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Evaluating firm's green supply chain management in linguistic preferences

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ABSTRACT

There has been an increasing interest towards firms' environmental sustainability activities to improve practices in their supply chain. Stringent environmental regulations in Europe and US challenge manufacturers to comply with these without losing their competitiveness. This study illustrates the case of a printed circuit board manufacturer in Taiwan that seeks to implement green supply chain management (GSCM) and selects a green supplier to meet its requirements. Choosing the suitable supplier is a key strategic direction in eliminating environmental impact on supply chain management for manufacturing firms. The firm's criteria and supplier selection need to be unified as a system to improve the firm's performance. This study identified the appropriate environmental and non-environmental GSCM criteria for the case firm and developed the following selection method: (i) evaluate the weights of criteria and alternatives as described both by qualitative and quantitative information; and (ii) rank alternative suppliers using a grey relational analysis. The result shows Alternative 3 ranks first among the four evaluated suppliers and demonstrated strong performance in the top three important criteria, namely, environmental management systems, profitability of supplier and relationship supplier closeness. Additionally, the perception weights on criteria itself are same as the most top five in weighted alternative.

1. Introduction

Environmental management has evolved to include boundary-spanning activities in the supply chain of Taiwan's electronic industry. All of these activities, whether upstream with the suppliers or downstream with the customers, relate to green supply chain management (GSCM), (Sarkis, 1998; Lee et al., 2009), which has become a challenge to manufacturers due to tighter environmental restrictions. For instance, the European Union has established a range of environmental policies such as RoHS (Restriction of Hazardous Substances) and WEEE (waste electronics and electrical equipment). These closely linked directives ban the use of six hazardous chemicals in the manufacture of electrical and electronic equipment and set collection, recycling and recovery targets for e-waste, respectively (Tseng et al., 2009a,c; Tseng, 2010a). Essentially, RoHS is applied to the design of products whereas WEEE is aimed at the life cycle of product. Because of these directives, manufacturers are led to be critical in choosing suppliers. However, the limited understanding of GSCM in environmental and non-environmental criteria has hampered the development of a widely accepted framework that would characterize and categorize firm's supply chain management (SCM) activities. Nevertheless, various studies can be found in the literatures (Zhu and Geng, 2001; Zhu and Sarkis, 2004; Zhu et al., 2008a,b; Srivastava, 2007).

Srivastava (2007) describes GSCM as the combination of environmental thinking and SCM 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. Firms typically expect their suppliers to go beyond environmental compliance and undertake efficient, green product design, life cycle assessment and other related activities. By having extensive supplier selection under their performance evaluation, firms tend to leverage staff resources throughout the firm to eliminate the environmental impacts (Tseng et al., 2009a; Tseng, 2010b). Hence, the firms' supplier alternatives must satisfy the GSCM criteria under the constraint of incomplete information and subjective human preferences, a phenomenon that has rarely been thoroughly examined.

Practicing GSCM requires identification of appropriate measures in order to complete robust study and to advance the body of knowledge in a field, both academically and practically. Academically, greater attention needs to be focused on employing multi-criteria, assessing the criteria for content validity and purifying them through extensive literature reviews to effectively and

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empirically advance theory within this field (Malhotra and Grover, 1998; Zhu and Sarkis, 2004; Zhu et al., 2008a,b; Srivastava, 2007; Tseng et al., 2009b; Lee et al., 2009). This case study contributes to this aspect through its attempt in integrating a number of criteria from various literatures in supply chain and environmental management (Tseng et al., 2008, 2009b; Zhu et al., 2008a,b; Srivastava, 2007; Lee et al., 2009) that may be used to help evaluate practices in GSCM. Practically, firms can benefit from the development of reliable and valid criteria to practices through implementation. The practitioner applies these criteria for benchmarking and continuous improvement when seeking to harmonize environmental and SCM goals. Another contribution of this study is to guide firms in understanding the different criteria in their implementation. To aid in optimal supplier selection of GSCM, this study finds practical application of the multi-criteria decision making (MCDM) tool in considering expert opinion regarding environmental concerns.

MCDM in real world systems very often deals with subjective human preferences. People express thoughts and perceptions using natural language which is often vague or difficult to state mathematically. Although meaning of a word might be well defined, determining the boundaries with which objects do or do not belong to become uncertain when using the word as a label for a set (Tseng, 2010a). Hence, the proposed method uses fuzzy set theory to appropriately express human's judgment in proposed criteria. Finally, grey relational analysis (GRA) is applied to the gathered data or information, as it is superior in theoretical analysis of systems with incomplete information (Tseng, 2008, 2010b). This study summarizes the principles of the theories and its modeling schemes in prediction and diagnosis, and reviews its practical applications combined with linguistic preferences. In this case stud, a hybrid approach is developed to determine and integrate GSCM criteria in choosing optimal alternative.

Considering the goal of the case firm to maintain competitiveness while at the same time complying with environmental regulations, this study aims to capture linguistic preferences in the selection of an alternative supplier using a proposed model. This paper contributes to the GSCM literature of the firm by: (i) developing valid and reliable GSCM criteria based on expert team and environmental and non-environmental literatures, (ii) developing an approach to use GRA given the linguistic preferences. The next section provides literature review and introduces GSCM implementation and practices of the firm. The methodology used to develop and validate the firm's GSCM criteria which satisfied content validity is presented in Section 3. Section 4 gives the results of this study, followed by discussions and implications of these results in Section 5. Section 6 concludes with a summary of findings, implications, limitations, and potential topics for future research.

2. Literature review

The firm's GSCM criteria have been used to explain the green planning, materials control and external information flows. Researchers categorize it into strategic, inter-organization, internal service quality, addressing the challenge of selecting green suppliers and purchasing perspective in order to improve firm's competitiveness (Farmer, 1997; Harland et al., 1999; Stanley and Wisner, 2001; Zhu and Sarkis, 2006; Vachon and Klassen, 2008; Shang et al., 2010; Olavarrieta and Ellinger, 1997). GSCM can be defined as the direct involvement of firms with its suppliers and customers in planning jointly for solutions to reduce the environmental impact from production processes and products, for environmental management and exchange of technical information with a mutual willingness to learn about each other's operations plan, and for setting goals for environmental improvement. These activities imply strengthening cooperation among those involved to reduce the environmental impact associated with material flows in the GSCM (Bowen et al., 2001; Tseng et al., 2009b).

2.1. Green supply chain management

GSCM philosophy focuses on how firms utilize their suppliers' processes, technology and capability, and integrating environmental concerns to enhance its competitive advantage (Vachon and Klassen, 2008). GSCM focus not only on products and production processes but also includes materials sourcing. Because GSCM focuses on the immediate outcome of the supplier on green efforts, and on the means by which more green operations or products might be achieved, buyer requirements are often incorporated in the conceptualization of green supply chain. Thus, such collaboration can take place simultaneously upstream with the green suppliers (Bowen et al., 2001; Zhu and Sarkis, 2004). Vachon and Klassen (2008) asserts that environmental collaboration was defined specifically to focus on inter-organizational interactions between supply chain members including aspects such as joint environmental goal-setting, shared environmental planning, and working together to reduce pollution or other environmental impacts. Furthermore, evidence suggests that upstream practices were more closely linked with process-based performance, while downstream collaboration was associated with product-based performance Vachon and Klassen (2008). GSCM, advocating efficiency and synergy between management systems of partner firms, facilitates environmental performance, minimal waste and cost savings (Rao and Holt, 2005).

A well-integrated GSCM involves coordinating the flow of materials and information between suppliers, manufacturers and customers, and implementing product postponement and mass customization in the supply chain. Higher level of integration with suppliers and customers in the supply chain is expected to result in more effective competitive advantage (Anderson and Katz, 1998; Birou et al., 1998; White et al., 1999; Narasimhan and Carter, 1998; Van Hoek, 1984). According to Zhu and Sarkis (2006), environmental directives issued by the European community may have led Chinese firms to have higher environmental awareness and stronger drive for GSCM practice. Moreover, the pressure to establish long-term relationship with foreign firms in China and export more products may also have driven Chinese firms to better implement GSCM.

Zhu et al. (2008a,b) empirically investigate the construct of and the scale for evaluating GSCM practices among 341 Chinese manufacturers. Two measurement models of GSCM practices were tested and compared by confirmatory factor analysis, and the empirical findings suggested that the two GSCM models are reliable and valid. Shang et al. (2010) identified six GSCM dimensions were: green manufacturing and packaging, environmental participation, green marketing, green suppliers, green stock and green eco-design, and indicated that based on the resource-based view, the capability of the green marketing oriented group was considered to be the deployment of a collection of resources that enables it to successfully compete against rivals. This can help manufacturing firms build up its competitive advantages from the valuable cues in this intensive review. Therefore, this study rises up the topic of GSCM criteria evaluation.

2.2. Selection of optimal suppliers

In a green supply chain, firms need to have extensive supplier selection and performance evaluation processes (Kainuma and Tawara, 2006) since the supplier plays an important role in GSCM implementation. Suppliers normally have long-term contracts with the users and provide their services for multiple functions or develop close service with customers. In the past decade, many studies discussed the green supplier selection model and a number of literatures focused on supplier involvement and performance (Choi and Hartley, 1996; Vonderenbse and Tracey, 1999; Stanley and Wisner, 2001; Li et al., 2007; Tseng et al., 2009b; Shang et al., 2010).

In terms of supplier selection, Chou and Chang (2008) proposed a system evaluating alternative suppliers that utilizes SCM strategy to identify supplier qualified criteria and the resulting model allows decision-maker to incorporate the supply risks of individual suppliers into final decision making. Chan and Kumar (2007) identified some of the important and critical criteria including risk factors for the development of an efficient system for global supplier selection. Tseng et al. (2009b) studied the selection of appropriate suppliers using analytical network process and choquet integral given a specific SCM strategy considering a set of requirements and evaluation criteria. However, none of these studies deal with supplier assessment in terms of GSCM criteria with subjective human preferences.

2.3. Proposed MCDM method

There are different approaches proposed to supplier selection problems. Carr and Smeltzer (1999) documented how firms with strategic purchasing are able to foster long-term, cooperative relationships and communication, and achieve greater responsiveness to the needs of their suppliers. Tan et al. (1998) explored the relationships between supplier management practices, customer relations practices and organizational performance, and then used purchasing, quality and customer relations to represent SCM practices. Chen et al. (2006) used TOPSIS to rank suitable suppliers based on quantitative and qualitative factors they identified such as quality, price, and flexibility and delivery performance.

Recent studies in multi-criteria supplier selection problems such as Humphreys et al. (2006) proposed a hierarchical fuzzy system with scalable fuzzy membership functions to facilitate incorporation of environmental criteria in the selection process. Lu et al. (2007) constructed an MCDM process for GSCM to help managers in measuring and evaluating performance of suppliers using fuzzy analytical hierarchy process (AHP). Xia and Wu (2007) developed an integrated approach of AHP improved by rough sets theory and multi-objective mixed integer programming to simultaneously determine the number of suppliers to employ and the order quantity allocated to these suppliers in the case of multiple sourcing and multiple products with multiple criteria and supplier capacity constraints.

Furthermore, Wang and Che (2007) presented a model using fuzzy performance indicators, and showed the integration of different criteria that allows the supplier selection of a specific commercial product to be explored and modeled. Li et al. (2007) presented another way of supplier selection using grey based approach, but the computation process seem to be insufficient, showing unreasonable approach for the fuzzy number. Given the recent studies, literature still lacks work in considering the optimal supplier selection in light of both environmental aspect and SCM criteria. With environmental awareness, much focus has been solely on incorporating such considerations. Tseng et al. (2009c) proposed the SCM strategy in the supplier selection problem with uncertainty. All conventional SCM criteria need to be incorporated together with environmental criteria to find the most suitable supplier in a comprehensive model.

Moreover, Tseng (2010b) proposed a hybrid fuzzy grey relational analysis method based to deal with a perception approach to deal with supplier evaluation of environmental knowledge management capacities with uncertainty and information lacking; the study presented the weights of criteria and alternatives are described both in qualitative and quantitative information using fuzzy set theory and uses a GRA to result the ranking order for all alternatives. There are very few studies applied this hybrid method in solving particular management solution. Therefore, this study evaluated alternative supplier using GSCM criteria by employing the fuzzy set theory with grey possible degree. Fuzzy set theory method accounts for the vagueness of the language used to express the qualitative criteria whereas GRA deals with the incomplete information.

2.4. Proposed GSCM criteria

The outcome of literature review together with inputs from industry and academia compose the proposed criteria in this study which are the GSCM requirements for an optimal supplier. Comprehensive discussion and literature reviews resulted to a total of 18 criteria (Cox and Blackstone, 1998; Carr and Pearson, 2002; Tan et al., 2002; Chen and Paulraj, 2004; Johnston et al., 2004; Li et al., 2006).

The following paragraphs discuss briefly the criteria (denoted by C and a number). In the current business environment, GSCM has become critical in establishing value-adding practices to a firm to ensure profitability of supplier (C2), as it is an important part of their supplier chain practices (Kathuria, 2000; Johnston et al., 2004; Yao et al., 2007). Supplier relationship closeness (C3) was among the criteria (purchasing, quality and customer relations) used by Tan et al. (1998) to construct a fitness model as they explore the relationships between supplier management, customer relations practices and organizational performance. In terms of customer service, delivery reliability (C1), the ability to meet delivery schedule or promises, is critical to respond quickly to customer orders. Moreover, the product conformance quality (C5) is a critical competitiveness criterion which seeks to satisfy customer needs (C4) (Chase et al., 2001).

In terms of green criteria, Sarkis (1998) categorized environmentally conscious business practices into five major components: design for the environment (Green design (C8)), life cycle analysis, total quality environmental management and environment related certificates such as ISO 14000 (C11). Farmer (1997), Harland et al. (1999), Stanley and Wisner (2001) have outlined tools to such as into strategic, internal green production plan (C12), cleaner production (C14) and internal service quality (C7) to address improve competitiveness of a firm by addressing the purchasing perspective. Carr and Smeltzer (1999) have documented how firms with strategic purchasing are able to foster long-term, cooperative relationships and communication, and achieve greater responsiveness to the needs of their suppliers (C15). Zhu and Geng (2001) studied Chinese firms and examined their environmental developments, in particular green purchasing (C9), in their business practices. Among the supplier selection models being used, environmentally preferable bidding and life cycle assessment (C10), which assesses green purchasing impacts and their financial consequences through the entire product life cycle, are the most popular in the firms. However, flexibility of supplier (C6) is also a complex and multi-dimensional capability that requires a firm-wide effort to increase a firm's responsiveness and reduce waste and environmental impact (Dreyer and Gronhaug, 2004). Chen et al. (2006) identified quantitative and qualitative factors such as quality, price, and flexibility and delivery performance that must be considered in the selection of suitable suppliers. Humphreys et al. (2003) identified the environmental criteria which influence a firm's management support (C13). A knowledge-based environmental management system requirements (C16) was developed next to integrate the environmental criteria to support their supplier selection process. Tseng (2010a,b) presented a perception approach to deal with supplier evaluation of environmental knowledge management capacities with uncertainty. Specifically, the R&D capability helps a firm expand its existing technologies and improve Green R&D function. The R&D capability refers to the number of patents (C17) (last 3 years average) and degree of innovativeness of R&D green products (C18) (last 3 years average); these criteria are measured quantitatively (Damanpour and Wischnevsky, 2006).

The hierarchical structure of evaluation framework in supplier selection for case firm considering GSCM criteria consists of MCDM analysis combining fuzzy set theory and grey possibility degree (Fig. 1). MCDM analysis assists the evaluators in selecting one or few most appropriate alternatives from a finite set of alternatives with reference to multiple, usually conflicting, criteria. Grey possibility degree deals with the uncertainty and incomplete samples problem (Chen and Tzeng, 2004; Zhang et al., 2005; Li et al., 2007). Fuzzy set theory concerns the linguistic preferences of subjective judgment problems (Zadeh, 1965; Tseng et al., 2008; Tseng, 2010b). In summary, this study uses 18 criteria in qualitative and quantitative scales to evaluate the suppliers.

3. Research method

GSCM, as a strategic and decision making perspective, improves the performance of a firm (Tseng, 2008). This section discusses the proposed hybrid method as well as their associations. The fuzzy set theory definitions, the GRA and the developed methodology are described as follows.

3.1. Transform the quantitative data

The quantitative (crisp) numbers of criteria have varying units that cannot be compared. The crisp value numbers must be normalized to achieve criteria values that are unit-free and therefore comparable. The normalized crisp values of W_{ij} are calculated following Eq. (1) (Tseng et al., 2009b).

$$W_{ij}^{\text{crisp}} = \frac{W_{ij}^k - \min W_{ij}^k}{\max W_{ij}^k - \min W_{ij}^k}, W_{ij}^{\text{crisp}} \in [0,1]; k = 1, 2, \ldots n \qquad (1)$$

where $\max W_{ij}^k = \max\{W_{ij}^1, W_{ij}^2, \ldots W_{ij}^n\}$ and $\min W_{ij}^k = \min\{W_{ij}^1, W_{ij}^2, \ldots W_{ij}^n\}$

3.2. Fuzzy set theory

Due to the uncertainty involved in this study, the proposed method uses the linguistic preferences for deriving the priorities of different selection alternatives and setting up grey numbers in all criteria and alternatives. The fuzzy set theory (Zadeh, 1965) is a mathematical theory designed to model the fuzziness of human cognitive processes. It is essentially a generalization of set theory where the classes lack sharp boundaries. The membership function $\mu_A(x)$ of a fuzzy set operates over the range of real numbers, generally scaled to the interval [0, 1].

An expert's uncertain judgment can be represented by a fuzzy number. A triangular fuzzy number (TFN) is a special kind of fuzzy number whose membership function is defined by three real numbers (l, m, u), provided that $l \le m \le u$. This membership function is illustrated in Fig. 2 and described mathematically below (Tseng et al., 2008; Tseng, 2010a,b). Triangular fuzzy membership function is presented as follows (Lin et al., 2007).

3.2.1. Definition 1

A TFN $\tilde{N}$can be defined as a triplet (l, m, u), and the membership function $\mu_{\tilde{N}}(x)$ is defined as:

$$\mu_{\tilde{N}}(x) \begin{cases} 0, & x < l \\ (x-l)/(m-l), & l \le x \le m \\ (u-x)/(u-m), & m \le x \le u \\ 0, & x > u \end{cases} \qquad (2)$$

Where l, m, and u are real numbers and $l \le m \le u$. See Fig. 2.

3.2.2. Definition 2

Let $\tilde{N}_1 = (l_1, m_1, u_1)$and $\tilde{N}_2 = (l_2, m_2, u_2)$ be two TFNs. The multiplication of $\tilde{N}_1$ and $\tilde{N}_2$ denoted by $\tilde{N}_1 \otimes \tilde{N}_2$. Two positive TFNs, $\tilde{N}_1 \otimes \tilde{N}_2$ approximates a TFNs as follows:

$$\tilde{N}_1 \otimes \tilde{N}_2 \cong (l_1 \otimes l_2, m_1 \otimes m_2, u_1 \otimes u_2) \qquad (3)$$

Therefore, l, m, u represents the lower, mean and upper bounds of the TFN. The membership function represents the degree to which any given element x in the domain X belongs to the fuzzy number A. In order to deal with linguistic preferences, linguistic variables have been defined for several levels of preferences (Table 1). The TFN used to represent these preferences are depicted in Fig. 2.

A fuzzy weighted sum performance matrix (P) can be derived for the criteria by multiplying the fuzzy weight vector related to criteria with the decision matrix for criteria.

$$P = \left[\begin{pmatrix} l_1 & , m_1 & , u \\ \ldots & \ldots & \ldots \\ l_n & , m_n & , u_n \end{pmatrix} \right] \qquad (4)$$

where, n represents the number of criteria. The defuzzification method, according to Pan (2008), uses TFN. The TFN can be applied

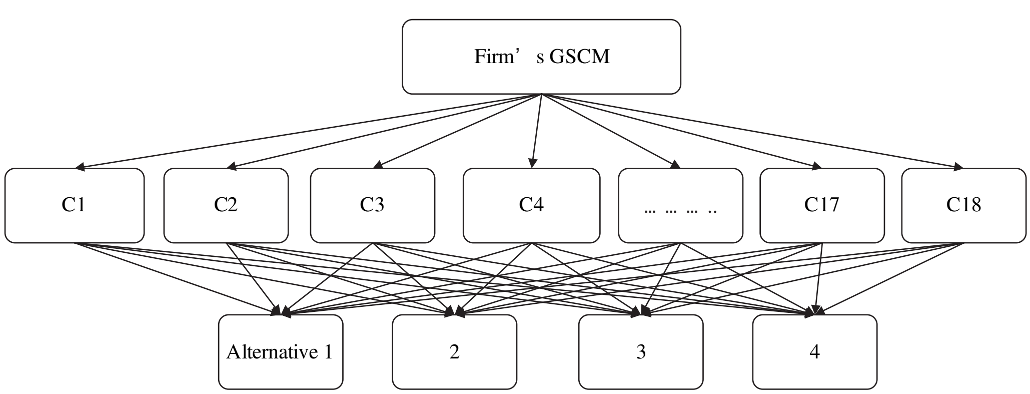


Fig. 1. Hierarchical structure.

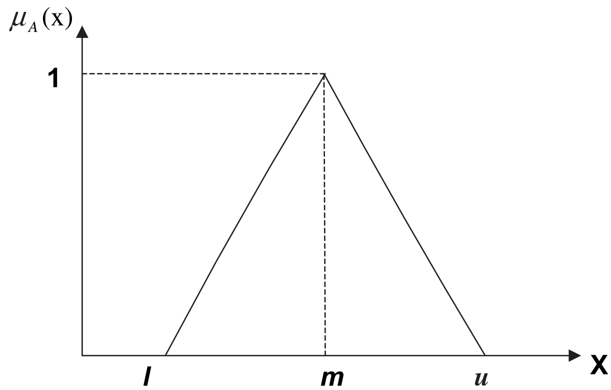


Fig. 2. A TFN A = (l, m, u).

to transform the total weighted performance matrices into interval performance matrices, which provide α_l and α_u for each criterion as follows:

$$P_\alpha = \left[\begin{pmatrix} \alpha_l & \alpha_m & ,\alpha_u \\ \dots & \dots & \dots \\ \alpha_{1n} & \alpha_{mn} & ,\alpha_{un} \end{pmatrix}\right] \tag{5}$$

where n is the number of criteria.

$$\begin{cases} \alpha_l = l \times (m - l) + l \\ \alpha_u = u - l \times (u - m) \end{cases} \tag{6}$$

This is done by applying the Lambda function, which also represents the attitude of the evaluator. Evaluators with optimistic, moderate and pessimistic attitudes take on a maximum, intermediate, or minimum Lambda values in the range [0, 1] respectively:

$$W_j = \begin{pmatrix} W_j^1 \\ W_j^2 \\ \dots \\ W_j^k \end{pmatrix} \tag{7}$$

$$W_j = \lambda \times \alpha_u + (1 - \lambda) \times \alpha_l$$

where the W_j are crisp values corresponding to Lambda. These values should be normalized to acquire comparable scales.

3.3. Grey relational analysis

When the units in which an alternative is measured are different for different criteria, the influence of some criteria may be neglected. This may be the case if some performance criteria have a very large range. In addition, if the goals and directions of these criteria are different, it will cause incorrect results in the analysis process (Huang and Liao, 2003). Therefore, processing all performance values for every alternative into a comparability sequence, in a process analogous to normalization, is necessary. For an MCDM problem, if there are m alternatives and n criteria, the i_{th} alternative can be expressed as $Y_i = (y_{i1}, y_{i2} \dots y_{ij} \dots y_{in})$, where y_{ij} is the performance value of criteria j of alternative i. The term Y_i can be translated into the comparability sequence $X_i = (x_{i1}, x_{i2} \dots x_{ij} \dots x_{in})$.

$$X_{ij} = \frac{y_{ij}}{\mathrm{Max}\left\{y_{ij}, i = 1, 2, \dots, m\right\}} \text{for } i = 1, 2, \dots, m \;\; j = 1, 2, \dots, n \tag{8}$$

All performance values will be scaled into [0, 1]. For a criteria j of criteria I having an x_{ij} value (processed by grey relational generating procedure) equal to 1 or nearer to 1 than the value for any other alternative, the performance of alternative I is the best for the criteria j. Therefore, this implies that an alternative will be the best choice if all of its performance values are closest to or equal to 1. However, this kind of alternative does not usually exist. This study then defines the reference sequence X_0 as $(x_{01}, x_{02} \dots x_{0j} \dots x_{0n}) = (1, 1 \dots 1 \dots 1)$, and then aims to find the alternative with a comparability sequence closest to the reference sequence.

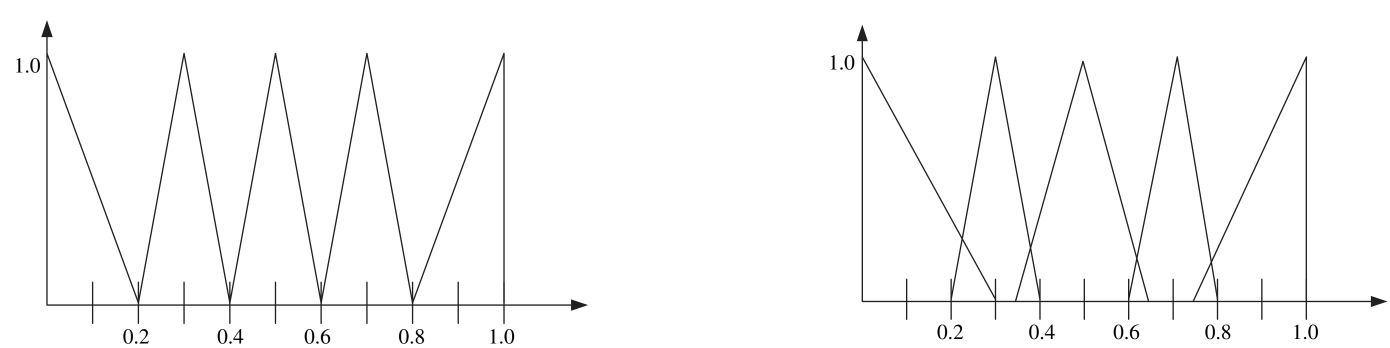
For each criterion, the total pair comparison fuzzy matrix from the defuzzification. The GRA coefficient is used for determining how close x_{ij} is to x_{0j}. A larger GRA coefficient translates to closer x_{ij} and x_{0j}. The GRA coefficient can be calculated as follows.

$$\gamma(x_{0j}, x_{ij}) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{ij} + \zeta\Delta_{\max}} \text{for } i = 1, 2, \dots, m \; j = 1, 2, \dots, n \tag{9}$$

In Eq. (9), $\gamma(x_{0j}, x_{ij})$ is the GRA coefficient between x_{ij} and x_{0j}, and

$$\begin{aligned} &\Delta_{ij} = \left|x_{0j} - x_{ij}\right|, \\ &\Delta_{\min} = \mathrm{Min}\left\{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\right\}, \\ &\Delta_{\max} = \mathrm{Max}\left\{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\right\}, \\ &\zeta \text{ is the distinguishing coefficient}, \; \zeta \in [0, 1] \end{aligned}$$

Table 1
Two linguistic variables for criteria and alternatives (importance and performance level).



(Criteria)	TFNs $\otimes G$	(Alternative)	TFNs $\otimes w$
VL	(0.00, 0.00, 0.20)	VP	(0.00, 0.00, 0.30)
L	(0.20, 0.30, 0.40)	P	(0.20, 0.30, 0.40)
M	(0.40, 0.50, 0.60)	F	(0.35, 0.50, 0.65)
H	(0.60, 0.70, 0.80)	G	(0.60, 0.70, 0.80)
VH	(0.80, 1.00, 1.00)	VG	(0.75, 1.00, 1.00)

Deng (1989) stated that the value of 0.5 is normally applied. After calculating for the grey relational coefficient $\gamma(x_{0j}, x_{ij})$, the grey relational grade can then be calculated.

$$\gamma(x_0, x_i) = \sum_{j=1}^{n} \beta_j \gamma(x_{0j}, x_{ij}) \text{ for } i = 1, 2, \ldots, m \quad (10)$$

Here, β_j denotes the normalized weight of criterion j where $\sum_{j=1}^{n} \beta_j = 1$and with equal weights. The proposed methodology that applies GRA to select the best supplier with respect to the GSCM is developed. The rank-ordering algorithm is applied to determine the ranking of the alternatives. The interactions of criteria are considered in this study.

The grey relational grade indicates the degree of similarity between the comparability sequence and the reference sequence (Fung, 2003). As mentioned of each criterion, the reference sequence represents the best performance that could be achieved by any among the comparability sequences. Therefore, if a comparability sequence for an alternative gets the highest grey relational grade with the reference sequence, it means that the comparability sequence is most similar to the reference sequence, and that alternative would be the best choice.

3.4. Proposed approach

This study attempts to apply the fuzzy set theory and GRA to the evaluation of 18 criteria. The study objective is to analyze how the proposed method can be used to determine criteria. The expert group followed the proposed solution with the five-step procedures.

1. Gather relevant information from a literature review and expert opinions; it is necessary to consult a group of experts to confirm the reliability of the GSCM measures.
2. Compose the evaluation GSCM criteria in qualitative and quantitative scale and confirm reliable criteria influences and directions. Transform the crisp numbers into comparable scale using Eq. (1).
3. Interpret the linguistic preferences into fuzzy linguistic scales. Use linguistic preferences to convert TFNs into crisp values, and then perform fuzzy assessments according to the definitions of Eqs. (2) and (3). Apply Eqs. (4)–(7) to remove the fuzziness and aggregate the measures into a crisp value (W_j).
4. Prepare factor compatibility (W_j) from multi-alternatives and criteria. Employ GRA to process all performance values for every alternative into a comparability sequence using Eq. (8).
5. Derive reference sequences. The entire GRA coefficient can be calculated using Eq. (9). Use Eq. (10) to determine the most weighted supplier from the grey relational grade.

4. Results

This section aims to execute the proposed evaluation method of the GSCM to the case firm. First, the case firm continues to improve its manufacturing processes and faces the challenge to manage the environmental management and SCM. Second, the case firm has to follow the criteria in the environmental regulations in order to deal with the green criteria in supplier selection. The expert team is composed of two professors, two vice-president and six management professionals with extensive experience in this field of study.

4.1. Case information

With the prosperous and expanding electronics market, more plants are built to supply IC substrates and subsequently enter IC packing industry to meet customer demand in related products in 2010. Currently, the firm is not only the largest professional printed circuit board (PCB) of original equipment manufacturing (OEM) in Taiwan, but is also ranked fifth worldwide. To offer the best service in green market, the PCB case firm continues to develop new generation technology and enhance competitiveness to fully satisfy the customer demands, and develop green products to comply with environmental regulations. With rapid product replacement and ease of development of new green technologies, GSCM presents as an option for the PCB firm to sustain a competitive edge in the market.

Hence, the chief executive officer of the firm wishes to deliberate on the role of GSCM, with special emphasis on green market. Therefore, the researchers presented this assessment to the expert group to develop the GSCM criteria. This evaluation aims to aid the firm establish competitiveness in the electronics market of the USA and EU countries by complying with requirements such as purchasing orders social responsibility and RoHS and WEEE Directives to acquire significant purchase orders. This study analyzes the four green suppliers in Taiwan with respect to GSCM criteria. The expert group identified an analytical and systematic way of evaluating the suppliers in management procedures. For better handling of this study problem, the ten expert group adopted possible evaluation from the criteria. The result of this study provides recommendations to the firm for effective and efficient GSCM implementation.

4.2. Empirical result

There are four alternatives $A_i = (i = 1, 2, 3, 4)$ against 18 criteria Cj $(j = 1, 2, 3\ldots18)$ as detailed in Fig. 1. The expert group followed a five-phase procedure, described below:

1. The relevant empirical information was identified and gathered to ensure that the objective was achievable and that the qualitative and quantitative measures are able to merge and be comparable. It was necessary to form an expert committee with knowledge of GSCM to achieve the objectives.
2. A set of measures for the case firm evaluation was established based on consultation with a group of experts whose role was to anticipate the influence of each measure.
3. Linguistic preferences were used to convert measures into TFNs (shown in Table 1), and the TFNs were converted into crisp values. Table 2 presents the fuzzy synthetic evaluation of 10 experts regarding linguistic preferences. For a criterion C1, the

Table 2
Example of fuzzy synthetic evaluation.

	l	m	u	α_l	α_r	C_λ	Ranking
C1	0.35	0.60	0.90	0.44	0.80	0.8375	**4**
C2	0.50	0.60	0.90	0.55	0.75	0.8650	**2**
C3	0.40	0.60	0.90	0.48	0.78	0.8425	**3**
C4	0.60	0.65	0.80	0.63	0.71	0.7000	12
C5	0.50	0.80	0.90	0.65	0.85	0.7500	9
C6	0.40	0.65	0.80	0.50	0.74	0.6200	15
C7	0.65	0.80	0.90	0.75	0.84	0.7913	7
C8	0.50	0.60	0.70	0.55	0.65	0.6000	17
C9	0.55	0.60	0.80	0.58	0.69	0.6338	14
C10	0.50	0.80	0.90	0.65	0.85	0.7500	10
C11	0.60	0.60	0.70	0.60	0.64	0.6200	16
C12	0.70	0.75	0.85	0.74	0.78	0.7575	8
C13	0.60	0.70	0.80	0.66	0.74	0.7000	13
C14	0.70	0.80	0.90	0.77	0.83	0.8000	6
C15	0.80	0.80	0.90	0.80	0.82	0.8100	**5**
C16	0.70	0.70	0.85	0.70	0.75	0.8775	**1**
C17	0.65	0.70	0.90	0.68	0.77	0.7263	11
C18	0.45	0.55	0.75	0.50	0.66	0.5775	18

total weighted performance matrix was constructed using Eq. (4) and (5). Eq. (6) was applied to arrive at the α_l and α_r. For instance, $i_l = 0.35 \times (0.6 - 0.35) + 0.35 = 0.44$, and $\alpha_r = 0.9 - 0.35 \times (0.9 - 0.6) = 0.8$. Lastly, the crisp value C_λ was computed using Eq. (7). Table 2 gives the result of this study.

4. Prepare criteria compatibility ($\tilde{T}$) from multi-alternatives and criteria and grey relational generating. Table 5 shows that the eigenvector derived from the four suppliers (A, B, C, D) for GRA input table. The main purpose of grey relational generating is transforming the original data into comparability sequences. The proposed criteria yielding a value (using Eq. (8)) closer to the desired value is considered better (the desired value being 1, shown in Table 3). For example, in the case of the C1 criteria, the maximum value is 0.65 from Alternative 3 and the minimum value is 0.48 from Alternative 4. Using Eq. (9) the results of grey relational generating of supplier A is equal to 0.48/0.65 = 0.738. The entire results of grey relational generating are shown in Table 4.
5. To derive reference sequences, the entire GRA coefficient can be calculated using Eq. (10). Calculation of grey relational coefficient and determination of the optimal supplier from the grey relational grade follows. In Table 5, X_0 is reference sequence. After calculating Δ_{ij}, Δ_{max} and Δ_{min}, all grey relational coefficients can be calculated. For example $\Delta C1 = |1 - 0.738| = 0.262$, $\Delta_{max} = 1$ and $\Delta_{min} = 0.16$, if $\zeta = 0.5$, then $\gamma(x_{0j}, x_{ij}) = (0 + 0.5 \times 1)/(0.262 + 0.5 \times 1) = 0.656$. The results for the grey relational coefficient are shown in Table 5.

The weights of the 18 criteria were all the same (1/18). Hence, the importance of all GSCM criteria was assumed to be equal. Using Eq. (10), the grey relational grade and ranking were calculated and are shown in Table 6. The result of the proposed fuzzy GRA procedure suggests that the priority green supplier is Alternative 3 with a GRA coefficient of 0.765. Next in rank is Alternative 4 with GRA coefficient 0.665. For comparison, the ranking results of all suppliers on GSCM criteria are shown in Table 6. However, another constraint of the firm pertains to the need to pick a single alternative as their optimal supplier prior to GSCM implementation. Moreover, the management level would like to know which of the criteria appear to be most critical to the case firm. Based on the results, the criteria ranking are C16 > C3 > C2 > C17 > C15 > C1 > C18 > C7 > C4 > C12 > C13 > C10 > C9 > C11 > C5 > C6 > C8 > C14. Although an optimal solution may not exist due to the MCDM nature of the proposed problem, the proposed method leads to the choice of alternative as a possible final supplier. The systematic evaluation of the MCDM problem can reduce the risk of a poor choice.

Table 3
C_λ for GRA input table andcriteria weights.

	Alternative 1		Alternative 2		Alternative 3		Alternative 4	
	C_λ	weight	C_λ	weight	C_λ	weight	C_λ	weight
C1	0.62	0.0499	0.58	0.0692	0.65	0.0910	0.48	0.0484
C2	0.65	0.0523	0.32	0.0382	0.68	0.0952	0.55	0.0554
C3	0.63	0.0507	0.35	0.0418	0.75	0.1050	0.56	0.0565
C4	0.67	0.0539	0.47	0.0561	0.24	0.0336	0.33	0.0333
C5	0.75	0.0603	0.22	0.0263	0.20	0.0280	0.65	0.0655
C6	0.62	0.0499	0.47	0.0561	0.20	0.0280	0.75	0.0756
C7	0.79	0.0636	0.27	0.0322	0.27	0.0378	0.45	0.0454
C8	0.60	0.0483	0.55	0.0656	0.19	0.0266	0.75	0.0756
C9	0.63	0.0507	0.58	0.0692	0.21	0.0294	0.75	0.0756
C10	0.75	0.0603	0.38	0.0453	0.22	0.0308	0.36	0.0363
C11	0.62	0.0499	0.62	0.0740	0.21	0.0294	0.45	0.0454
C12	0.76	0.0611	0.29	0.0346	0.24	0.0336	0.40	0.0403
C13	0.70	0.0563	0.45	0.0537	0.23	0.0322	0.55	0.0554
C14	0.80	0.0644	0.45	0.0537	0.19	0.0266	0.46	0.0464
C15	0.81	0.0652	0.71	0.0847	0.66	0.0924	0.68	0.0685
C16	0.72	0.0579	0.35	0.0418	0.78	0.1092	0.58	0.0585
C17	0.73	0.0587	0.77	0.0919	0.68	0.0952	0.65	0.0655
C18	0.58	0.0467	0.55	0.0656	0.54	0.0756	0.52	0.0524

Table 4
Results of grey relational generating for supplier alternatives.

X_0	Alternative 1	Alternative 2	Alternative 3	Alternative 4
C1	0.738	0.140	0.827	1.000
C2	0.848	1.000	0.690	0.882
C3	0.496	0.495	0.859	1.000
C4	0.493	0.141	0.712	1.000
C5	0.149	1.000	0.939	0.954
C6	0.728	1.000	0.427	0.148
C7	0.348	0.612	0.594	1.000
C8	0.218	0.539	1.000	0.948
C9	0.942	0.668	1.000	0.429
C10	0.354	0.170	1.000	0.570
C11	0.812	0.725	1.000	0.783
C12	0.487	0.742	0.604	1.000
C13	0.453	0.192	1.000	0.521
C14	0.176	0.239	1.000	0.032
C15	0.658	0.568	1.000	0.668
C16	1.000	0.822	0.4892	0.429
C17	1.000	0.355	0.940	0.249
C18	1.000	0.107	0.750	0.564

5. Managerial implications

The GSCM framework (having environmental and non-environmental criteria) can be used to evaluate the impact at various supplier selection activities and thus provide a mechanism to monitor and establish evaluation platform for the firms in green supply chain. Although previous studies report a great deal of varieties in GSCM measures, these varieties did not generally appear to have a clear link to a firm's decision contexts. Indeed, prior studies that stress only few variables, and single model or variables were not good enough to explain the criteria. The GSCM is the nature of multi-criteria concept and upstream or downstream selection in supply chain. Careful consideration on the effect on the organizational context must be made when evaluating the impact of introducing developed activities to a firm's overall production enhancement.

The proposed framework can provide managers and researchers a better understanding of the differences in the operations activities and specific management interventions that would improve

Table 5
Results of grey relational coefficient.

X_0	Alternative 1	Alternative 2	Alternative 3	Alternative 4
C1	0.656	0.365	0.738	1.000
C2	0.724	1.000	0.615	0.808
C3	0.596	0.578	0.759	1.000
C4	0.594	0.366	0.652	1.000
C5	0.467	1.000	0.891	0.914
C6	0.565	1.000	0.464	0.368
C7	0.552	0.561	0.551	1.000
C8	0.385	0.518	1.000	0.905
C9	0.794	0.599	1.000	0.465
C10	0.334	0.374	1.000	0.535
C11	0.625	0.643	1.000	0.690
C12	0.482	0.658	0.555	1.000
C13	0.495	0.380	1.000	0.509
C14	0.395	0.395	1.000	0.339
C15	0.492	0.534	1.000	0.599
C16	0.735	1.000	0.492	0.465
C17	1.000	0.434	0.892	0.398
C18	1.000	0.357	0.665	0.532

Table 6
The final result of optimal supplier and GSCM criteria ranking.

Order	Alternative 1			Alternative 2			Alternative 3*			Alternative 4		
	GRA	0.645		GRA	0.620		GRA	0.765		GRA	0.665	
	Criteria	C_λ	Weight	Criteria	C_λ	Weight	Criteria	C_λ	Weight	Criteria	C_λ	Weight
1	C15	0.81	0.0652	C17	0.77	0.0919	C16	0.78	0.1092	C6	0.75	0.0756
2	C14	0.80	0.0644	C15	0.71	0.0847	C3	0.75	0.1050	C8	0.75	0.0756
3	C7	0.79	0.0636	C11	0.62	0.0740	C2	0.68	0.0952	C9	0.75	0.0756
4	C12	0.76	0.0611	C1	0.58	0.0692	C17	0.68	0.0952	C15	0.68	0.0685
5	C5	0.75	0.0603	C9	0.58	0.0692	C15	0.66	0.0924	C5	0.65	0.0655
6	C10	0.75	0.0603	C8	0.55	0.0656	C1	0.65	0.0910	C17	0.65	0.0655
7	C17	0.73	0.0587	C18	0.55	0.0656	C18	0.54	0.0756	C16	0.58	0.0585
8	C16	0.72	0.0579	C4	0.47	0.0561	C7	0.27	0.0378	C3	0.56	0.0565
9	C13	0.70	0.0563	C6	0.47	0.0561	C4	0.24	0.0336	C2	0.55	0.0554
10	C4	0.67	0.0539	C13	0.45	0.0537	C12	0.24	0.0336	C13	0.55	0.0554
11	C2	0.65	0.0523	C14	0.45	0.0537	C13	0.23	0.0322	C18	0.52	0.0524
12	C3	0.63	0.0507	C10	0.38	0.0453	C10	0.22	0.0308	C1	0.48	0.0484
13	C9	0.63	0.0507	C3	0.35	0.0418	C9	0.21	0.0294	C14	0.46	0.0464
14	C1	0.62	0.0499	C16	0.35	0.0418	C11	0.21	0.0294	C7	0.45	0.0454
15	C6	0.62	0.0499	C2	0.32	0.0382	C5	0.20	0.0280	C11	0.45	0.0454
16	C11	0.62	0.0499	C12	0.29	0.0346	C6	0.20	0.0280	C12	0.40	0.0403
17	C8	0.60	0.0483	C7	0.27	0.0322	C8	0.19	0.0266	C10	0.36	0.0363
18	C18	0.58	0.0467	C5	0.22	0.0263	C14	0.19	0.0266	C4	0.33	0.0333

Note: * is presented the optimal selection.

the likelihood of excellent and useful research by examining the 18 criteria. The framework also provides for monitoring and control by management to track a firm's GSCM supplier selection dilemmas. For example, step five represents the overall importance of each of the alternatives based on the perception of evaluators. Here, the top five criteria crisp values (Table 6) are 1.environmental management systems (C16); 2.relationship supplier closeness (C3); 3.profitability of supplier (C2); 4.success rate of R&D green products (last 3 years average) (C17); and 5.reduce to use of hazardous products in production process (C15), respectively. Analysis of the GSCM criteria by expert team showed that supplier performance is determined mostly by environmental management systems (C16) and relationship supplier closeness (C3). The results help reduce management risks in GSCM practices.

Marazza et al. (2010) points out that the basis for evaluating the efficacy of an environmental management systems implementation should be the decrease in the number of high significance environmental aspects in addition to the management performance indicators, and the integration of environmental and non-environmental criteria in a single framework. Similarly, the study of Tseng et al. (2009c) on sustainable production indicators show two major criteria contributed to sustainable production which is to reduce amount of hazardous waste generated. In the broader sense, the framework can be used as an analytical and monitoring tool to develop and construct an overall environmental development strategy and criteria of the case firm or even other cases. As for management, it is beneficial for organizational managers to greatly understand GSCM evaluation that accounts for the linguistic preferences and incomplete information.

This study demonstrated that GSCM is not limited to the green technical aspects, but also on the non-environmental criteria. Through actual application of the framework, the managers are able to capture a fairly complete picture the context of GSCM implementation. In other words, operationalizing the framework for assessing the relative performance of the criteria in the environmental production and activities of managers proved to be useful for reviewing and improving sustainable evaluation and strategic development, which may lead to enhancing productivity and sustaining their competitive advantage.

In addition, several implications may be drawn for the case firm. The hierarchical model (Fig. 1) provides a useful guideline for GSCM implementation as a structured and logical means of synthesizing judgments for evaluating appropriate supplier for an OEM firm. It helps structure a difficult and often emotion-burdened decision. Secondly, the constructed framework, which has been modeled and examined through a comprehensive review within the firm's operational conditions, can be used for multi-criteria decision making. Moreover, the modeled aptly tailored for the case firm can easily be modified to suit and be applied to another firm's management activities. In this manner, evaluators need only to set relevant criteria to their firm in order to apply it. Consequently, the GSCM can be applied using different criteria, and can be further modified and refined if required.

6. Concluding remarks

This study focused on developing quantitative evaluation measures in uncertainty using fuzzy set theory. An outcome of representing linguistic preference in model formulation is that results are expressed as fuzzy set theory which reflects these uncertainties. Ultimately, the proposed 18 qualitative and quantitative criteria must be considered and evaluated simultaneously. Qualitative data is typically inaccurately depicted while the quantitative data needs to be transformed into a comparable scale. An evaluator's judgment cannot be always evaluated with exact numerical numbers. Hence, the linguistic expressions were transformed into crisp values. The hierarchical model also enables an evaluator to utilize quantitative method with inherent imprecision in weighting criteria. Using TFN to represent linguistic variables in dealing with subjective judgments by evaluators reduces the cognitive burden during the proposed evaluations. The defuzzification method developed by Pan (2008) is effective in the final weighting of each criterion by various evaluators. The above-mentioned methods are also useful for evaluating the final aggregate performance of case firm.

This study proposes a hybrid MCDM approach to deal with the alternatives problem in linguistic preferences, quantitative data and incomplete information. The method presented can be applied by electronic firms to evaluate and determine the criteria weights, and reduce the management risks. In summary, this study contributes to literature by: (i) proposing a GSCM hierarchical framework that integrates environmental and non-environment SCM criteria in a single framework; (ii) developing valid and reliable measures for the GSCM based on expert's qualitative preferences together with quantitative data; and (iii) developing a hybrid method to solve the supplier selection problem given linguistic constraints.

This empirical example of green supplier selection problem was used to resolve the proposed GSCM criteria in an OEM firm. The experimental result shows that the proposed approach is reliable and reasonable. Alternative 3 is the optimal solution out of the four evaluated green suppliers. The model can also easily and effectively accommodate criteria that are evaluated. This proposed model with a hierarchical structure and fuzzy measure establishes a foundation for future research and is appropriate for predicting uncertain criteria. Furthermore, the management can apply this model to evaluate and determine a firm's GSCM supplier selection to improve the firm's performance and provide the information that will have a great effect in reducing overall uncertainty and risks for management.

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