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A fuzzy multi criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach

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ABSTRACT

Sustainable supply chain management has received much attention from practitioners and scholars over the past decade owing to the significant attention given by consumers, profit and not-for-profit organizations, local communities, legislation and regulation to environmental, social and corporate responsibility. Sustainable supply chain initiatives like supplier environmental and social collaboration can play a significant role in achieving the "triple bottom line" of social, environmental, and economic benefits. Supplier selection plays an important role in the management of a supply chain. Traditionally, organizations consider criteria such as price, quality, flexibility, etc. when evaluating supplier performance. While the articles on the selection and evaluation of suppliers are abundant, those that consider sustainability issues are rather limited. This paper explores sustainable supply chain initiatives and examines the problem of identifying an effective model based on the Triple Bottom Line (TBL) approach (economic, environmental, and social aspects) for supplier selection operations in supply chains by presenting a fuzzy multi criteria approach. We use triangular fuzzy numbers to express linguistic values of experts' subjective preferences. Qualitative performance evaluation is performed by using fuzzy numbers for finding criteria weights and then fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is proposed for finding the ranking of suppliers. The proposed approach is illustrated by an example.

1. Introduction

In recent years, there has been a considerable shift in thinking with regard to improving the social and environmental (sustainability) performance of organizations (Hart and Milstein, 2003). Sustainability has increasingly become important to business research and practice over the past decades as a result of rapid depletion of natural resources and concerns over wealth disparity and corporate social responsibility. This concern has displayed itself in legislation expanding the responsibility of organizations, increasing attention on training managers in sustainable management, and the development of theory to support sustainable managerial decision making (Dao et al., 2011). Within supply chain management, the supplier selection decision is one of the critical issues faced by operations and purchasing managers to help organizations maintain a strategically competitive position. Supplier selection and management can be applied to a variety of suppliers throughout a product's life cycle from initial raw material acquisition to end-of-life service providers. As has been evidenced in the research literature, the evaluation of suppliers requires consideration of both tangible and intangible factors which are not always very clearly defined (Bai and Sarkis, 2010a).

Traditionally, organizations consider criteria such as price, quality, flexibility, etc. when evaluating supplier performance. Nowadays, sustainability factors play a vital role for the long term success of a supply chain and the purchasing process becomes more complicated with environmental and social pressures. Now, many organizations have considered environmental, social, and economic concerns and have measured their suppliers' sustainability performance resulting from the adoption of sustainable supply chain initiatives (Bai and Sarkis, 2010a; Buyukozkan and Çifçi, 2011; Seuring and Müller, 2008). There are several evaluation models for supplier selection and evaluation in the literature. Methodologies typically found in reviews of supplier selection approaches include: weighted linear model

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approaches, mixed integer programming, the analytical hierarchy process, linear and goal programming models, matrix methods, clustering methods, human judgment models, statistical analysis, neural networks/case-based reasoning approaches, etc. A majority of the mentioned methodologies are based on multiple supplier attributes. A detailed overview of supplier selection methods can be found in De Boer et al. (2001), Huang and Keskar (2007), and Ho et al. (2010).

The number of papers concerning green supplier selection is increasing. Lu et al. (2007) presented a paper for environmental principles applicable to green supplier evaluation by using multi objective decision analysis. Tsai and Hung (2009) studied a fuzzy goal programming approach for green supply chain optimization under activity based costing and performance evaluation with a value chain structure. Tuzkaya et al. (2009) applied a hybrid fuzzy multi criteria decision approach for evaluating suppliers' environmental performance. Hsu and Hu (2009) incorporated hazardous substance management (HSM) into supplier selection in GSCM and proposed a HSM-based supplier selection model by using the ANP methodology. Awasthi et al. (2010) presented a fuzzy TOPSIS approach for evaluating environmental performance of suppliers. Bai and Sarkis (2010a) integrated sustainability into supplier selection with grey systems and rough set methodologies and Buyukozkan and Çifçi (2011) proposed a novel fuzzy multi criteria decision framework for sustainable supplier selection with incomplete information. Increasingly more authors are addressing supplier selection issues in the light of environmental aspects. It is necessary that the dual concerns of economic and environmental criteria in supplier selection be expanded even further to include social and sustainability criteria such as employee health, child labor, and social equity. Although these papers brought great insights to the literature on sustainable/green supplier evaluations, little attention has been devoted to supplier evaluations that consider all of the economic, environmental, and social criteria. The main contribution of this paper includes modeling the supplier selection decision problem within the context of a sustainable supply chain based on triple bottom line (TBL) concept. The concept of TBL was developed by Elkington (1997) who stressed the distinction of the economic and social dimensions of sustainability, which have been absorbed by the environmental dimension of sustainability.

In this research, given the above mentioned concerns and multiple criteria nature of the sustainable supply chain measurement problem, we propose a multi criteria framework in order to evaluate sustainability performance of a supplier. A multi criteria decision method (MCDM) in real world systems very often deals with subjective human preferences. Because human judgments and preferences are often vague and complex, and decision makers (DMs) cannot estimate their preferences with an exact scale, linguistic assessments can only be given instead of exact assessments. Therefore, fuzzy set theory is introduced into the proposed MCDM framework, which is put forward to solve such uncertainty problems (Erol et al., 2011).

The paper is organized as follows. Section 2 reviews the principle of sustainability supplier selection by reviewing green supply chain management and corporate social responsibility and by identifying the sustainability criteria that influence a company's purchasing decision. Sections 3 and 4 present the principles of fuzzy set theory and fuzzy TOPSIS approach, respectively, for evaluating environmental performance of suppliers. In Section 5 we present a numerical application of the proposed approach which followed by the sensitivity analyses of the results. Finally, in Section 6, we present some concluding remarks and future works.

2. Sustainability supplier selection literature and criteria

One of the principal challenges of sustainability is to make the Brundtland Commission (World Commission on Environment and Development) definition operational, that is, to use its mandate to guide decisions. An alternative definition of sustainability begins to provide some assistance on the issue: "design and operation of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment". This definition makes it clear that measures of performance are needed in order to judge the effectiveness of any decision on the resulting sustainability (Hutchins and Sutherland, 2008).

To meet the increasing market pressures and demands from various stakeholder groups and to comply with more demanding environmental legislation, companies start to look at their supply chain to enhance their overall sustainability profile. Nowadays, sustainability has become a significant concern for companies that integrate environmental and social issues in their strategy. Many companies invest in voluntary environmental management and communication tools, such as standardized environmental management systems (ISO 14001), life cycle assessments, environmental labeling of products, carbon disclosure projects, and sustainability reporting schemes (Srivastava, 2007; Buyukozkan and Çifçi, 2011). Firms are aware of the importance of their partners' sustainable responsibility in their own development, and that the environmental sustainability of any organization is impossible without incorporating Sustainable Supply Chain Management (SSCM) practices (Bai and Sarkis, 2010a; Ageron et al., in press).

SSCM is defined as the management of material and information flows as well as cooperation among organizations along the supply chain while integrating the 'triple-bottom-line' selection factors that include all three dimensions of sustainable development (economic, environmental, and social) into account (Seuring and Müller, 2008; Erol et al., 2011). The TBL approach suggests that besides economic performance, organizations need to engage in activities that positively affect the environment and the society. By adopting the triple bottom line approach, an organization takes a responsible position on economic prosperity, environmental quality, and social justice (Bai and Sarkis, 2010a). For a complete review of SSCM, see Carter and Rogers, 2008; Seuring and Muller, 2008; Srivastava, 2007; Ageron et al., in press; Hassini, et al., 2012).

2.1. Green supply chain management (GSCM)

Green supply chain management is the integration of natural environmental concerns into supply chain management (Sarkis, 2006). The objective of green supply chain initiatives is to eliminate or minimize negative environmental impacts (air, water, and land pollution) and waste of resources (energy and materials) from the extraction of raw materials up to final use and disposal of products (Vachon and Klassen, 2008; Eltayeb et al., 2011). Organizations implementing successful GSCM initiatives may benefit both from a reduction in energy and logistics costs and by an enhanced competitive advantage. Many researchers have defined a green supply chain in various manners using different terms. Srivastava (2007) describes GSCM as the combination of environmental thinking and supply chain management encompassing product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumer, and end-of-life management of the product. GSCM philosophy focuses on how firms utilize their suppliers' processes, capability, and technology to

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Table 1
Economic supplier selection criteria (De Boer et al., 2001; Huang and Keskar, 2007; Wang et al., 2009; Ho et al., 2010; Chen, 2011; Liao and Kao, 2011; Amin and Zhang, 2012).

Criteria	Sub criteria	Definition
Costs (Ec1)	Product cost	The production cost that determines the final price of the product includes the processing cost, maintenance cost, and warranty cost
	Ordering cost	Sum of unit variable and fixed ordering costs
	Logistics cost	Sum of unit variable and allocated fixed transportation costs
Delivery reliability (Ec2)	Lead time	Time between placement and arrival of an order
	On time Delivery	The ability to follow the predefined delivery schedule
Quality (Ec3)	Quality assurance	The attainment of quality assurance such as certificates
	Rejection ratio	Number of rejected incoming material detected by quality control
Technology Capability (Ec4)	Technology level	Technology development of the supplier to meet current and future demand of the firm
	Capability of R&D	Capability of R&D of the supplier to meet current and future demand of the firm
	Capability of design	Capability of new product design of the supplier to meet current and future demand of the firm

integrate environmental concerns and thereby to enhance their competitive advantage (Vachon and Klassen, 2008).

Many researchers have investigated green supply chain initiatives and practices in various manners (e.g. Zhu and Sarkis, 2006; Zhu et al., 2007; Tsoulfas and Pappis, 2008; Hsu and Hu, 2009; Testa and Iraldo, 2010; Diabat and Govindan, 2011; Tseng and Chiu, in press; Eltayeb et al., 2011; Lin, in press; Teixeira et al., 2012; Azevedo et al., in press). There are many activities that may be incorporated into green supply chain initiatives and practices. Examples include eco-design, green purchasing, reverse logistics, supplier environmental collaboration, and the implementation of environmental management systems into suppliers' organizational structures (Sarkis, 2006; Eltayeb et al., 2011). Supplier environmental collaboration includes activities that aim at improving environmental performance and capabilities of suppliers at undertaking joint projects for developing green products and innovations (Eltayeb et al., 2011). Supplier selection in GSCM is clearly a critical activity in purchasing management because a firm's environmental sustainability and ecological performance can be demonstrated by its suppliers (Kuo et al., 2010). The green supply management literature has focused on encouraging existing suppliers to improve their environmental performance by 'requiring' these suppliers to acquire certifications or to introduce green practices. Alternatively, some companies "green" their supply chains through the selection of existing green suppliers (Fu et al., in press). Significant formal modeling effort has focused on aspects of green supplier management (e.g. Sarkis, 2006; Lee et al., 2009; Hsu and Hu, 2009; Tseng and Chiu, in press; Bai and Sarkis, 2010a, b).

Table 2
Green supplier selection criteria (Bai and Sarkis, 2010a, b; Tseng and Chiu, in press; Kuo et al., 2010; Awasthi et al., 2010; Buyukozkan and Çifçi, 2011; Eltayeb et al., 2011; Amin and Zhang, 2012; Nikolaou et al., in press).

Criteria	Definition
Pollution production (Ev1)	Average volume of air emission pollutant, waste water, solid wastes and harmful materials releases per day during measurement period
Resource consumption (Ev2)	Resource consumption in terms of raw material, energy, and water during the measurement period
Eco-design (Ev3)	Design of products for reduced consumption of material/energy, design of products for reuse, recycle, recovery of material, design of products to avoid or reduce use of hazardous materials
Environmental management system (Ev4)	Environmental certifications like ISO 14000, environmental policies, planning of environmental objectives, checking and control of environmental activities

Table 3
Social measures in supplier selection (Bai and Sarkis, 2010a; Nikolaou et al., in press).

Categories	Measures	Sub measures
Internal social measures	Employment practices (So1)	Disciplinary and security practices, employee contracts, equity labor sources, diversity, discrimination, flexible working arrangements, job opportunities, employment compensation, career development
	Health and safety (So2)	Health and safety incidents, health and safety practices
External social measures	Local communities influence (So3)	Health, education, service infrastructure, housing, health and safety incidents, regulatory and public services, supporting educational institutions, security, cultural properties, economic welfare and growth, social pathologies, grants and donations, supporting community projects
	Contractual stakeholders influence (So4)	Procurement standards, partnership standards, consumers education, stakeholder empowerment, stakeholder engagement

2.2. Social supply chain management

Today, corporate social responsibility (CSR) is not only a prominent research theme but it can also be found in corporate missions and value statements (Cruz, in press). Despite the long history of CSR, applications of CSR (and also sustainability) concepts in supply chain have only emerged in the last few years (Ciliberti et al., 2008). Indeed, there is an increased pressure placed upon organizations from stakeholders, consumers, non-governmental organizations (NGOs), local communities, legislation, and regulation, to implement CSR management systems across the supply chain. Such systems can be used to transfer socially responsible behaviors along the supply chain and, in particular, to influence the practices of their business partners and to provide a baseline of social and environmental principles to be satisfied (Ciliberti et al., 2008; Ciliberti et al., 2011).

CSR can be defined as "the voluntary integration, by organizations, of social and environmental concerns in their commercial operations and in their relationships with interested parties" (Commission of the European Communities, 2001). Organizations increasingly realize that their actions in purchasing and supply chain management strongly affect their reputation and long term success. Organizations are held accountable for promoting and

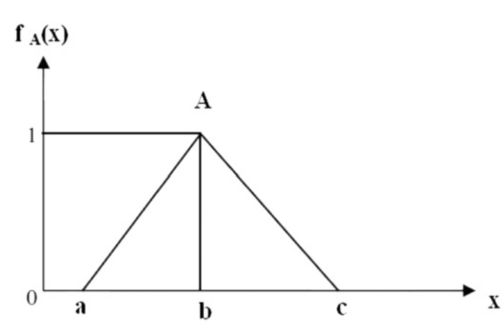

Fig. 1. Membership function of triangular fuzzy number *A*.

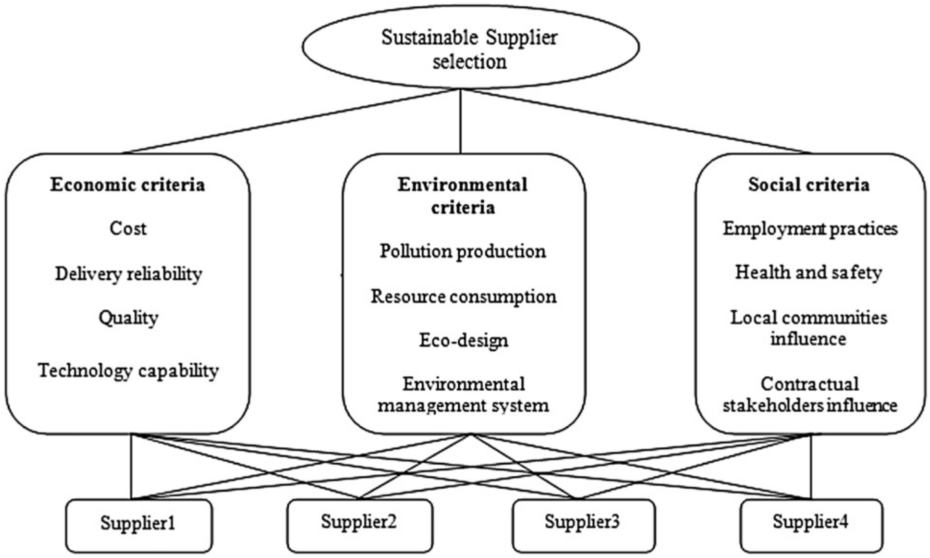

Fig. 2. Hierarchical structure of decision problem.

protecting the environmental, health, and safety regulations of workers that make their products, regardless if they are direct employees or if they work for their suppliers (Cruz and Wakolbinger, 2008).

CSR has been a subject of much research. Carroll (1991) and Carroll and Buchholtz (2002) argued that CSR encompasses the economic, legal, ethical, and philanthropic expectations placed on organizations by society at a given point in time. Carter and Jennings (2002) proposed the following categories as important aspects of the social dimension: ethics, diversity, working conditions, human rights, safety, philanthropy, and community involvement. Ciliberti et al. (2008) analyzed the practices adopted and difficulties experienced by small- and medium-sized enterprises to transfer socially responsible behaviors to suppliers that operate in developing countries. Cruz and Matsypura (2009) considered CSR activities and risk management in a single country supply chain network setting in addition to the concept of environmental decision-making. Cruz (in press) developed a framework for the modeling and analysis of a complex global supply chain network with CSR through integrated environmental decision-making and risk management. Ciliberti et al. (2011) examined how a specific code of conduct (i.e., Social Accountability 8000) can address the principal-agent problem between chain directors and partners, by Italian and Dutch small and medium enterprises (SMEs) SMEs. Nikolaou et al. (in press) proposed an integrated model for introducing CSR and sustainability issues in reverse logistics systems as a means of developing a complete performance framework model.

Table 4
Linguistic variable for the rating and relative importance weights of criteria (Awasthi et al., 2010).

Linguistic variable for relative importance weights of criteria		Linguistic variable for rating	
Linguistic variable	Fuzzy numbers	Linguistic variable	Fuzzy numbers
Very Low (VL)	(0.1, 0.1, 0.3)	Very Poor (VP)	(1, 1, 3)
Low (L)	(0.1, 0.3, 0.5)	Poor (P)	(1, 3, 5)
Medium (M)	(0.3, 0.5, 0.7)	Fair (F)	(3, 5, 7)
High (H)	(0.5, 0.7, 0.9)	Good (G)	(5, 7, 9)
Very High (VH)	(0.7, 0.9, 0.9)	Very Good (VG)	(7, 9, 9)

2.3. Sustainable supplier selection criteria definition

Supplier selection decisions are complicated by the fact that various criteria must be considered in decision-making processes. The analysis of such criteria for the selection and performance evaluation of potential suppliers has been the focus of many researchers and purchasing practitioners since the 1960s. Dickson (1966) was one of the first ones in this field of study. He identified 23 different criteria for supplier selection based on a questionnaire sent to managers of companies in North America. These criteria include quality, delivery, performance, warranty and claim policy, production facilities and capacity, net price, and technical capabilities. Dickson concluded that quality, delivery, and performance history are the three most important criteria. Weber et al. (1991); Weber and Current, 1993 and Ghodsypour and O'Brien (1998) did a comprehensive review of supplier evaluation methods on the past research and concluded that price was the highest-ranked criteria, followed by delivery and quality. Ho et al. (2010) reviewed the literature of the MCDM approaches for supplier evaluation and selection. Related articles appearing in international journals from 2000 to 2008 are gathered and analyzed to address the most popular criterion considered by the decision-makers for supplier selection and evaluation. The most popular criterion is quality, followed by delivery, price/cost, manufacturing capability, and service. Liao and Kao (2011) summarized the economic criteria that have appeared in literature since 1966 and concluded most of the related articles suggest that quality, price, and delivery performance are the most important supplier selection economic criteria.

Social and green supplier development is also necessary for effective sustainable supply chain management. In addition, the consideration of both environmental and social factors needs to be

Table 5
Importance weights of the criteria from three DMs.

	Cost criteria				Environmental criteria				Social criteria			
DMs	Ec1	Ec2	Ec3	Ec4	En1	En2	En3	En4	So1	So2	So3	So4
DM1	H	H	VH	M	VH	H	H	M	H	H	M	M
DM2	VH	H	H	M	H	VH	H	H	H	H	H	M
DM3	H	H	VH	M	VH	H	H	M	VH	H	M	H

Table 6
Evaluation of suppliers on sustainability criteria by DM1.

	Cost criteria				Environmental criteria				Social criteria			
DMs	Ec1	Ec2	Ec3	Ec4	En1	En2	En3	En4	So1	So2	So3	So4
Supplier 1	G	F	F	F	F	G	G	F	G	F	F	G
Supplier 2	F	F	G	F	F	G	G	VG	G	F	G	F
Supplier 3	VG	G	VG	G	F	F	G	G	VG	VG	G	F
Supplier 4	P	F	F	P	P	F	F	F	P	G	F	F

Table 7
Evaluation of suppliers on sustainability criteria by DM2.

	Cost criteria				Environmental criteria				Social criteria			
DMs	Ec1	Ec2	Ec3	Ec4	En1	En2	En3	En4	So1	So2	So3	So4
Supplier 1	G	F	F	F	G	G	G	F	F	VG	G	G
Supplier 2	F	G	G	F	F	F	G	G	G	F	F	G
Supplier 3	G	G	VG	F	G	G	VG	F	VG	F	G	G
Supplier 4	F	P	P	F	F	G	F	P	F	G	P	P

at the forefront of organizations' supplier selection agenda (Bai and Sarkis, 2010a). Supplier selection in GSCM is clearly a critical activity in purchasing management because a firm's environmental sustainability and ecological performance can be demonstrated by its suppliers (Kuo et al., 2010).

Organizations have taken various approaches to address the supplier selection criteria and have interpreted them in a variety of ways. We selected some representative criteria from economic, environmental, and social sustainability views, and we have precisely defined them. The criteria that have been selected are not meant to describe thoroughly the sustainable performance of a supplier, but rather to serve as an example of the measures that could be established. We summarize a number of criteria and measures that can be considered in the literature from a sustainability perspective in Tables 1–3. Internal social criteria refer to employment practices such as employment compensation, human resources, and health and safety committees at work. External social criteria regard the relationship with local communities and contractual stakeholders such as suppliers, customers, local communities, and NGOs.

3. Fuzzy sets theory in MCDM

Natural language to express perception or judgment is always subjective, uncertain, vague, or all three. Such uncertainty and subjectivity have long been handled with probability and statistics. Because words are less precise than numbers, the concept of a linguistic variable approximately characterizes events that are too poorly defined to be described with conventional quantitative terms (Wang and Chang, 2007). To resolve the vagueness, ambiguity, and subjectivity of human judgment, the fuzzy sets theory was introduced by Zadeh (1965, 1976) to express the linguistic terms in the decision-maker's process. Fuzzy theory enables DMs to deal with the ambiguities involved in the process of the linguistic assessment of the data. Zadeh and Bellman were the first researchers who surveyed the decision making problem using fuzzy sets, and they initiated the FMCDM methodology (Bellman and Zadeh, 1970). Triangular fuzzy numbers are used in this paper to assess the preferences of DMs. The reason for using a triangular fuzzy number is that it is intuitively easy for the DMs to use and calculate.

Table 8
Evaluation of suppliers on sustainability criteria by DM3.

	Cost criteria				Environmental criteria				Social criteria			
DMs	Ec1	Ec2	Ec3	Ec4	En1	En2	En3	En4	So1	So2	So3	So4
Supplier 1	G	F	F	F	G	G	F	VG	VG	G	G	G
Supplier 2	F	F	G	G	G	G	F	F	F	P	F	G
Supplier 3	G	G	G	F	G	VG	G	F	G	G	VG	F
Supplier 4	P	F	P	F	M	P	G	F	F	P	F	G

Table 9
Fuzzy aggregated decision matrix and fuzzy weights of criteria.

	Ec1			Ec2			Ec3			Ec4			En1			En2		
Weight	0.5	0.77	0.9	0.5	0.7	0.9	0.5	0.77	0.9	0.3	0.5	0.7	0.5	0.83	0.9	0.5	0.77	0.9
Supplier 1	5	7	9	3	5	7	3	5	7	3	5	7	3	6.3	9	5	7	9
Supplier 2	3	5	7	3	5.7	9	5	7	9	3	5.7	9	3	5.7	9	3	6.7	9
Supplier 3	5	7.7	9	5	7	9	7	8.3	9	3	5.7	9	3	6.7	9	3	7	9
Supplier 4	1	3.7	7	1	4.3	7	1	3.7	7	1	4.3	7	1	4.3	7	1	5	9

	En3			En4			So1			So2			So3			So4		
Weight	0.5	0.7	0.9	0.3	0.57	0.7	0.5	0.76	0.9	0.5	0.7	0.9	0.3	0.57	0.9	0.3	0.57	0.9
Supplier 1	3	6.7	9	3	6.7	9	3	7	9	3	7	9	3	6.7	9	5	7	9
Supplier 2	5	6.7	9	3	7	9	3	6.7	9	1	4.3	7	3	5.7	9	3	6.7	9
Supplier 3	5	7.7	9	3	5.7	9	5	8.3	9	3	7	9	5	7.7	9	3	5.7	9
Supplier 4	3	5.7	9	1	4.3	7	1	4.3	7	1	5.7	9	1	4.3	7	1	5	9

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Table 10
Normalized fuzzy decision matrix.

	Ec1			Ec2			Ec3			Ec4			En1			En2		
Supplier 1	0.11	0.14	0.2	0.33	0.56	0.78	0.33	0.56	0.78	0.33	0.56	0.78	0.33	0.7	1	0.56	0.78	1
Supplier 2	0.14	0.2	0.33	0.33	0.63	1	0.56	0.78	1	0.33	0.63	1	0.33	0.63	1	0.33	0.74	1
Supplier 3	0.11	0.13	0.2	0.56	0.78	1	0.78	0.92	1	0.33	0.63	1	0.33	0.74	1	0.33	0.78	1
Supplier 4	0.14	0.27	1	0.11	0.48	0.78	0.11	0.41	0.78	0.11	0.48	0.78	0.11	0.48	0.78	0.11	0.56	1

	En3			En4			So1			So2			So3			So4		
Supplier 1	0.33	0.74	1	0.33	0.74	1	0.33	0.78	1	0.33	0.78	1	0.33	0.74	1	0.56	0.78	1
Supplier 2	0.55	0.74	1	0.33	0.78	1	0.33	0.74	1	0.11	0.48	0.78	0.33	0.63	1	0.33	0.74	1
Supplier 3	0.55	0.85	1	0.33	0.63	1	0.56	0.92	1	0.33	0.78	1	0.56	0.85	1	0.33	0.63	1
Supplier 4	0.33	0.63	1	0.11	0.48	0.78	0.11	0.48	0.78	0.11	0.63	1	0.11	0.48	0.77	0.11	0.55	1

A fuzzy set is a class of objects, with a continuum of membership grades, where the membership grade can be taken as an intermediate value between 0 and 1. A fuzzy subset A of a universal set X is defined by a membership function $f_A(x)$ which maps each element x in X to a real number [0, 1]. When the grade of membership for an element is 1, it means that the element is absolutely in that set. When the grade of membership is 0, it means that the element is absolutely not in that set. Ambiguous cases are assigned values between 0 and 1. A triangular fuzzy number can be shown as (a, b, c). The parameters a, b, and c respectively, denote the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event. In the following, some important definitions and notations of fuzzy set theory will be reviewed (Zadeh, 1965, 1976; Zimmermann, 2001):

Definition 3.1. The membership function of the fuzzy number $f_A(x)$ is defined as (see Fig. 1):

$$f_A(x) = \begin{cases} 0 & x < a, x > c \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{c-x}{c-b}, & b \le x \le c \end{cases} \tag{1}$$

Definition 3.2. Let $A = (a, b, c)$ and $B = (a_1, b_1, c_1)$ be two triangular fuzzy numbers. Then the operational laws of these two triangular fuzzy numbers are as follows:

$$A(+)B = (a,b,c)(+)(a1,b1,c1) = (a+a_1, b+b_1, c+c_1) \tag{2}$$

$$A(-)B = (a,\ b,c)(-)(a1,b1,c1) = (a-a_1, b-b_1, c-c_1) \tag{3}$$

$$A(*)B = (a,b,c)(*)(a1,b1,c1) = (a*a_1, b*b_1, c*c_1) \tag{4}$$

$$(A(/)B = (a,b,c)(/)(a1,b1,c1) = (a/a_1, b/b_1, c/c_1)) \tag{5}$$

$$K*A = (k*a, k*b, k*c) \tag{6}$$

$$(A)-1 = (1/c, 1/b, 1/a) \tag{7}$$

The distance between fuzzy numbers A, B is calculated as:

$$d(A,\ B) = \sqrt{1/3\left[(a-a_1)^2+(b-b_1)^2+(c-c_1)^2\right]} \tag{8}$$

Definition 3.3. Assume that a decision group has K DMs, and the fuzzy rating of each DM (k = 1, 2,..,K) can be represented as a positive triangular fuzzy number R_k (k = 1, 2,…,K) with membership function f_{Rk} (x). Then the aggregated fuzzy rating can be defined as:

$$R = (a,b,c), k = 1,\ 2,..,K \tag{9}$$

Where $a = \min_k\{a_k\}$, $b = 1/k\sum_{k=1}^{k} b_k$, $c = \max_k\{c_k\}$

4. The fuzzy TOPSIS method

Functionally associated with problems of discrete alternatives, multi attribute decision making (MADM) techniques are practical tools for solving real world problems. Since there are many MADM techniques involved, Hwang and Yoon (1981) provide a taxonomy for classifying the techniques as the types of information from DMs, prominent features of information, and a major class of methods. The classification indeed gives us a clear direction for learning MADM techniques (Shih et al., 2007; Hwang and Yoon, 1981). Among these techniques, the category of information on attributes from DMs with main information is convenient for making decisions due to an explicitly represented procedure. In this category, TOPSIS, the concept of distance measures of the alternatives from the positive ideal solution (PIS) and the negative ideal solution

Table 11
Weighted normalized fuzzy decision matrix.

	Ec1			Ec2			Ec3			Ec4			En1			En2		
Supplier 1	0.06	0.11	0.18	0.17	0.39	0.7	0.17	0.43	0.7	0.10	0.28	0.54	0.17	0.58	0.9	0.28	0.60	0.9
Supplier 2	0.07	0.15	0.3	0.17	0.44	0.9	0.28	0.60	0.9	0.10	0.32	0.7	0.17	0.53	0.9	0.17	0.57	0.9
Supplier 3	0.06	0.10	0.18	0.28	0.54	0.9	0.39	0.71	0.9	0.10	0.32	0.7	0.17	0.62	0.9	0.17	0.60	0.9
Supplier 4	0.07	0.21	0.9	0.06	0.33	0.7	0.06	0.32	0.7	0.03	0.24	0.54	0.06	0.40	0.7	0.06	0.43	0.9

	En3			En4			So1			So2			So3			So4		
Supplier 1	0.17	0.52	0.9	0.10	0.42	0.7	0.17	0.59	0.9	0.17	0.54	0.9	0.10	0.42	0.9	0.17	0.44	0.9
Supplier 2	0.28	0.52	0.9	0.10	0.44	0.7	0.17	0.57	0.9	0.06	0.33	0.7	0.10	0.36	0.9	0.10	0.42	0.9
Supplier 3	0.28	0.60	0.9	0.10	0.36	0.7	0.28	0.70	0.9	0.17	0.54	0.9	0.17	0.49	0.9	0.10	0.36	0.9
Supplier 4	0.17	0.44	0.9	0.03	0.27	0.54	0.06	0.36	0.7	0.06	0.44	0.9	0.03	0.27	0.7	0.03	0.32	0.9

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Table 12
Distances between suppliers and A^*, A^- with respect to each criterion.

	EC1	EC2	EC3	EC4	EN1	EN2	EN3	EN4	SO1	SO2	SO3	SO4
d (supplier 1, A^*)	0.53	0.52	0.43	0.46	0.40	0.79	0.48	0.38	0.46	0.47	0.54	0.50
d (supplier 2, A^*)	0.50	0.40	0.41	0.48	0.46	0.73	0.42	0.38	0.47	0.60	0.56	0.54
d (supplier 3, A^*)	0.41	0.31	0.41	0.45	0.46	0.79	0.40	0.40	0.38	0.47	0.49	0.56
d (supplier 4, A^*)	0.60	0.60	0.48	0.58	0.56	0.62	0.50	0.47	0.59	0.55	0.63	0.60
d (supplier 1, A^-)	0.42	0.43	0.33	0.58	0.59	0.08	0.47	0.45	0.58	0.57	0.55	0.55
d (supplier 2, A^-)	0.54	0.59	0.42	0.56	0.58	0.15	0.47	0.45	0.57	0.41	0.54	0.55
d (supplier 3, A^-)	0.58	0.65	0.42	0.59	0.58	0.08	0.50	0.43	0.63	0.57	0.57	0.53
d (supplier 4, A^-)	0.41	0.40	0.32	0.42	0.53	0.50	0.45	0.33	0.41	0.54	0.41	0.52

(NIS), proposed by Hwang and Yoon (1981) is the most straightforward technique in MADM.

The following features of the TOPSIS method make it a major MADM technique as compared with other related techniques such as AHP and ELECTRE (Zanakis et al., 1998; Shanian and Savadogo, 2006; Shih et al., 2007; Wang and Chang, 2007):

- An unlimited range of criteria and performance attributes can be included.
- It allows explicit trade-offs and interactions among attributes. More precisely, changes in one attribute can be compensated for in a direct or opposite manner by other attributes.
- Preferential ranking of alternatives with a numerical value that provides a better understanding of differences and similarities between alternatives, whereas other MADM techniques (such as the ELECTRE) methods only determine the rank of each alternative.
- Pair wise comparisons, required by methods such as the AHP, are avoided. This method is especially useful when dealing with a large number of alternatives and criteria.
- It is a relatively simple computation process with a systematic procedure.
- According to the simulation comparison from Zanakis et al. (1998), TOPSIS has the fewest rank reversals when an alternative is added or removed among the MADM methods.

The TOPSIS solution method consists of the following steps (Hwang and Yoon, 1981; Chen and Lin, 2006):

Step 1. Calculate the normalized decision matrix. The normalized fuzzy-decision matrix can be represented as:

$$R = \left[r_{ij}\right]_{m+n}$$

Where B and C are the sets of benefit and cost criteria, respectively, and

$$r_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \quad j \in B \qquad c_j^* = \max_i c_{ij}, \quad j \in B \tag{10}$$

$$r_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \quad j \in C \qquad a_j^- = \min_i a_{ij}, \quad j \in C \tag{11}$$

Table 13
Computations of d^+, d^- and CC_i according to Eq. (15) till Eq. 17.

	d^+	d^-	CC_i	Rank
Supplier 1	5.95	5.61	0.485	3
Supplier 2	5.93	5.84	0.496	2
Supplier 3	5.53	6.12	0.525	1
Supplier 4	6.78	5.24	0.436	4

The normalization method mentioned above is designed to preserve the property in which the elements r_{ij} are standardized (normalized) triangular fuzzy numbers.

Step 2. Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as:

$$V = \left[v_{ij}\right]_{m*n} \quad i = 1,2,\ldots,m \quad j = 1,2,\ldots, \quad n \tag{12}$$

Where $v_{ij} = r_{ij} \cdot w_{ij}$ and w_{ij} is the weight of the jth attribute or criterion.

Step 3. Determine the positive- and negative-ideal solution: the fuzzy positive-ideal solution (FPIS, A^*) and fuzzy negative-ideal solution (FNIS, A^-) can be defined as:

$$A^* = \left(v_1^*, v_2^*, \ldots, v_n^*\right) \tag{13}$$

$$A^- = \left(v_1^-, v_2^-, \ldots, v_n^-\right) \tag{14}$$

Where $v_j^* = \max_i\{v_{ij3}\}$ and $v_j^- = \min_i\{v_{ij1}\}, i = 1,2,\ldots,m$, $j = 1,2,\ldots,n$

Step 4. The distance of each alternative from the positive and negative ideal solution A^*, A^- can be calculated as:

$$d_i^* = \sum\nolimits_{j=1}^{n} d_v\left(v_{ij}, v_j^*\right), \quad i = 1,\ 2, \ldots,\ m \tag{15}$$

$$d_i^- = \sum\nolimits_{j=1}^{n} d_v\left(v_{ij}, v_j^-\right), \quad i = 1,2,\ldots,m \tag{16}$$

and $d_v(0,0)$ is the distance measurement between two fuzzy numbers.

Step 5. Calculate the relative closeness to the ideal solution. A closeness coefficient is defined to determine the ranking order of all possible suppliers after d_i^+ and d_i^- of each alternative A_i (i = 1, 2,…,m) has been calculated. The closeness coefficient (CC_I) of each alternative is calculated as:

$$CC_I = d_i^- / \left(d_i^+ + d_i^-\right), \quad i = 1,2,\ldots,m \tag{17}$$

Step 6. Rank the preference order. Alternative A_i is closer to the FPIS (A^*) and farther from FNIS (A^-) as CC_I approaches to 1. According to the descending order of CC_I we can determine the ranking order of all alternatives and select the best one of possible alternatives.

5. A case illustration

To examine the practicality and the effectiveness of the proposed approach for supplier selection and evaluation, a case is illustrated for evaluating sustainability performance of suppliers. The hierarchical structure of this decision problem is shown in Fig. 2. We propose main criteria according to supplier selection

Table 14
Results of sensitivity analysis of fuzzy TOPSIS method for sustainable supplier selection.

Condition	Decision criteria	Decision makers	Suppliers ranking (Respectively)
Initial condition	Ec1, Ec2, Ec3, Ec4, En1, En2, En3, En4, So1, So2, So3, So4	DM1,DM2,DM3	Supplier 3, Supplier2, Supplier 1, Supplier 4
Condition 1	En1, En2, En3, En4	DM1, DM2, DM3	Supplier 3, Supplier 1, Supplier 2, Supplier 4
Condition 2	So1, So2, So3, So4	DM1, DM2, DM3	Supplier 3, Supplier 1, Supplier 2, Supplier 4
Condition 3	Ec1, Ec2, Ec3, Ec4	DM1, DM2, DM3	Supplier 3, Supplier 2, Supplier 4, Supplier 1
Condition 4	Ec1, Ec2, Ec3, Ec4, En1, En2, En3, En4	DM1, DM2, DM3	Supplier 3, Supplier 2, Supplier 4, Supplier 1
Condition 5	Ec1, Ec2, Ec3, Ec4, So1, So2, So3, So4	DM1, DM2, DM3	Supplier 3, Supplier 2, Supplier 1, Supplier 4
Condition 6	En1, En2, En3, En4, So1, So2, So3, So4	DM1, DM2, DM3	Supplier 3, Supplier 1, Supplier 2, Supplier 4
Condition 7	Ec1, Ec2, Ec3, Ec4, En1, En2, En3, En4, So1, So2, So3, So4	DM1	Supplier 3, Supplier 2, Supplier 1, Supplier 4
Condition 8	Ec1, Ec2, Ec3, Ec4, En1, En2, En3, En4, So1, So2, So3, So4	DM2	Supplier 3, Supplier 2, Supplier 1, Supplier 4
Condition 9	Ec1, Ec2, Ec3, Ec4, En1, En2, En3, En4, So1, So2, So3, So4	DM3	Supplier 3, Supplier 1, Supplier 2, Supplier 4

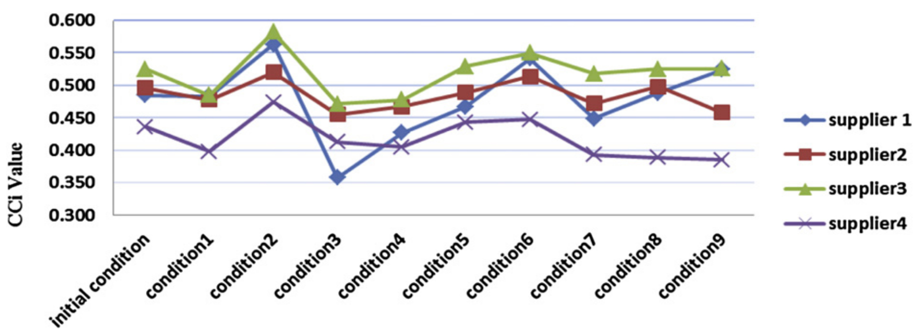

Fig. 3. Sensitivity analysis result.

literature identified in Tables 1–3 A survey was conducted through the distribution of a questionnaire to managers in operational, purchasing, and environmental fields. Survey results determined the relative importance weights of the various criteria and ratings. As mentioned in Tables 1–3, there are four economic criteria (Ec1, Ec2, Ec3 and Ec4), four environmental criteria (Ev1, Ev2, Ev3 and Ev4), and four social criteria (So1, So2, So3 and So4). The Ec1 is a cost criterion and the others are the benefit criteria. The proposed method is currently applied to solve this problem. The relative importance weights and the ratings importance of the criteria which described using linguistic variables are defined in Table 4. The three DMs express their opinions on the importance weights of the twelve criteria and the ratings of each supplier with respect to the twelve criteria independently. Tables 5–8 show the original assessment information provided by the three DMs. The Fuzzy decision matrix and fuzzy weights of criteria, normalized fuzzy decision matrix, weighted normalized fuzzy decision matrix, the distance of each supplier from FPIS and FNIS with respect to each criterion, and the closeness coefficient of each supplier are shown, respectively, in Tables 9–13. All the calculations were done using Ms Excel.

5.1. Results

The final results of fuzzy TOPSIS analysis are summarized in Table 13. Based on the closeness coefficients $_{(CCI)}$ values, the ranking order of four suppliers according to sustainability performance is:

Supplier 3>Supplier 2>Supplier 1>Supplier 4

Therefore, we can conclude that supplier 3 has the best sustainability performance according to the opinion of the DMs. We have just shown the results of an analysis of the suppliers given a situation where all the sustainability criteria are considered. In the next section we will investigate a few conditions determining the sensitivity of the solutions when the number of criteria and decision makers are altered.

5.2. Sensitivity analysis

The aim of sensitivity analysis is to consider what happens to a supplier's ranking when we choose a different decision maker and/or different criteria. This inquiry is useful in situations where uncertainties exist in the definition of the importance of different factors. The details of nine additional conditions are presented in Table 14, and Fig. 3 illustrates a graphical representation of these results. For example, the first condition considers only economic criteria (Ec1, Ec2, Ec3 and Ec4), with decision makers DM1, DM2, and DM3. According to this sensitivity analysis, changing the fuzzy weights alters the sequence of the suppliers. Although the ranks of the sustainable suppliers are changed with respect to different weights bases, generally supplier 3 is selected as the best supplier. Because the decision making process is sensitive to the type of criteria, the number of participants involved, and their expertise with the subject, their selection should be carefully done.

6. Conclusion

Sustainable supply chain initiatives like supplier environmental and social collaboration can play a significant role in achieving the "triple bottom line" benefits and contributing to sustainable development of the society. This paper focuses mainly on the environmental, social, and economic criteria for supplier evaluation based on the triple bottom line concept. A comprehensive analysis of sustainable business operations should consider all three dimensions simultaneously. In this paper we have introduced a fuzzy MCDM approach for supplier selection decisions with consideration of sustainability criteria and a numerical example was presented to exemplify the proposed framework. First, the criteria for evaluating sustainable performance are identified based on the literature. Second, the experts provide linguistic ratings to the criteria and the alternatives, and fuzzy TOPSIS is used to aggregate the ratings and to generate an overall performance score

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by which we measure the sustainable performance of each supplier. Finally, we perform sensitivity analysis to determine the influence of criteria weights on the decision making process. The results guide companies in four ways: to choose the best supplier among the candidates, to continue work with a supplier group, to recommend that certain suppliers improve some of their defects, or to stop work with certain suppliers. Furthermore, suppliers are enabled to benchmark and compare themselves and to develop better products and processes. Also, based on implementation of sustainable supplier evaluation, companies can identify and prioritize opportunities for improving their sustainability performances which may lead to a reduction in the negative environmental and social impacts of their activities.

One of the limitations of the paper is that we have introduced a hypothetical illustrative example rather than providing a real world application. Practical questions pertaining to the validity and accuracy of these decisions would need to be investigated for operational feasibility of this methodology. The availability of the information and data needed for the application of the methodology is one of the limitations to this operational feasibility. Over time, supply chain managers should be encouraged to maintain this type of data, not only for application of this methodology, but for the general future management of their organization. As decision makers face situations such as time pressure, lack of expertise in related issues, etc., during the evaluation process, evaluations cannot be performed with perfect information. We suggest looking at the issue of sustainable supplier selection problems despite having incomplete preferences. This study may be a subject of future research. Dynamic evaluation models that are able to integrate the selection phase with monitoring and continuous analysis of the supplier selection can be investigated. In addition, order quantity allocation, after ranking all suppliers, is another important issue that could become a new trend in the future.

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