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A green supplier selection model for high-tech industry

Amy H.I. Lee [a], He-Yau Kang [b], Chang-Fu Hsu [c,d,*], Hsiao-Chu Hung [e]

[a] Department of Industrial Engineering and System Management, Chung Hua University, Taiwan
[b] Department of Industrial Engineering and Management, National Chin-Yi University of Technology, Taiwan
[c] Quality Assurance Division, United Microelectronics Company, Taiwan
[d] Department of Industrial Engineering and Management, National Chiao Tung University, 1001 Ta-Hsueh Road, HsinChu, Taiwan
[e] Graduate Institute of Technology Management, Chung Hua University, Taiwan

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ABSTRACT

With growing worldwide awareness of environmental protection, green production has become an important issue for almost every manufacturer and will determine the sustainability of a manufacturer in the long term. A performance evaluation system for green suppliers thus is necessary to determine the suitability of suppliers to cooperate with the firm. While the works on the evaluation and/or selection of suppliers are abundant, those that concern environmental issues are rather limited. Therefore, in this study, a model for evaluating green suppliers is proposed. The Delphi method is applied first to differentiate the criteria for evaluating traditional suppliers and green suppliers. A hierarchy is constructed next to help evaluate the importance of the selected criteria and the performance of green suppliers. Since experts may not identify the importance of factors clearly, the results of questionnaires may be biased. To consider the vagueness of experts' opinions, the fuzzy extended analytic hierarchy process is exploited. With the proposed model, manufacturers can have a better understanding of the capabilities that a green supplier must possess and can evaluate and select the most suitable green supplier for cooperation.

1. Introduction

With increasing government regulation and stronger public awareness in environmental protection, firms today simply cannot ignore environmental issues if they want to survive in the global market. In addition to complying with the environmental regulations for selling products in certain countries, firms need to implement strategies to voluntarily reduce the environmental impacts of their products. The integration of environment, economic and social performances to achieve sustainable development is a major business challenge for the new century (Verghese & Lewis, 2007).

Environmental management is becoming more and more important for corporations as the emphasis on the environmental protection by organizational stakeholders, including stockholders, governments, customers, employees, competitors and communities, keeps increasing. Programs such as design for the environment, life cycle analysis, total quality environmental management, green supply chain management and ISO 14000 standards are popular for environmentally conscious practices (Sarkis, 1998). Both proactive and reactive methods have been implemented to protect the environment. For instance, environmentally conscious design and manufacturing (ECD&M) is a proactive method that aims to reduce the resource consumption, hazardous emission and energy usage by reengineering the design and manufacturing process and selecting appropriate materials (Zhang, 2004). On the other hand, end-of-life (EoL) strategy and management is a reactive method that provides technology and methodologies to handle the wastes which are already present (Zhang, 2004).

As environmental awareness increases, buyers today are learning to purchase goods and services from suppliers that can provide them with low cost, high quality, short lead time, and at the same time, with environmental responsibility. Legislative and regulatory initiatives have also emerged in developed countries, especially in Europe and Japan. Some pioneer enterprises have already joined the trend of green supply chain long before the EU environmental orders were enforced. In order to have a long-term success in the global market, a firm not only should stress on financial terms in evaluating suppliers, but also should take various criteria, including pro-environmental concerns, into consideration. Therefore, green procurement approach must be compliant with customers, laws and regulations, and a green supplier evaluation system is necessary for a firm in determining the suitability of a supplier as a partner in the green supply chain.

The rest of this paper is organized as follows. Section 2 reviews some recent works on environmental management and green supplier evaluation. Analytic hierarchy process (AHP), fuzzy set theory and fuzzy-extended AHP (FAHP) are presented in Section

* Corresponding author. Address: Department of Industrial Engineering and Management, National Chiao Tung University, 1001 Ta-Hsueh Road, HsinChu, Taiwan. Tel.: +886 3 518 6582; fax: +886 3 518 6575.
E-mail address: hcf2330@yahoo.com.tw (C.-F. Hsu).

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3. Section 4 proposes a FAHP model applied to evaluate green suppliers. Some concluding remarks are made in the last section.

2. Environmental management and green supplier evaluation

2.1. Environmental management

People are increasingly aware of the strong links between the economy and the environment these days. Exploiting the synergies between the two is essential to maximize both well-being and economic growth. As a result, many countries have started to enforce environmental legislations and regulations for controlling the use of products, processes and wastes that may be detrimental to the environment. For instance, EU has set a range of environmental policies such as RoHS and WEEE. The RoHS Directive (the restriction of the use of certain hazardous substances in electrical and electronic equipment) bans manufacturers, sellers, distributors and recyclers of electrical and electronic equipment (EEE) the placing on the EU market of new electrical and electronic equipment containing more than agreed levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) flame retardants (RoHS, 2008). The RoHS Directive came into force on 1 July 2006. The WEEE (waste electronics and electrical equipment) Directive aims to reduce waste arising from electrical and electronic equipment (EEE), decrease the wastes of natural resources, prevent pollutions from occurring, and make manufacturers, sellers, distributors and recyclers of EEE responsible for the environmental impact of their products (Netregs, 2008). The WEEE Regulations came into force on 1 January 2007 with the main requirements and obligations on producers and distributors of EEE into force from 1 April 2007 (Netregs, 2008). WEEE is aimed at the life cycle of product, and RoHS is exploited during the design stage of products. While there are environmental regulations and mandatory programs, pressures to protect the environment also come from other external stakeholders. Thus, many firms are introducing voluntary environmental programs for gaining competitive advantages. Indeed, environmental management is becoming the focus of corporate strategy and an arena of competition, rather than simply as a compliance-driven function (Sarkis, 1995). Sarkis (1998) categorized environmentally conscious business practices into five major components: design for the environment, life cycle analysis, total quality environmental management, green supply chain and ISO 14000 environmental management system requirements.

In order to reap the greatest benefits from environmental management, firms must integrate all members in the green supply chain. Green supply chain management has emerged as a way for firms to achieve profit and market share objectives by lowering environmental impacts and increasing ecological efficiency (van Hock & Erasmus, 2000). The definition of green supply chain management ranges from simple green purchasing to an integrated supply chain flowing from supplier, manufacturer, customer, and to reverse logistics (Zhu & Sarkis, 2004). Working on reducing product life cycle impact in saving energy, saving resources and eliminating hazardous substances are important issues for all members in the supply chain. In fact, one effective way to facilitate environmental protection is to focus on waste prevention and control at the source through green purchasing (Min & Galle, 1997). That is, firms must include suppliers in environmentally-friendly practices for purchasing and materials management, starting even from suppliers' design for environment (DfE). Green purchasing, or green procurement, is linked to the product and process aspects of the supplier, including "eco-labels, the avoidance of environmentally relevant substances, energy use, use of recycled materials, product mass, re-usability of some parts, recyclability, the use of environmental management systems and the application of DfE or life cycle assessment (LCA)" (Nagel, 2003). A green supplier is expected not only to achieve environmental compliance but also to undertake efficient, green product design and life cycle analysis activities. Thus, in a green supply chain, companies need to have extensive supplier selection and performance evaluation processes (Kainuma & Tawara, 2006).

Manufacturers and exporters these days need to overcome the green obstacle to increase competition power (Deng & Wang, 1998). For instance, EU forces importers to follow the environmental policies, change their working processes, and purchase more environmental-friendly equipment and costly green materials. With the enforcement of environmental regulations and arising eco-awareness, manufacturers need to find substitutes to replace the detrimental substances if they want to export their products to environmental-conscious countries. Since many Taiwanese businesses are OEM (original equipment manufacturing) and ODM (own design manufacturing), in order to export their products overseas, the firms not only need to comply with the environmental policies, but also need to have their own corporate environmental policies.

The LCD industry in Taiwan has expanded tremendously in the past ten years. Taiwan is currently the world's largest supplier of TFT–LCDs, and produces more than 40% of the world's supply (Hung, 2006). By 2005, there were 123 companies in Taiwan's flat-panel display industry, creating a value of US$15.49 billion, of which TFT–LCDs accounted for around 66% (Government Information Office (GIO). Taiwan yearbook, 2005). However, in order to maintain the competitiveness, manufacturers in the TFT–LCD supply chain not only need to adapt to the increasing demands, scale of economies and lower price, they also need to comply with the environmental regulations of the countries they export the products to. On top of that, a higher green standard than the baseline of the regulations may even need to be met by the manufacturers in order to maintain a good relationship with existing customers and to attract new international customers.

2.2. Green supplier evaluation

In the current business environment, purchasing has become critical in establishing value-added contents of products and a vital determinant to ensure the profitability and survival of a company. The research on supplier selection is abundant. First publications can be traced back to the 1960s, and Weber, Current, and Benton (1991) and Ghodsypour and O'Brien (1998) did a comprehensive review on the past research. Some popular methods include the categorical method, the weighted-point method, the matrix method, the vendor profile analysis, and the ANP approach, to name a few (Noci, 1997). Recent works were reviewed in Kahraman, Cebeci, and Ulukan (2003), Lin and Chen (2004), Bayazit (2006), Talluri, Narasimhan, and Nair (2006), and Lee (2009). While literature related to supplier evaluation is plentiful, the works on green supplier evaluation or supplier evaluation that consider environmental factors are rather limited (Handfield, Steven, Srouft, & Melnyk, 2002; Humphreys, McIvor, & Chan, 2003b; Humphreys, Wong, & Chan, 2003a; Noci, 1997).

The purchasing process becomes more complicated when environmental issues are considered. This is because green purchasing must consider the supplier's environmental responsibility, in additional to the traditional factors such as the supplier's costs, quality, lead-time and flexibility. The management of suppliers based on strict environmental compliance is not sufficient, and a more proactive or strategic approach is required. Noci (1997) designed a green vendor rating system for the assessment of a supplier's environmental performance based on four environmental categories, namely, 'green' competencies, current environmental efficiency, suppliers' 'green' image and net life cycle cost, by applying AHP.

Walton, Handfield, and Melnyk (1998) designed a simple flowchart for determining appropriate methods and criteria for supplier evaluation and selection in environmental management. Enarsson (1998) used an Ishikawa fishbone diagram for evaluating suppliers from an environmental viewpoint by adopting a quality improvement prospective. Zhu and Geng (2001) studied large and medium-sized state-owned enterprises (LMSOEs) in China and examined their environmental developments such as green purchasing in their business practices. Among the supplier selection models being used, environmentally preferable bidding and life-cycle assessment (LCA), which assesses green purchasing impacts and their financial consequences through the entire product life-cycle, are the most popular in these enterprises. Handfield et al. (2002) used AHP to evaluate the relative importance of various environmental traits and to assess the relative performance of several suppliers. Humphreys et al. (2003a) identified the environmental criteria which influence a firm's purchasing decision, and categorized the criteria into two groups: quantitative environmental criteria and qualitative environmental criteria. A knowledge-based decision support system was developed next to integrate the environmental criteria into the supplier selection process. Humphreys et al. (2003b) proposed a similar system as in Humphreys et al. (2003a). A knowledge-based system, which employs both case-based reasoning (CBR) and decision support components including multi-attribute analysis (MAA), was constructed to integrate environmental factors into the supplier selection process. Chen (2005) divided the supplier selection into two stages: first stage, environmental performance as the minimum requirement; and second stage, general purchase practices such as quality, delivery, performance records, etc. Only the suppliers that have the certification of ISO 14000 can be included in the second-stage evaluation. The procedure, however, has its flaws. The implementation of ISO 14000 does not guarantee that the supplier indeed has a good environmental performance, and the environmental issues are not considered at all in the second stage. Humphreys, McCloskey, McIvor, Maguire, and Glackin (2006) proposed a hierarchical fuzzy system with scalable fuzzy membership functions to facilitate the supplier selection process by incorporating environmental criteria. Lu, Wu, and Kuo (2007) constructed a multi-objective decision making process for green supply chain management to help managers in measuring and evaluating suppliers' performance using fuzzy AHP. Among all the above studies, however, most of them only focused on an environmental viewpoint and did not consider other important non-environmental factors. In a comprehensive green supplier selection model, all conventional factors, on top of environmental issues, need to be incorporated together to find the most suitable supplier that performs well in all important perspectives.

With environmental awareness, increasing amount of works on green supplier selection has been done in the past decade. However, the existing works generally only considered environmental aspect only. For a firm to select the most appropriate supplier for cooperation, it needs to consider both the environmental protection issue and the traditional supplier selection factors. Therefore, a comprehensive green supplier selection model is proposed in this paper.

3. AHP, fuzzy set theory and FEAHP

3.1. Analytic hierarchy process (AHP)

The analytic hierarchy process (AHP) was first proposed by Saaty in 1971, and it is one of the most commonly used methods for solving multiple-criteria decision-making (MCDM) problems in political, economic, social and management sciences (Saaty, 1980). Through AHP, opinions and evaluations of decision makers can be integrated, and a complex problem can be devised into a simple hierarchy system with higher levels to lower ones. The qualitative and quantitative factors can then be evaluated in a systematic manner. The application of AHP to a complex problem involves six essential steps (Chi & Kuo, 2001; Lee, Kang, & Wang, 2006; Murtaza, 2003):

1. Define the unstructured problem and state clearly the objectives and outcomes.
2. Decompose the complex problem into a hierarchical structure with decision elements (criteria and alternatives).
3. Employ pairwise comparisons among decision elements and form comparison matrices.
4. Use the eigenvalue method to estimate the relative weights of decision elements.
5. Check the consistency property of matrices to ensure the judgments of decision makers are consistent.
6. Aggregate the relative weights of decision elements to obtain an overall rating for the alternatives.

3.2. Fuzzy set theory

The conventional AHP has some shortcomings, and one of them is that the experiences and judgments of humans are not well-defined; that is, they are not quantitatively digital (Cheng, 1999). To overcome the problem, fuzzy set theory can be combined with the AHP. Fuzzy set theory was introduced by Zadeh in 1965 to solve problems involving the absence of sharply defined criteria (Zadeh, 1965). If the uncertainty (fuzziness) of human decision-making is not taken into account, the results can be misleading. Since its introduction, fuzzy theory has been applied in a variety of fields.

A fuzzy number is a fuzzy subset of real numbers whose membership function is $u_M(x): R \to (0,1)$. There are two most commonly used fuzzy numbers: trapezoidal fuzzy number and triangular fuzzy number. The membership function of a triangular fuzzy number is shown in Fig. 1 and is defined as follows (Lee et al., 2006):

$$u_M(x) = \left\{ \begin{array}{ll} (x-m^-)/(m-m^-), & m^- \leqslant x \leqslant m \\ (x-m^+)/(m-m^+), & m \leqslant x \leqslant m^+ \\ 0, & \text{otherwise} \end{array} \right\} \quad (1)$$

The m^- and m^+ represent respectively the lower bound and the upper bound of the triangular fuzzy number of M, and m is the strongest grade of membership. Thus, the triangular fuzzy number of M is indicated by (m^-, m, m^+).

3.3. Fuzzy extended AHP (FEAHP)

Many fuzzy AHP methods are proposed to solve various types of problems. The main theme of these methods is to use the concepts of fuzzy set theory and hierarchical structure analysis to present systematic approaches in selecting or justifying alternatives (Bozbura, Beskese, & Kahraman, 2007). In this paper, FEAHP is used to solve the green supplier selection problem because the steps of this approach are relatively easier, less time taking and less computational ex-

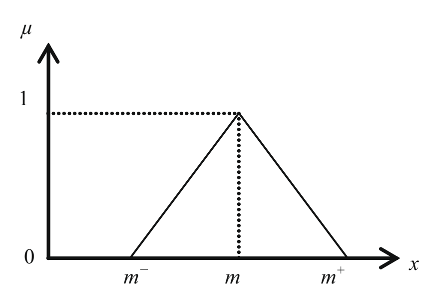

Fig. 1. A triangular fuzzy number.

pense than many other fuzzy AHP approaches, and at the same time, it can overcome the deficiencies of the conventional AHP. The approach not only can adequately handle the inherent uncertainty and imprecision of the human decision making process but also can provide the robustness and flexibility needed for the decision maker to understand the decision problem (Chan & Kumar, 2007).

FEAHP was first introduced by Chang (1992, 1996). To determine the priorities of decision criteria, pairwise comparison of triangular fuzzy numbers is carried out, and the extent analysis method for the synthetic extent value of the pairwise comparison is applied. By FEAHP, the fuzziness of the data involved in deciding the preferences of different decision variables can be handled (Chan & Kumar, 2007). Bozbura et al. (2007) applies the FEAHP to prioritize human capital measurement indicators. Chan and Kumar (2007) adopt FEAHP to provide a framework for the organization to select the global supplier considering risk factors.

The extent analysis method (EAM) is briefly introduced here. Two triangular fuzzy numbers $M_1(m_1^-, m_1, m_1^+)$ and $M_2(m_2^-, m_2, m_2^+)$ shown in Fig. 2 are compared. When $m_1^- \geqslant m_2^-$, $m_1 \geqslant m_2$, $m_1^+ \geqslant m_2^+$, we define the degree of possibility $V(M_1 \geqslant M_2) = 1$. When $m_2^- \geqslant m_1^+$, we define the degree of possibility $V(M_1 \geqslant M_2) = 0$. Otherwise, the degree of possibility $V(M_1 \geqslant M_2)$ is the ordinate of the highest intersection point between $\mu\ (M_1)$ and $\mu\ (M_2)$ (Chang, 1996; Lee, 2009; Lee, Kang, & Chang, in press; Zhu, Jing, & Chang, 1999):

$$V(M_2 \geqslant M_1) = hgt(M_1 \cap M_2) = \mu(\mathrm{d}) = \frac{m_1^- - m_2^+}{(m_2 - m_2^+) - (m_1 - m_1^-)} \tag{2}$$

where M is a convex fuzzy set, and $\alpha \in [0, 1]$. If $x_1 \in M_\alpha$ and $x_2 \in M_\alpha$, then $\mu_M\ (x_1) \geqslant \alpha$ and $\mu_M\ (x_2) \geqslant \alpha$. M_α is a closed interval and $x_1 < x < x_2$, so $x \in M_\alpha$ and $\mu_M\ (x) \geqslant \alpha = \min(\mu_M\ (x_1), \mu_M\ (x_2))$.

4. Green supplier selection model

Many works have been done on issues about supply chain and suppliers; however, limited literatures are found on green supplier and green supply chain until recent years. While some recent studies have stressed on the green supplier selection problem, they considered environmental attributes solely, but not the traditional criteria. In this paper, a comprehensive green supplier selection model is proposed by considering the important criteria in various aspects for evaluating green suppliers. The steps are as follows:

(1) Define the green supplier selection problem, and identify the overall objective.
(2) Collect the evaluation criteria for green suppliers through literature review and discussion with managers in industries and eco-experts.
(3) Select the most important criteria and sub-criteria by the Delphi method. Based on Saaty (1980), if there are more than seven factors at the same level, there are too many selections on the questionnaires, and it is tough for participants to make a choice. This problem can be overcome by the way of elimination or combination. The Delphi method is to reduce the number of sub-criteria while keeping real important attributes. The process is summarized as follows (Fowles, 1978):
    3.1 Formation of a team to study the subject, and the panelists are experts in the area to be investigated;
    3.2 Development of the first round Delphi questionnaire;
    3.3 Transmission of the results of the first questionnaire to the panelists and analysis of the first round responses;
    3.4 Preparation of the second round questionnaire;
    3.5 Transmission of the results of the second round questionnaire to the panelists and analysis of the second round responses (steps 3.4 and 3.5 are reiterated as long as desired or necessary to achieve stability in the results); and
    3.6 Preparation of a report to present the conclusions.
(4) Based on the selected criteria and sub-criteria, a hierarchy for evaluating green suppliers is prepared.
(5) Based on the hierarchy, a pairwise comparison questionnaire is prepared. In this research, a five-point scale is used. Experts are invited to fill out the questionnaire, and the pairwise comparison results from each expert are analyzed first to make sure that the expert's opinion is consistent throughout the questionnaire. The consistency test (Saaty, 1980) is performed by calculating the consistency index (CI) and consistency ratio (CR):

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1}, \text{ and} \tag{3}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \tag{4}$$

where n is the number of items being compared in the matrix, and RI is random index, the average consistency index of randomly generated pairwise comparison matrix of similar size (Saaty, 1980). If CR is less than 0.1, the threshold for consistency, the expert's judgment is consistent. If the consistency test is not passed, the expert will be asked to re-do the part of the questionnaire.
(6) From each expert's questionnaire results, establish fuzzy pairwise comparison weights for criteria (sub-criteria or suppliers) i and j according to the membership functions defined in Table 1. For expert t, the fuzzy pairwise comparison weight for i and j is $(p_{ijt}, q_{ijt}, r_{ijt})$.
(7) Calculate the fuzzy integrated pairwise comparison weights for criteria (sub-criteria and suppliers) using the geometric mean method. A triangular fuzzy number $\tilde{D}_{ij}$ is obtained by combining the experts' opinions.

$$\tilde{D}_{ij} = (b_{ij}^-, b_{ij}, b_{ij}^+) \tag{5}$$

$$\text{where } b_{ij}^- = \left(\prod_{t=1}^{s} p_{ijt}\right)^{\frac{1}{s}}, \forall \quad t = 1, 2, \ldots, s. \tag{6}$$

$$b_{ij} = \left(\prod_{t=1}^{s} q_{ijt}\right)^{\frac{1}{s}}, \forall \quad t = 1, 2, \ldots, s. \tag{7}$$

$$b_{ij}^+ = \left(\prod_{t=1}^{s} r_{ijt}\right)^{\frac{1}{s}}, \forall \quad t = 1, 2, \ldots, s. \tag{8}$$

and $(p_{ijt}, q_{ijt}, r_{ijt})$ is the pairwise comparison weight of criteria (sub-criteria or suppliers) i and j from expert t.
(8) Examine the consistency of the integrated opinions of the experts. The fuzzy geometric pairwise comparison weight from step 7 is defuzzified first by (Kwong & Bai, 2003):

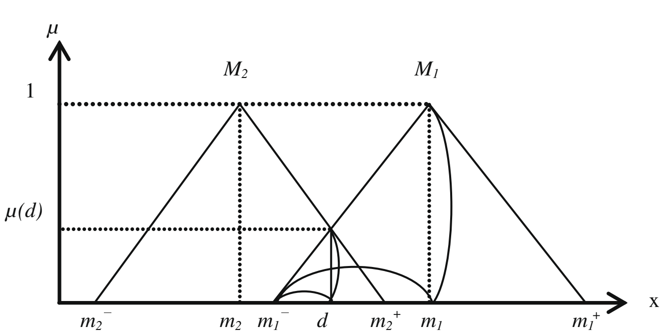

Fig. 2. Two triangular fuzzy numbers M_1 and M_2 (Lee, 2009).

Table 1
Characteristic function of the fuzzy numbers (Lee, 2009).

Fuzzy number	Characteristic (membership) function
$\tilde{1}$	(1, 1, 2)
$\tilde{x}$	$(\boldsymbol{x}-1, \boldsymbol{x}, \boldsymbol{x}+1)$ for $\boldsymbol{x}$ = 2,3,4,5,6,7,8
$\tilde{9}$	(8, 9, 9)
$1/\tilde{1}$	$(2^{-1}, 1^{-1}, 1^{-1})$
$1/\tilde{x}$	$((x+1)^{-1}, x^{-1}, (x-1)^{-1})$ for x = 2,3,4,5,6,7,8
$1/\tilde{9}$	$(9^{-1}, 9^{-1}, 8^{-1})$

$$\bar{b}_{ij} = (b_{ij}^- + 4b_{ij} + b_{ij}^+)/6 \tag{9}$$

The consistency test as in step 5 is performed again to examine the integrated opinions of the experts.

(9) Calculate the value of fuzzy synthetic extent with respect to criterion (sub-criterion or supplier) i (Chang, 1996; Lee, 2009; Lee et al., in press):

$$F_i = \sum_{j=1}^{n} B_{ij} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{n} B_{ij}\right]^{-1}, \quad i=1,2,\ldots,n \text{ and } j=1,2,\ldots,n \tag{10}$$

$$\text{where } \sum_{j=1}^{n} B_{ij} = \left(\sum_{j=1}^{n} b_{ij}^-, \sum_{j=1}^{n} b_{ij}, \sum_{j=1}^{n} b_{ij}^+\right) \text{ and } \left[\sum_{i=1}^{n}\sum_{j=1}^{n} B_{ij}\right]^{-1} \tag{11}$$

$$= \left(1/\sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij}^+,\ 1/\sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij},\ 1/\sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij}^-\right) \tag{12}$$

i=1,2,..., n and j=1,2,..., n

(10) Compare F_i, and calculate membership function $\mu(d)$ (shown in Fig. 2) to represent the relative importance between two criteria (sub-criteria or suppliers). The degree possibility for a convex fuzzy number to be greater than k convex fuzzy number F_k can be defined by (Chang, 1996; Lee, 2009; Lee et al., in press):

$$V(F \geqslant F_1, F_2, \ldots, F_k) = \min V(F \geqslant F_i), \quad i=1,2,\ldots,k \tag{13}$$

(11) Calculate the weights, w_i', of criteria (sub-criteria and suppliers) using Eq. (2), and normalize w_i' into W. Assume that:

$$d(F_i) = \min V(F_i \geqslant F_k) = w_i' \ (k=1,2,\ldots,n \text{ and } k \neq i), \tag{14}$$

the weights, w_i', of criteria (sub-criteria or suppliers) are:

$$W' = (w_1', w_2', \ldots, w_n')^T \tag{15}$$

After normalization, the priority weights of criteria (sub-criteria and suppliers) are:

$$W = (w_1, w_2, \ldots, w_n)^T \tag{16}$$

(12) Aggregate the weights of sub-criteria and criteria and the performance of suppliers with respect to each sub-criterion to obtain an overall rating for suppliers.

5. Case study

Global environmental concern is a reality, and an increasing attention is focusing on the green production in various industries. Regarding the current production facilities in TFT–LCD industry, many different materials are procured and included in the products. A TFT panel (with TFT-array substrate, liquid crystal and color filter substrate), a driving-circuit unit (with LCD driver IC (LDI) chips, multi-layer PCBs and driving circuits) and a backlight & chassis unit (with backlight, lamp, light-guide panel (LGP) and chassis) are required to assemble a TFT–LCD module. These components are produced in different kinds of production processes, and many of them are purchased from different suppliers. In order to manufacture an environmental friendly TFT–LCD module, a TFT–LCD manufacturer needs to cooperate with suppliers who can provide environmental friendly components in the first place. The objective of the case study is to construct an analytic framework for the decision making in selecting the most appropriate supplier.

In the first part of the study, the most important factors for evaluating traditional suppliers and for evaluating green suppliers are examined. A total of 11 criteria and 41 sub-criteria are identified after a detailed review of the literature and interviews with domain experts. Based on Saaty (1980), if there are more than seven factors in the same cluster, it is very confusing and difficult for participants to make pairwise comparisons. Therefore, the concept of the Delphi method is used to generate a consensus of opinions among experts and to extract the most important sub-criteria. A nine-point scale is used in the questionnaires to collect experts' opinions, with preferences of very unimportant, unimportant, normal, important and very important (scores of 1, 3, 5, 7 and 9, respectively), and the value of 2, 4, 6 and 8 is the mid-opinion between 1, 3, 5, 7 and 9. An excerpt of the questionnaire is as shown in Table 2. Eleven experts are asked to fill out the first questionnaire, which is composed of two parts: rating of sub-criteria for evaluating traditional suppliers and rating of sub-criteria for evaluating green suppliers. The results of the two parts of the first questionnaires are analyzed and are given to the ex-

Table 2
An excerpt of the questionnaire for evaluating sub-criteria.

An excerpt of the questionnaire for evaluating sub-criteria

Criteria/Sub-criteria	The importance of sub-criteria for evaluating green suppliers								
	1	2	3	4	5	6	7	8	9
	Very unimportant		Unimportant		Normal		Important		Very important
Green product									
1. Recycle	☐	☐	☐	☐	☐	☐	☐	☐	☐
2. Green packaging	☐	☐	☐	☐	☐	☐	☐	☐	☐
Green competencies									
1. Clean production technology	☐	☐	☐	☐	☐	☐	☐	☐	☐
2. Materials used in the supplied components that reduce the impact on natural resources	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Ability to alter process and product for reducing the impact on natural resources	☐	☐	☐	☐	☐	☐	☐	☐	☐

Table 3
Criteria and sub-criteria for evaluating traditional suppliers.

Criteria	Sub-criteria	Average	Ranking
Quality	Quality-related certificates	7.590909	8
	Capability of quality management	7.909091	4
	Capability of handling abnormal quality	8.045455	1
Finance	Past finance performance	6.727273	23
	Stability of finance	7.318182	13
	Price	7.863636	5
Organization	Attitudes of managers	7.272727	15
	Future strategy direction	7.090909	17
	Degree of strategic cooperation	7.318182	13
Technology capability	Capacity	7.363636	12
	Technology level	7.727273	7
	Capability of R&D	7.545455	9
	Capability of design	7.272727	15
	Capability of preventing pollution	6.909091	20
Service	Credible delivery	8.045455	2
	Capability of delivery on time	8	3
	Capability of technology support	7.772727	6
	Flexibility	7.5	11
Total product life cycle cost	Cost of supplied components	7.545455	9
Green image	Green purchase trend of customers	6.954545	18
Pollution control	Use of harmful materials	6.954545	18
Environment management	Environment-related certificates	6.909091	20
	Internal control process	6.818182	22

perts as a reference, and the experts are asked to fill out the second round questionnaire. The results of the second round questionnaire are used to calculate the mean score of each sub-criterion under the two parts. Under each part, the sub-criteria with higher scores are extracted. We arbitrarily set threshold at 56%, and 23 sub-criteria are selected from each part. The selected criteria and sub-criteria for evaluating traditional suppliers and green suppliers are listed in Tables 3 and 4, respectively. According to the results, the most important criteria for evaluating traditional suppliers include capability of handling abnormal quality, credible delivery, capability of delivery on time, and capability of quality management. Note that some environmental sub-criteria, such as green purchase trend of customers, use of harmful materials, and environment-related certificates, are with some degree of importance too. For evaluating green suppliers, the most important sub-criteria are environment-related certificates, capability of preventing pollution, and use of harmful materials. In addition to environmental-related sub-criteria, some sub-criteria of quality and technology capability are included. An interesting finding is that cost is not included in the green supplier sub-criteria list. An inquiry with the experts leads to the reason behind: cost is deemed as the baseline for evaluating suppliers. That is, only suppliers that can meet the basic cost requirement will be further evaluated in all other aspects.

In the second part of the research, a green supplier selection model is constructed. By using the results from the Delphi method, a hierarchy is developed for incorporating the criteria and sub-criteria into the supplier evaluation process. Because some criteria only have one or two sub-criteria selected after the Delphi method, a combination is done to reduce the number of criteria. Cost of component disposal, the only sub-criterion under criterion *total product life cycle cost*, is combined into criterion *green product*. The two sub-criteria under *green image* are combined into criterion *green competencies*. The finalized hierarchy is as shown in Fig. 3, and the definitions of the criteria and sub-criteria are listed in Table 5.

A questionnaire is constructed based on the hierarchy, and an excerpt of the questionnaire is as shown in Table 6. Eight managers

Table 4
Criteria and sub-criteria for evaluating green supplier.

Criteria	Sub-criteria	Average	Ranking
Quality	Quality-related certificates	8.227273	12
	Capability of quality management	8.227273	12
	Capability of handling abnormal quality	8.090909	16
Technology capability	Technology level	8.045455	19
	Capability of R&D	8.272727	10
	Capability of design	8.227273	12
	Capability of preventing pollution	8.545455	2
Total product life cycle cost	Cost of component disposal	8.090909	16
Green image	Ratio of green customers to total customers	8.090909	16
	Social responsibility	8	23
Pollution control	Air emissions	8.318182	7
	Waste water	8.318182	7
	Solid wastes	8.318182	7
	Energy consumption	8.181818	15
	Use of harmful materials	8.5	3
Environment management	Environment-related certificates	8.727273	1
	Continuous monitoring and regulatory compliance	8.363636	4
	Green process planning	8.363636	4
	Internal control process	8.045455	19
Green product	Recycle	8.272727	10
	Green packaging	8.045455	19
Green competencies	Materials used in the supplied components that reduce the impact on natural resources	8.045455	19
	Ability to alter process and product for reducing the impact on natural resources	8.363636	4

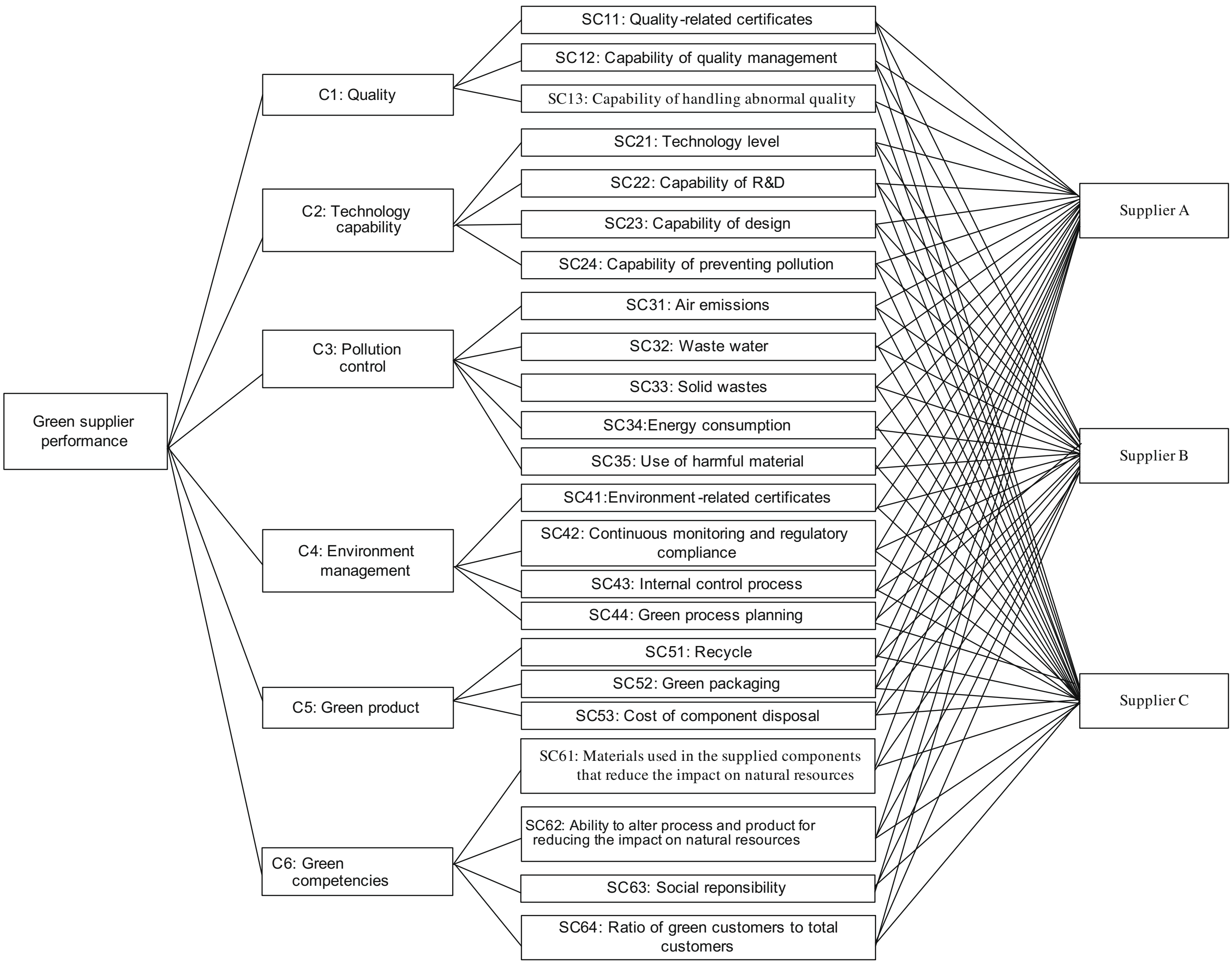

Fig. 3. The hierarchy for green supplier selection.

in an anonymous TFT–LCD manufacturer located in the Hsinchu Science-Based Industrial Park in Taiwan are invited to contribute their professional experience and fill out the questionnaire. The company aims to choose the most suitable green glass supplier.

Based on the results of the questionnaires, the consistency of the pairwise comparisons of each expert is examined. For instance, the pairwise comparison matrix for the criteria of an expert is as follows:

$$\beta_1 = \begin{bmatrix} 1 & 2 & 3 & 2 & 1 & 2 \\ 1/2 & 1 & 2 & 2 & 1 & 2 \\ 1/3 & 1/2 & 1 & 1 & 2 & 2 \\ 1/2 & 1/2 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1/2 & 1 & 1 & 1 \\ 1/2 & 1/2 & 1/2 & 1 & 1 & 1 \end{bmatrix}, \text{ and } \lambda_{\max} = 6.464.$$

The consistency test is performed by calculating the consistency index (CI) and consistency ratio (CR):

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1} = \frac{6.464 - 6}{6-1} = 0.093, \text{ and}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{0.093}{1.24} = 0.075,$$

Since CR is less than 0.1, the expert's judgment is consistent. If the consistency test is not passed, the expert will be asked to re-do the part of the questionnaire.

After the consistency test on the questionnaire results of all experts is completed, the fuzzy importance weights for criteria (sub-criteria) for each expert are established using the membership functions defined in Table 1. The above matrix from the expert is transformed into a fuzzy matrix as follows:

$$\tilde{\beta}_1 = \begin{bmatrix} (1,1,1) & (1,2,3) & (2,3,4) & (1,2,3) & (1,1,2) & (1,2,3) \\ (1/3,1/2,1) & (1,1,1) & (1,2,3) & (1,2,3) & (1,1,2) & (1,2,3) \\ (1/4,1/3,1/2) & (1/3,1/2,1) & (1,1,1) & (1,1,2) & (1,2,3) & (1,2,3) \\ (1/3,1/2,1) & (1/3,1/2,1) & (1/2,1,1) & (1,1,1) & (1,1,2) & (1,1,2) \\ (1/2,1,1) & (1/2,1,1) & (1/3,1/2,1) & (1/2,1,1) & (1,1,1) & (1,1,2) \\ (1/3,1/2,1) & (1/3,1/2,1) & (1/3,1/2,1) & (1/2,1,1) & (1/2,1,1) & (1,1,1) \end{bmatrix}$$

Table 5
Definitions of criteria and sub-criteria for evaluating green supplier.

Criteria/sub-criteria	Definitions
Quality (C1): The factors that can improve the quality of products from the supplier	
Quality-related certificates (SC11)	Whether the supplier has quality-related certificates, such as ISO 9000 and QS 9000, etc.
Capability of quality management (SC12)	The comprehensiveness of the supplier's quality management system
Capability of handling abnormal quality (SC13)	The capability of the supplier in handling abnormal quality problems
Technology capability (C2): The factors that can facilitate the new product/process development of the supplier and that can provide new and upgraded products to the firm	
Technology level (SC21)	Technology development of the supplier to meet current and future demand of the firm
Capability of R&D (SC22)	Capability of R&D of the supplier to meet current and future demand of the firm
Capability of design (SC23)	Capability of new product design of the supplier to meet current and future demand of the firm
Capability of preventing pollution (SC24)	Capability of product design and manufacturing tools of the supplier to prevent pollution
Pollution control (C3): The factors that show the control of supplier in producing pollution	
Air emissions (SC31)	The quantity control and treatment of hazardous emission, such as SO_2, NH_3, CO and HC_1
Waste water (SC32)	The quantity control and treatment of waste water
Solid wastes (SC33)	The quantity control and treatment of solid waste
Energy consumption (SC34)	The control of energy consumption
Use of harmful materials (SC35)	The control of the use of harmful materials in the production
Environment management (C4): The factors that show the effort of supplier in environment management	
Environment-related certificates (SC41)	Whether the supplier has environment-related certificates, such as ISO 14000
Continuous monitoring and regulatory compliance (SC42)	The level of continuous monitoring and regulatory compliance of environment-related issues
Internal control process (SC43)	The capability of continuous checking and revising emergency response plan
Green process planning (SC44)	The level of green process planning of the supplier
Green product (C5): The factors that show the effort of supplier in producing green products	
Recycle (SC51)	The level of recycling of the products
Green packaging (SC52)	The level of green materials used in packaging
Cost of component disposal (SC53)	The processing cost at the end of life of the products (The cost is reduced as recycling increases)
Green competencies (C6): The factors that show the competencies of supplier in improving green production	
Materials used in the supplied components that reduce the impact on natural resources (SC61)	The use of materials in the components that has a lower impact on natural resources
Ability to alter process and product for reducing the impact on natural resources (SC62)	The ability of the supplier to alter process and product design in order to reduce the impact on natural resources
Social responsibility (SC63)	The autonomous social responsibility of the supplier towards environment protection
Ratio of green customers to total customers (SC64)	The ratio of customers that demand green products to the total customers of the supplier

Table 6
An excerpt of the questionnaire for supplier selection problem.

	Absolute	Very strong	Strong	Weak	Equal	Weak	Strong	Very strong	Absolute	
	9:1	7:1	5:1	3:1	1:1	1:3	1:5	1:7	1:9	
Under criterion green product, which sub-criterion is more important?										
Recycle										Green packaging
Recycle										Cost of component disposal
Green packaging										Cost of component disposal
Under sub-criterion recycle, which supplier performs better?										
Supplier A										Supplier B
Supplier A										Supplier C
Supplier B										Supplier C

A fuzzy integrated matrix is formed next by combining the data from all experts through the geometric mean method, and is as follows:

$$\tilde{\beta} = \begin{bmatrix} (1,1,1) & (2.79,3.95,6.16) & (1.23,1.83,3.83) & (0.90,1.99,3.49) & (0.60,0.74,1.73) & (0.50,1.00,2.24) \\ (0.16,0.25,0.36) & (1,1,1) & (1.15,1.61,3.79) & (1.15,1.85,4.04) & (0.90,1.73,3.27) & (1.15,1.61,3.79) \\ (0.26,0.55,0.81) & (0.26,0.62,0.87) & (1,1,1) & (0.80,1.22,2.70) & (1.56,1.93,4.21) & (0.94,1.85,3.75) \\ (0.29,0.50,1.11) & (0.25,0.54,0.87) & (0.37,0.82,1.25) & (1,1,1) & (0.74,1.15,2.51) & (0.67,1.11,2.59) \\ (0.58,1.36,1.68) & (0.31,0.58,1.11) & (0.24,0.52,0.64) & (0.40,0.87,1.36) & (1,1,1) & (1.04,1.15,3.01) \\ (0.45,0.99,1.99) & (0.26,0.62,0.87) & (0.26,0.54,1.07) & (0.39,0.90,1.50) & (0.33,0.87,0.96) & (1,1,1) \end{bmatrix}$$

To ensure that the integrated opinions are still consistent, the integrated fuzzy matrix is deffuzified using Eq. (9) first and the consistency test is carried out again.

After the consistency test is passed, the value of fuzzy synthetic extent with respect to each criterion is calculated next. Based on the integrated fuzzy matrix for criteria, the values of $\sum_{j=1}^{n} b_{ij}^{-}$, $\sum_{j=1}^{n} b_{ij}$, $\sum_{j=1}^{n} b_{ij}^{+}$ and $\sum_{j=1}^{n} B_{ij}$ are calculated and shown in Table 7. Fuzzy synthetic extent with respect to each criterion is shown in Table 8. The priorities of the criteria are calculated in

Table 7
Integration of experts' opinions on criteria.

Criteria	$\sum_{j=1}^{n} b_{ij}^{-}$	$\sum_{j=1}^{n} b_{ij}$	$\sum_{j=1}^{n} b_{ij}^{+}$
Quality	7.0231	10.5132	18.4431
Technology capability	5.503501	8.050217	16.24838
Pollution control	4.822784	7.162916	13.3447
Environment management	3.308808	5.12159	9.33316
Green product	3.562026	5.474975	8.790769
Green competencies	2.696967	4.924577	7.380746
Sum	26.91719	41.24748	73.54086

Table 8
Fuzzy synthetic extent with respect to criterion F_i.

Criteria	$\sum_{j=1}^{n} b_{ij}^{-} / \sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij}^{+}$	$\sum_{j=1}^{n} b_{ij} / \sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij}$	$\sum_{j=1}^{n} b_{ij}^{+} / \sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij}^{-}$
Quality (F_1)	0.0955	0.2549	0.6852
Technology capability (F_2)	0.0748	0.1952	0.6036
Pollution control (F_3)	0.0656	0.1737	0.4958
Environment management (F_4)	0.0450	0.1242	0.3467
Green product (F_5)	0.0484	0.1327	0.3266
Green competencies (F_6)	0.0367	0.1194	0.2742

Table 9
Calculation of $\mu(d)$ and $\boldsymbol{w}_i$.

Comparison	$\mu(d_{F1})$	Comparison	$\mu(d_{F2})$	Comparison	$\mu(d_{F3})$
$F_1 > F_2$	1	$F_2 > F_1$	0.8948	$F_3 > F_1$	0.8313
$F_1 > F_3$	1	$F_2 > F_3$	1	$F_3 > F_2$	0.9514
$F_1 > F_4$	1	$F_2 > F_4$	1	$F_3 > F_4$	1
$F_1 > F_5$	1	$F_2 > F_5$	1	$F_3 > F_5$	1
$F_1 > F_6$	1	$F_2 > F_6$	1	$F_3 > F_6$	1
w_1'	1	w_2'	0.8948	w_3'	0.8313
$\boldsymbol{w}_1$	**0.2171**	$\boldsymbol{w}_2$	**0.1942**	$\boldsymbol{w}_3$	**0.1804**
Comparison	$\mu(d_{F4})$	Comparison	$\mu(d_{F5})$	Comparison	$\mu(d_{F6})$
$F_4 > F_1$	0.6578	$F_5 > F_1$	0.6542	$F_6 > F_1$	0.5688
$F_4 > F_2$	0.7929	$F_5 > F_2$	0.8013	$F_6 > F_2$	0.7246
$F_4 > F_3$	0.8503	$F_5 > F_3$	0.8645	$F_6 > F_3$	0.7936
$F_4 > F_5$	0.9721	$F_5 > F_4$	1	$F_6 > F_4$	0.9796
$F_4 > F_6$	1	$F_5 > F_6$	1	$F_6 > F_5$	0.9442
w_4'	0.6578	w_5'	0.6542	w_6'	0.5688
$\boldsymbol{w}_4$	**0.1428**	$\boldsymbol{w}_5$	**0.1925**	$\boldsymbol{w}_6$	**0.1235**

Table 9. According to the experts' opinions, the most important criterion is *quality*, with a priority of 0.2171. The next two important criteria are *technology capability* and *green product*, with priorities of 0.1942 and 0.1925, respectively. In fact, the four environmental-related criteria, *pollution control, environment management*, *green product* and *green competencies*, comprise of 0.6392 of the total priority.

A similar procedure is carried out to calculate the priorities of the sub-criteria and alternatives. The results are shown in Table 10. According to the final scores, supplier A is the most preferred supplier with a priority weight of 0.3709, followed by supplier C with 0.3481. Detailed information of priorities of sub-criteria can also be found in Table 10. For example, under *quality*, the most important sub-criterion is *capability of handling abnormal quality*, with a local priority of 0.3571, followed by *capability of quality management* and *quality-related certificates*, with local priorities of 0.3266 and 0.3163, respectively. A comparison of all 23 sub-criteria shows that the most important sub-criterion is *capability of handling abnormal quality*, with an integrated priority of 0.0775. The second to fourth sub-criteria are *capability of quality management* (0.0709), *quality-related certificates* (0.0687) and *green packaging* (0.0648), respectively. Note that even though the model is to evaluate green suppliers, many non-environmental-related sub-criteria have relatively high priorities. To be in more detail, six out of the top ten sub-criteria are non-environmental sub-criteria. This implies that the selection of green suppliers should not only consider environmental factors, but also the traditional factors.

The performances of suppliers with respect to each criterion and each criterion are shown in Figs. 4 and 5, respectively. As can be seen from Fig. 4, supplier A performs relatively better than other two suppliers under most of the sub-criteria, and supplier C performs better than supplier B under most of the sub-criteria too. From Fig. 5, we can see that supplier A performs the best under all criteria, except C3, *pollution control*, and supplier C performs better than supplier B under all criteria. To summarize, supplier A should be selected for cooperation.

Table 10
Priorities of criteria, sub-criteria and alternatives.

Criteria	Sub-criteria	Local priorities	Integrated priorities	Integrated ranking	Priorities of alternatives
Quality (0.2171)	Quality-related certificates	0.3163	0.0687	3	Supplier A: 0.3709
	Capability of quality management	0.3266	0.0709	2	
	Capability of handling abnormal quality	0.3571	0.0775	1	
Technology capability (0.1942)	Technology level	0.2450	0.0476	7	
	Capability of R&D	0.2604	0.0506	6	
	Capability of design	0.2165	0.0420	9	
	Capability of preventing pollution	0.2780	0.0540	5	
Pollution control (0.1804)	Air emissions	0.2125	0.0383	11	Supplier B: 0.2810
	Waste water	0.1965	0.0355	15	
	Solid wastes	0.1893	0.0341	18	
	Energy consumption	0.1900	0.0343	17	
	Use of harmful materials	0.2118	0.0382	12	
Environment management (0.1428)	Environment-related certificates	0.2430	0.0347	16	
	Continuous monitoring and regulatory compliance	0.2282	0.0326	21	
	Internal control process	0.2586	0.0369	13	
	Green process planning	0.2702	0.0386	10	
Green product (0.1925)	Recycle	0.3102	0.0441	8	Supplier C: 0.3481
	Green packaging	0.4561	0.0648	4	
	Cost of component disposal	0.2337	0.0332	20	
Green competencies (0.1235)	Materials used in the supplied components that reduce the impact on natural resources	0.2972	0.0367	14	
	Ability to alter process and product for reducing the impact on natural resources	0.2302	0.0284	22	
	Social responsibility	0.2757	0.0341	19	
	Ratio of green customers to total customers	0.1969	0.0243	23	

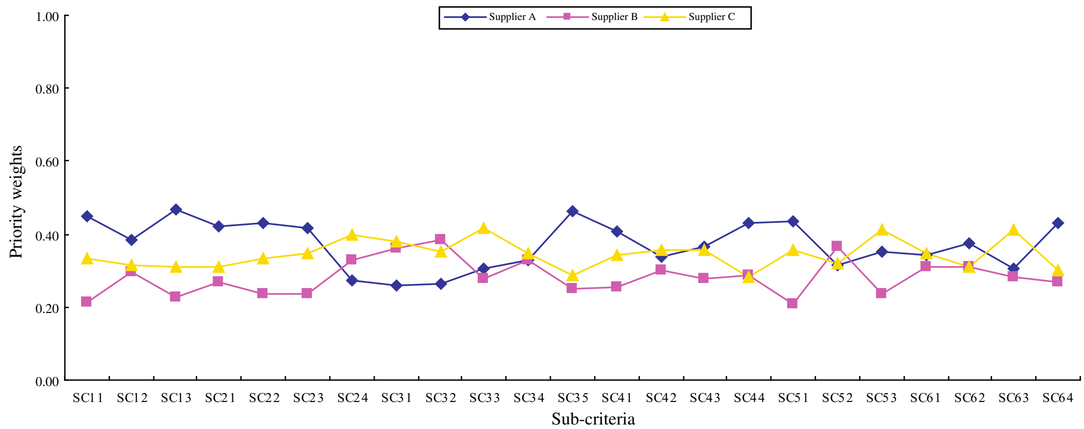

Fig. 4. Performance of suppliers with respect to each sub-criterion.

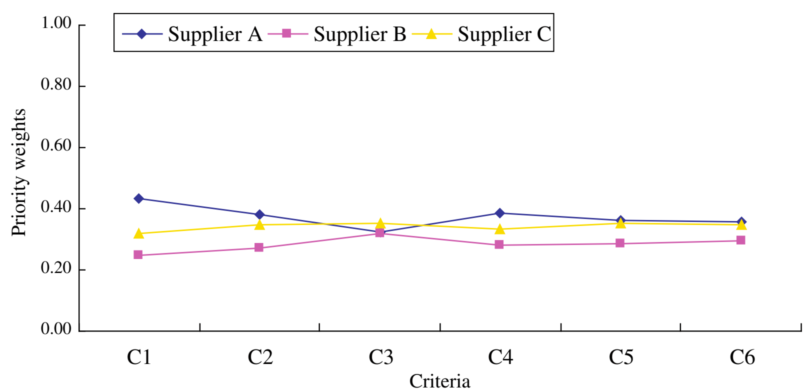

Fig. 5. Performance of suppliers with respect to each criterion.

6. Conclusion

Environmental protection and sustainable development are getting more and more attention in industry. In order to extend the product life cycle and to pursue enterprise perpetuity, a firm needs to emphasize environment protection and green production as a critical part of its social responsibility. A good green supplier selection model in a dynamic competitive and regulatory environment can help lessen the environmental and legal risks and increase the competitiveness of a firm. This paper proposes a model to select the factors for evaluating green suppliers, and to evaluate the performance of suppliers. The Delphi method is applied first to select the most important sub-criteria for traditional suppliers and for green suppliers. The results for green supplier are applied next to construct a hierarchy for green supplier evaluation problem. A FEAHP model is constructed next based on the hierarchy to evaluate green suppliers for an anonymous TFT–LCD manufacturer in Taiwan, and the most suitable supplier can be selected. The strength of the proposed model is that the vagueness of experts' opinions is considered in the evaluation process and the model is easy to apply. Manufacturers of related industries can use our proposed model, or tailor the model to meet their own needs, to evaluate their green suppliers or to select the best green supplier for cooperation.

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