	Financial and nonfinancial metrics at strategic, tactical, and operational levels	Measurement with respect to strategic, tactical, and operational levels of management	Difficult to put measures into different levels that reduce conflicts among the supply chain partners
Interface based (IBMS)	Lambert and Pohlen (2001)	Cost, activity time, customer responsiveness, and flexibility as single or joint dimensions	Measurement of the stages of a SC which forms the total SC to optimize the total SC as well as each company	Requirement of openness and sharing of information along the chain, difficult in actual business setting
Perspective based (PBMS)	Otto and Kotzab (2003)	System dynamics, operations research, logistics, marketing, organization, strategy	Measurement of the SC in all the possible perspectives based on measures for each perspective	There can be trade-off between measures of one perspective and other perspectives

In order to handle the multidimensionality of the performance, multi-criteria decision-making methods have been employed in the literature. Bhagwat and Sharma (2007a) make use of AHP in order to combine a hierarchical performance measurement system and SC balance scorecard. They have defined the AHP model with strategic, tactical and operational levels at the upper stage and the dimensions of balance scorecard at the lower stage of AHP. Later, in 2009, Bhagwat and Sharma (2007b) propose an integrated AHP-PGP (pre-emptive goal programming) model to consider both quantitative and qualitative performance measures in optimizing the overall performance of the system. Berrah and Cliville (2007) suggests to employ a multi-criteria methodology by considering the SCOR model break-down and then an aggregation methodology, based on the Choquet integral operator and MACBETH framework. In this way, the overall performance is associated to a global objective of overall SC performance whose break-down is provided by SCOR model's elementary objectives.

Bai and Sarkis (2012) introduce an application of neighbourhood rough-set theory for the identification and selection of performance measures related to the sourcing function using the elements of SCOR model. Their model allows determining a core set of external logistics and SC performance measures to internal performance expectations and outcomes.

In this study, we propose a fuzzy multi-criteria decision-making methodology to apply a dimension based performance measurement. Our methodology first prioritizes the criteria using fuzzy DEMATEL and then we investigate the effect of linguistic variable scales. We offer a fuzzy decision-making methodology in order to include the uncertainties of SC and the imprecision of the assessment of criteria used in performance measurement system.

8.4 A Fuzzy Multi-criteria Approach

In this section, we present the basics of the fuzzy set theory and define linguistic variables. Then we briefly give the steps of fuzzy DEMATEL method.

8.4.1 Fuzzy Set Theory

The fuzzy set theory is founded by Zadeh in 1965, and he defined the fuzzy set as a class of objects with a continuum of grades of membership, which is characterized by a membership function which assigns to each object a grade of membership ranging between zero and one. A fuzzy set A in U characterized by a membership function $\mu_A(x)$ which associates with each point in U a real number in interval [0, 1], with the value of $\mu_A(x)$ at x representing "the grade of membership" of x in A (Zadeh 1965).

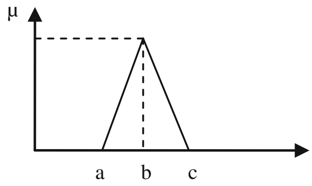

Fig. 8.2 Membership function of a TFN

A formula for membership function $\mu_A(x)$ of a triangular fuzzy number (TFN) $\tilde{x}$ which has a shape shown in Fig. 8.2, is given in Eq. (8.1), where a, b, and c denotes real numbers (Ross 1995):

$$\mu_A(x) = (l, m, r) = \begin{cases} \frac{x-a}{b-a}; & a \le x \le b \\ \frac{c-x}{c-b}; & b \le x \le c \\ 0; & \text{otherwise} \end{cases} \tag{8.1}$$

Algebraic operations for TFNs are given by (8.2)–(8.8) where all the fuzzy numbers are positive (here it is assumed to mean $a \ge 0, e \ge 0$) (Chen et al. 1992):

$$(a, b, c) + (d, e, f) \cong (a + d, b + e, c + f) \tag{8.2}$$

$$(a, b, c) - (d, e, f) \cong (a - f, b - e, c - d) \tag{8.3}$$

$$(a, b, c) \otimes (d, e, f) \cong (ad, be, cf) \tag{8.4}$$

$$(a, b, c) \div (d, e, f) \cong \left(\frac{a}{f}, \frac{b}{e}, \frac{c}{d}\right) \tag{8.5}$$

$$\lambda \otimes (a, b, c) \cong \begin{cases} (\lambda a, \lambda b, \lambda c), & \text{if} \quad \lambda \ge 0 \\ (\lambda c, \lambda b, \lambda a), & \quad \forall \lambda \in \Re \quad \lambda \le 0 \end{cases} \tag{8.6}$$

$$\lambda \div (a, b, c) \cong \begin{cases} \left(\frac{\lambda}{c}, \frac{\lambda}{b}, \frac{\lambda}{a}\right), & \text{if} \quad \lambda \ge 0 \\ \left(\frac{\lambda}{a}, \frac{\lambda}{b}, \frac{\lambda}{c}\right), & \quad \lambda \le 0 \end{cases}, \forall \lambda \in \Re \tag{8.7}$$

$$(a, b, c)^{\lambda} \cong \begin{cases} \left(a^{\lambda}, b^{\lambda}, c^{\lambda}\right), & \text{if} \quad \lambda \ge 0 \\ \left(\frac{1}{c^{\lambda}}, \frac{1}{b^{\lambda}}, \frac{1}{a^{\lambda}}\right), & \quad \lambda \le 0 \end{cases} \quad \forall \lambda \in \Re \tag{8.8}$$

8.4.2 Linguistic Variables

Linguistic variables are the variables whose values are not numbers but words or sentences in a natural or artificial language (Zimmermann 1991). Linguistic

Table 8.3 Fuzzy linguistic scale for fuzzy DEMATEL

Linguistic terms	Triangular fuzzy numbers
Very high influence (VIH)	(0.75, 1.0, 1.0)
High influence (HI)	(0.5, 0.75, 1.0)
Low influence (LI)	(0.25, 0.5, 0.75)
Very low influence (VLI)	(0, 0.25, 0.5)
No influence (NI)	(0, 0, 0.25)

variables can reflect the different levels of human language. The totality of values of a linguistic variable constitutes its term-set, which in principle could have an infinite number of elements (Zadeh 1975). In addition to the primary terms, a linguistic value may involve connectives such as and, or, either, neither, etc.; the negation not; and the hedges such as very, more or less, weakly, moderately, greatly, absolutely, etc. The hedges as well as the connectives are treated as nonlinear operators which modify the meaning of their operands in a specified fashion (Zadeh 1975).

In this study, the linguistic variable ''influence'' is used with five linguistic terms (Li 1999) as {Very high, High, Low, Very low, No} that are expressed in positive triangular fuzzy numbers (l_{ij}, m_{ij}, r_{ij}) as shown in Table 8.3.

8.4.3 Fuzzy DEMATEL Method

Decision-making trial and evaluation laboratory (DEMATEL) method, originated from the Geneva Research Centre of the Battelle Memorial Institute, is an effective method which collects group knowledge, analyzes the inter-relationships among system factors, and visualizes this structure by cause-effect relationship diagram (Gabus and Fontela 1972, 1973). The most important feature of DEMATEL in multi-criteria decision-making area is its function of building the relation and structure factors (Zhou et al. 2011). Although DEMATEL is a novel technique for evaluating problems, the relationships of systems are generally given by crisp values. The fact that human judgments about preferences are often unclear and hard to estimate by exact numerical values, necessitates fuzzy logic for handling problems characterized by vagueness and imprecision (Chang et al. 1998; Chen and Chiou 1999). Therefore, many researchers use the fuzzy DEMATEL method to extend the DEMATEL technique with fuzzy concept for making better decisions in fuzzy environments (Jeng and Tzeng 2012; Zhou et al. 2011; Chang et al. 2011; Lin and Wu 2008; Liou et al. 2008; Tseng 2009; Wu and Lee 2007).

The steps of the fuzzy DEMATEL method which is proposed by Wu and Lee (2007) are defined as follows:

Step 1: *Identifying the decision goal and forming a committee.* Decision-making is the process of defining the decision goals, gathering relevant information, generating the broadest possible range of alternatives, evaluating the alternatives for advantages and disadvantages, selecting the optimal alternative, and monitoring the results to ensure that the decision goals are achieved (Hess and Siciliano 1996; Opricovic and Tzeng 2004). Thus, the first step is to identify the decision goal. Also, it is necessary to form a committee for gathering group knowledge for problem solving.

Step 2: *Developing evaluation factors and designing the fuzzy linguistic scale*. In this step, it is necessary to establish sets of significant factors for evaluation. However, evaluation factors have the nature of causal relationships and are usually comprised of many complicated aspects. To gain a structural model dividing involved factors into cause group and effect group, the DEMATEL method must be used here. For dealing with the ambiguities of human assessments, the linguistic variable ''influence'' is used with five linguistic terms (Li 1999) as $\{\text{Very high, High, Low, Very low, No}\}$ that are expressed in positive triangular fuzzy numbers (l_{ij}, m_{ij}, r_{ij}) as given in Table 8.3.

Step 3: *Acquiring and aggregating the assessments of decision makers.* To measure the relationship between evaluation factors $C = \{\, C_i |\, i = 1, 2, \ldots, n\}$, it is usually necessary to ask a group of experts to make assessments in terms of influences and directions between factors. Then, using the CFCS (Converting Fuzzy data into Crisp Scores) method, those fuzzy assessments are defuzzified and aggregated as a crisp value which is the z_{ij}. Hence, the initial direct-relation matrix $Z = \left[z_{ij}\right]_{nxn}$ can be obtained using formulas (8.9)–(8.16).

Converting fuzzy data into crisp scores method

Let $\tilde{z}_{ij}^k = \left(z_{lij}^k, z_{mij}^k, z_{rij}^k\right)$ indicate the fuzzy assessment of evaluator $k(k = 1, 2, \ldots, p)$ about the degree to which the criterion i affects the criterion j. The CFCS method includes five step algorithms described as follows:

Normalization

$$x_{lij}^k = \frac{(z_{lij}^k - \min z_{lij}^k)}{\max z_{rij}^k - \min z_{lij}^k} \tag{8.9}$$

$$x_{mij}^k = \frac{(z_{mij}^k - \min z_{lij}^k)}{\max z_{rij}^k - \min z_{lij}^k} \tag{8.10}$$

$$x_{rij}^k = \frac{(z_{rij}^k - \min z_{lij}^k)}{\max z_{rij}^k - \min z_{lij}^k} \tag{8.11}$$

Compute left (x_{lsij}^k) and right (x_{rsij}^k) normalized values:

$$x_{lsij}^k = \frac{x_{mij}^k}{(1 + x_{mij}^k - x_{lij}^k)} \tag{8.12}$$

$$x_{rsij}^{k} = \frac{x_{rij}^{k}}{(1 + x_{rij}^{k} - x_{mij}^{k})} \tag{8.13}$$

Compute total normalized crisp value:

$$x_{ij}^{k} = \frac{[x_{lsij}^{k}(1 - x_{lsij}^{k}) + (x_{rsij}^{k})^{2}]}{[1 - x_{lsij}^{k} + x_{rsij}^{k}]} \tag{8.14}$$

Compute crisp values:

$$z_{ij}^{k} = \min z_{lij}^{k} + x_{ij}^{k}\left(\max z_{rij}^{k} - \min z_{lij}^{k}\right) \tag{8.15}$$

Integrate crisp values:

$$z_{ij} = \frac{1}{p}(z_{ij}^{1} + z_{ij}^{2} + \ldots + z_{ij}^{p}) \tag{8.16}$$

Step 4: *Establishing and analyzing the structural model*. On the base of the initial direct-relation matrix $Z = \left[z_{ij}\right]_{nxn}$, the normalized direct-relation matrix $X = \left[x_{ij}\right]_{nxn}$ where $0 \leq x_{ij} \leq 1$, can be obtained through formula (8.17) where $i, j = 1, 2, \ldots, n$

.

$$X = \frac{1}{\max\limits_{0 \leq i \leq 1} \sum_{j=1}^{n} z_{ij}} Z \tag{8.17}$$

Then, the total-relation matrix T can be acquired by using formula (8.18).

$$T = X(I - X)^{-1} \tag{8.18}$$

The causal diagram can be acquired through formulas (8.19)–(8.21).

$$T = t_{ij}, \quad i, j = 1, 2, \ldots, n \tag{8.19}$$

$$D = \sum_{j=1}^{n} t_{ij} \tag{8.20}$$

$$R = \sum_{i=1}^{n} t_{ij} \tag{8.21}$$

The causal diagram is constructed with the horizontal axis (D+R) named "Prominence" and the vertical axis ($D-R$) named "Relation." The horizontal axis "Prominence" shows how much importance the factor has, whereas the vertical axis "Relation" may divide factors into cause group and effect group. Generally, when the ($D-R$) axis is plus, the factor belongs to the cause group. Otherwise, the factor belongs to the effect group if the $(D-R)$ axis is minus. Hence, causal diagrams can visualize the complicated causal relationships of factors into a visible structural model, providing valuable insight for problem solving. Further, with the help of a causal diagram, we may make proper decisions by recognizing the difference between cause and effect factors.

8.5 Performance Criteria Prioritization of Suppliers Using Fuzzy DEMATEL Method

Step 1: *Identifying the decision goal and forming a committee.*

Decision goal is defined as "prioritization of SC performance measurement criteria". The decision group consists of one general manager one manufacturing department manager and one logistics department manager.

Step 2: *Developing evaluation factors and designing the fuzzy linguistic scale*. Performance factors of SC are defined in four groups which are customer satisfaction, productivity, flexibility, and risk management due to the literature review given in Sect. 8.3.

Organizations always intend to satisfy their customers. Therefore customer satisfaction which affects all of the departments and facilities of the organizations is one of the critical factors. On time delivery (C1) and satisfying industry regulations (C2) are determined as performance criteria of customer satisfaction factor.

Productivity which is the second performance factor of suppliers is an integral part of performance. It is defined one of the most crucial area for operational and process management (Sink and Tuttle 1989; Hoehn 2003). Cost minimization (C3) and quality (C4) are determined as performance criteria of customer satisfaction factor.

Flexibility is another critical performance factor for organizations if the product type or demand could change easily. In such conditions, speed and manner of reaction (C5) and technical capability (C6) are defined as performance criteria of flexibility.

Risk management policies of suppliers have to handle the impact of the natural disasters. The sub criteria of risk management performance factor are defined as security awareness (C7), physical security (C8), and geographical location (C9). Hierarchical structure of performance factors and criteria is given in Fig. 8.3.

Step 3: *Acquiring and aggregating the assessments of decision makers.*

Influences and directions between evaluation factors are determined by the group of experts to measure the relationship between them. The influence matrices are given in Table 8.4.

Linguistic terms are expressed in positive triangular fuzzy numbers (l_{ij}, m_{ij}, r_{ij})as given in Table 8.3.

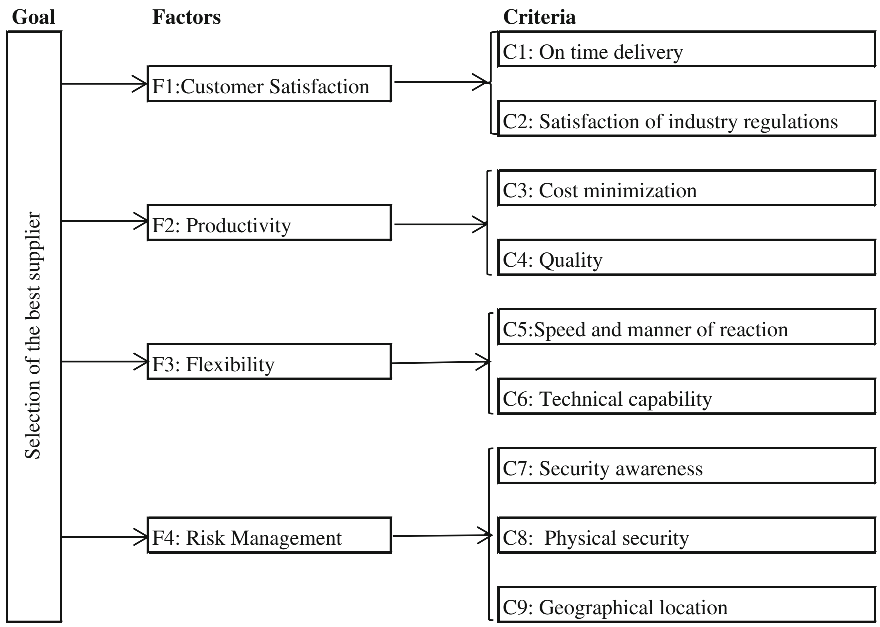

Fig. 8.3 Hierarchical structure of performance factors and criteria

Then, using the CFCS (method, fuzzy assessments are defuzzified and aggregated as a crisp value. The initial direct-relation matrix $Z = \left[z_{ij}\right]_{nxn}$ is obtained and given in Table 8.5.

Step 4: *Establishing and analyzing the structural model.*

On the base of the initial direct-relation matrix, the normalized direct-relation matrix is obtained and given in Table 8.6.

Then, the total-relation matrix is obtained and given in Table 8.7. The causal diagram is constructed with the horizontal axis $(D + R)$ and the vertical axis $(D-R)$ and given in Fig. 8.4.

The horizontal axis shows how much importance the factor has. Quality (C4) is the most important performance criteria in SC performance measurement systems whereas security awareness (C7) is the least important one. The vertical axis divides factors into cause and effect groups. We can see that technical capability (C6), geographical location (C9), and satisfaction in industry regulations (C2) are in the cause group and on time delivery (C1), cost minimization (C3), speed and manner of reaction (C5), security awareness (C7), and physical security (C8) are in the effect group. Quality (C4) is located on the vertical axis which means it has neutral effect on the other criteria. Decision makers should focus on the cause group criteria (C2, C6, and C9) and the neutral criterion (C4).

Table 8.4 The influence matrices

Expert 1_General manager									
	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0	HI	VLI	VLI	VHI	NI	NI	NI	LI
C2	LI	0	HI	VHI	VLI	VLI	HI	HI	VLI
C3	HI	NI	0	VHI	HI	VHI	NI	LI	HI
C4	LI	HI	HI	0	LI	VHI	LI	HI	NI
C5	VHI	HI	LI	HI	0	HI	NI	LI	VLI
C6	HI	HI	VHI	VHI	VHI	0	NI	HI	NI
C7	NI	HI	VLI	VLI	VLI	VLI	0	VHI	NI
C8	NI	VLI	LI	HI	VLI	VLI	HI	0	LI
C9	VHI	NI	HI	VLI	HI	NI	NI	HI	0
Expert 2_Manager of manufacturing department									
	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0	LI	HI	LI	HI	VLI	NI	NI	HI
C2	HI	0	HI	VHI	LI	LI	VHI	VHI	VLI
C3	HI	VLI	0	HI	VHI	VHI	NI	NI	HI
C4	HI	VHI	HI	0	LI	HI	HI	HI	VLI
C5	VHI	LI	HI	LI	0	LI	NI	NI	NI
C6	VHI	HI	HI	VHI	VHI	0	VLI	HI	NI
C7	NI	VLI	NI	LI	NI	NI	0	VHI	VLI
C8	NI	VHI	LI	HI	LI	NI	HI	0	LI
C9	HI	LI	VHI	LI	LI	LI	LI	LI	0
Expert 3_Manager of logistics department									
	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0	HI	HI	LI	HI	NI	VLI	VLI	VLI
C2	HI	0	LI	HI	LI	LI	LI	HI	LI
C3	LI	NI	0	HI	VHI	HI	VLI	HI	LI
C4	HI	VHI	HI	0	HI	VLI	HI	VHI	VLI
C5	VHI	HI	HI	LI	0	VLI	NI	VLI	LI
C6	HI	VHI	HI	VHI	VHI	0	VLI	LI	NI
C7	NI	HI	VLI	LI	NI	NI	0	VHI	NI
C8	NI	LI	LI	LI	VLI	NI	LI	0	VLI
C9	HI	VLI	VHI	LI	VHI	VLI	VLI	LI	0

Table 8.5 Initial direct relation matrix

i	Ci1	Ci2	Ci3	Ci4	Ci5	Ci6	Ci7	Ci8	Ci9
1	0	0.66	0.58	0.41	0.82	0.11	0.11	0.11	0.50
2	0.66	0	0.66	0.89	0.41	0.41	0.74	0.82	0.34
3	0.66	0.11	0	0.82	0.89	0.89	0.11	0.42	0.66
4	0.66	0.89	0.75	0	0.59	0.66	0.66	0.82	0.18
5	0.96	0.66	0.66	0.59	0	0.50	0.04	0.26	0.26
6	0.82	0.82	0.82	0.96	0.96	0	0.18	0.66	0.04
7	0.04	0.58	0.18	0.41	0.11	0.11	0	0.96	0.11
8	0.04	0.58	0.50	0.66	0.34	0.11	0.66	0	0.41
9	0.82	0.26	0.89	0.41	0.74	0.26	0.26	0.59	0

Table 8.6 The normalized direct-relation matrix

i	Ci1	Ci2	Ci3	Ci4	Ci5	Ci6	Ci7	Ci8	Ci9
1	0	0.1	0.1	0.1	0.2	0	0.02	0.02	0.1
2	0.1	0	0.1	0.2	0.1	0.1	0.14	0.16	0.06
3	0.1	0	0	0.2	0.2	0.2	0.02	0.08	0.13
4	0.1	0.2	0.1	0	0.1	0.1	0.13	0.16	0.03
5	0.2	0.1	0.1	0.1	0	0.1	0.01	0.05	0.05
6	0.2	0.2	0.2	0.2	0.2	0	0.03	0.13	0.01
7	0	0.1	0	0.1	0	0	0	0.18	0.02
8	0	0.1	0.1	0.1	0.1	0	0.13	0	0.08
9	0.2	0	0.2	0.1	0.1	0	0.05	0.11	0

Table 8.7 The total-relation matrix

i	Ci1	Ci2	Ci3	Ci4	Ci5	Ci6	Ci7	Ci8	Ci9
1	0.34	0.43	0.45	0.43	0.48	0.26	0.22	0.33	0.28
2	0.55	0.44	0.58	0.64	0.53	0.39	0.41	0.57	0.32
3	0.57	0.46	0.48	0.62	0.62	0.47	0.29	0.48	0.37
4	0.58	0.62	0.63	0.53	0.59	0.45	0.41	0.59	0.31
5	0.56	0.49	0.53	0.52	0.41	0.37	0.25	0.4	0.28
6	0.64	0.63	0.67	0.71	0.68	0.36	0.35	0.58	0.31
7	0.23	0.33	0.28	0.33	0.25	0.18	0.17	0.4	0.16
8	0.32	0.4	0.41	0.45	0.37	0.25	0.32	0.31	0.25
9	0.54	0.43	0.57	0.5	0.54	0.33	0.28	0.46	0.24

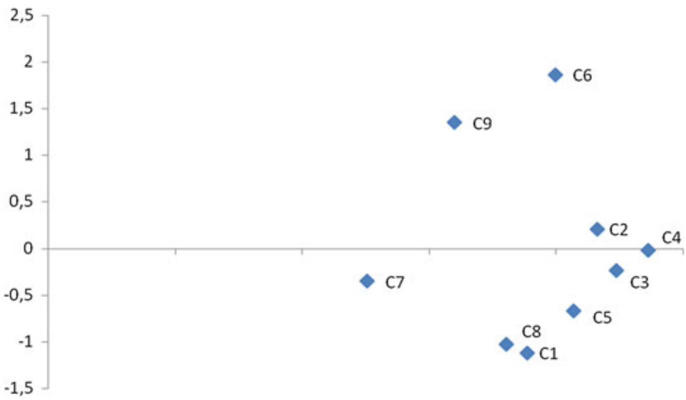

Fig. 8.4 The casual diagram of performance criteria

8.6 The Effect of the Fuzzy Linguistic Scale

There are many applications of fuzzy DEMATEL to prioritize the criteria on different decision-making problems. Mostly, the scale given in Table 8.3 is used to determine the linguistic variables. In this section, we will use another scale to

Table 8.8 Fuzzy linguistic scale for fuzzy DEMATEL

Linguistic terms	Triangular fuzzy numbers
Very high influence (VIH)	(0.7, 0.9, 1.0)
High influence (HI)	(0.5, 0.7, 0.9)
Low influence (LI)	(0.3, 0.5, 0.7)
Very low influence (VLI)	(0.1, 0.3, 0.5)
No influence (NI)	(0, 0.1, 0.3)

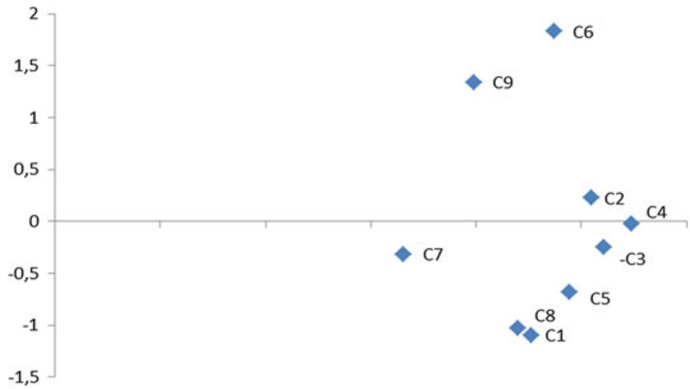

Fig. 8.5 The casual diagram of performance criteria by using Jeng and Tzeng (2012)'s scale

determine the effect of the fuzzy linguistic scale on the results. Jeng and Tzeng (2012) used the fuzzy scale which is given in Table 8.8 to determine the linguistic variables.

Jeng and Tzeng (2012)'s fuzzy linguistic scale is applied to the same influence matrix which is given in Table 8.4 and a scatter diagram is obtained and given in Fig. 8.5. We see that Figs. 8.4 and 8.5 are similar with respect to the importance rankings of the criteria as well as the grouping of cause and effect criteria. Although the places of the criteria with respect to the others do not change, only minor changes in the distances between a pair of criteria are observed. This shows that the results of fuzzy DEMATEL are robust to the selected scale of linguistic variables.

8.7 Conclusion

In this chapter, we present a review of SC performance measurement systems and offer a multi-criteria decision-making methodology, fuzzy DEMATEL in order to prioritize the performance measures of SC. Fuzzy DEMATEL enabled to collect the imprecise group judgments and analyze the inter-relationships among SC performance factors. We then visualize the factors in a cause-effect relationship diagram. We found that the most important factor of SC performance is quality. However, the structural factors which affect the other performance factors are obtained as technical capability, geographical location, and satisfaction of industry regulations. As a result, an enterprise should prioritize the improvement of technical capability, geographical location, and satisfaction of industry regulations factors since the improvement acquired in technical capability, geographical location, and satisfaction of industry regulations would also cause improvement of the factors in the effect group.

We have employed two different scales of linguistic variables in order to investigate whether the selected scale has a major effect on the results of fuzzy DEMATEL methodology. The results obtained with the use of different scales were found to be similar to each other showing that fuzzy DEMATEL is robust to the minor changes in linguistic variable scale. Our findings suggest that DEMATEL offers an effective prioritization of SC performance factors and provides a visual understanding among interrelationships of SC performance factors. For further research, the results of fuzzy DEMATEL may be used to together with analytical network process (ANP) to identify the relationships among the network structure of factors in a supplier selection problem.

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