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# Improving sustainable supply chain management using a novel hierarchical grey-DEMATEL approach

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ABSTRACT

Sustainable supply chain management has been studied in the past. However, the previous studies lack proper justification for a multi-criteria decision-making structure of the hierarchical interrelationships in incomplete information. To fill this gap, this study proposes a hierarchical grey decision-making trial and evaluation laboratory method to identify and analyze criteria and alternatives in incomplete information. Traditionally, the decision-making trial and evaluation laboratory method does not address a hierarchical structure and involves incomplete information within its analytical method. However, the grey theory compensates for incomplete information. This study's purpose is to apply the proposed hierarchical structure to identify aspects of and criteria for supplier prioritization. This includes an original set of criteria for structuring the following: aspects as a sustainable plan, communities for sustainability, sustainable operational process control and sustainable certification and growth. The results present the recycle/reuse/reduce option as a tool to increase the material savings percentage, which is the top criterion for supplier selection. This study concluded that the hierarchical analytical method provides a strong basis for future academic and practitioner research.



## 1. Introduction

Sustainable supply chain management (SSCM) implements corporate responsibility practices and achieves a higher efficiency in logistics performance and resource usage when pursuing the three dimensions of sustainability, i.e., economic goals, social goals and environment goals (Seuring and Muller, 2008; Seuring et al., 2008; Seuring and Gold, 2013; Tseng and Hung, 2014). A firm must consider environmental impacts across the entire supply chain, including the selection of suppliers, distributors, and partners and customer awareness. In addition, sustainability requires the integration of environmental problems and solutions across a firm's functional boundaries. This functional interaction across functional areas includes a firm's strategy, product design, production and inventory management, marketing and distribution, and regulatory compliance (Lin and Tseng, in press). Previous literature has addressed SSCM by proposing many sensible models or evaluation frameworks (Ahi and Searcy, 2015; Bai and Sarkis, 2010; Carter and Rogers, 2008; Chaabane et al., 2012; Gold et al., 2010; Govindan et al., 2013; Tseng et al., 2014). As previously noted, successfully managing the SSCM lies in measuring and monitoring information regarding critical aspects, criteria and supplier selection. Hence, what is the proposed SSCM hierarchical structure, its critical aspects and the criteria for achieving supplier selection to fulfill a business goal?

SSCM has multiple aspects and needs multi-operational functions to achieve competitive advantages in intensive competitions. It is a challenging to present various aspects and criteria to facilitate the attainment of competitive changes. For instance, Gupta and Palsule-Desai (2011) suggested that SSCM adopt a firm perspective instead of a societal or policy-maker perspective and focus on organizational decisions related to the entire product life cycle,

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which involves design, production, distribution, consumer use, post-use recovery and reuse. SSCM can include practices within a supply chain network that provides green products, excellent service and accurate information. Traditionally, prior studies have claimed sustainability to be an aspect closely tied to SSCM effectiveness. Many studies have presented the multi-level structure to achieve economic performance and reduce environmental impacts simultaneously (e.g., Govindan et al., 2013; Tseng, 2013; Tseng and Hung, 2014). However, firms are deploying various SSCM criteria derived from cross-operational sections, preventing resources wasting or preventing excesses in operational functions. The existing literature fails to identify the proper criteria within a hierarchical structure. This clearly suggests that determining key SSCM criteria aligns with supplier selection.

What are the key SSCM aspects of and criteria for the hierarchical structure and interrelationships? Which supplier is the best alternative according to SSCM aspects and criteria? The available natural resources and the interrelationships between suppliers and customers are always a sustainability issue (Chaabane et al., 2012; Schaltegger, 1997). The SSCM decision-making process always has a hierarchical structure, and interrelationships exist between its aspects and innate criteria (Govindan et al., 2013; Mafakheri et al., 2011; Tseng, 2013). Appropriate fit between SSCM and supplier selection requires a basis for analyzing how aspects and criteria fit into hierarchical structures within interrelationships. Few prior studies have considered the hierarchical structure with interrelationships to resolve incomplete information (Tseng, 2009a, 2010). In the SSCM literature, Carter and Rogers (2008) presented a framework and developed research propositions based on resource dependence theory, transaction cost economics and the resource-based view of the firm; however, the practical qualitative and quantitative information and innate hierarchical structure are omitted. Govindan et al. (2013) determined a multi-layer structure with dependent and driving powers but omits a discussion on incomplete information. Nonetheless, one distinctive feature of SSCM emerges: a focal firm is pressured and, in turn, pressures its suppliers (Seuring and Muller, 2008; Tseng et al., 2013, in press). Here, the focal firm must utilize a set of hierarchical structures with incomplete information measures to identify the key criteria preventing resource overuse.

However, qualitative and quantitative information exists in operational functions. Hence, this information is necessary to scale. Moreover, either the hierarchical structure or incomplete information is always presented in previous studies (Koplin et al., 2007; Tseng and Hung, 2014; Lin and Tseng, 2014., Govindan et al., 2013; Tseng et al., 2014; Tseng et al., in press). For instance, Tseng et al. (in press) proposed a balanced scorecard to evaluate SSCM performance with hierarchical structure and uncertainty; the interrelationship of aspects, criteria and supplier selection are ignored. However, supplier selection is critical to SSCM, and the formation of the hierarchical structure from operational attributes is usually omitted (Büyüközkan and Çifçi, 2011; Kahraman et al., 2003; Lee et al., 2009; Sarkis and Talluri, 2002; Tseng et al., 2009; Govindan et al., 2013). Büyüközkan and Çifçi (2011) proposed a novel, fuzzy multi-criteria decision-making (MCDM) model for an effective sustainable supplier selection problem; this model considers the increasing complexity and uncertainty of the socio-economic environment. Seuring and Gold (2013) presented a focal firm's supplier selection and interrelationships among the supplier, customers and stakeholders. However, the previous studies fail to address hierarchical structure with interrelationships, supplier selection and incomplete information.

In summary, this study's objective is to assess SSCM and supplier selection by utilizing the proposed grey decision-making trial and evaluation laboratory method (DEMATEL) in a focal electronic firm in Taiwan. Thus, this study fills the existing literature gap and proposes a hierarchical structure that is based on a systematic approach to SSCM. This study's objective is to integrate the grey theory and DEMATEL methods in the focal firm, which has rarely occurred in SSCM literature. Concerning scientific contributions in the literature, this proposed criteria set will use factor analysis to clarify the structure's validity and reliability; in addition, the proposed set will show the origins and the initial assessment of the model's aspects and criteria. This analytical method will characterize SSCM as a hierarchical structure with interrelationships and incomplete information issues. The contribution includes (1) modeling the decision problem within the context of a proposed SSCM hierarchical structure; (2) incorporating hierarchical structure with interrelationships and incomplete information for decision-maker weighted relation schemes; and (3) transforming the qualitative and quantitative information into a comparable scale and applying grey theory to evaluate the incomplete information and the DEMATEL in measuring the interrelationships among the criteria.

This paper is organized as follows. This study discusses the shortcomings of the SSCM literature; the definitions of the grey theory, the DEMATEL and the proposed hybrid method are discussed in section 2. Section 3 presents the methods applied in this study. Section 4 shows the results of aspects, criteria and data analysis, which are based on the proposed steps. This discussion focuses on a hierarchical grey-DEMATEL model; aspects and the criteria are presented in quantitative and qualitative scales using a hierarchical structure with interrelationships and incomplete information. Section 5 presents the managerial and theoretical implications. The last section presents the discussion, implications, contributions, limitations, and conclusions.

## 2. Literature review

This session discusses the theoretical background of prior SSCM studies and the proposed method and measures.

### 2.1. Sustainable supply chain management

Sustainability management is defined as *"strategic business activities to minimize risks from environmental, economic, and social sustainability, to maximize corporate value including shareholder value"* (WBCSD, 2000; Tseng et al., 2008; Wong et al., 2014). Diaz-Garrido et al. (2011) noted that the competitive priorities in SSCM refer to the manufacturing units' objectives, which enable firms to compete, achieve capabilities established for the activity, and reinforce the firm's competitive advantage. Lin and Tseng (in press) determined that dynamic flexibility in operations has become a competitive necessity for firms in SSCM. Chardine-Baumann and Botta-Genoulaz (2014) noted that sustainable development in supply chain management has been identified to be not only a constraint but also an approach for improving performance; this impacts a firm's competitiveness and its supply chain organizations. Although the SSCM concept and framework have been developed, the combination of incomplete information methods and interrelationships exist to distort the decision-making process at the firm and industry levels; this decision-making involves the monitoring and evaluation of business operations' impact on the environment and society (Koplin et al., 2007; Lee, 2011; Lee and Saen, 2012). The firm must address MCDM problems, such as sourcing green materials, green-technology applications and supplier selection, to enhance their competitive advantage. The evaluation approach must consider incomplete information and interrelationships as a whole; however, incomplete information and interrelationships are innately present in an organization. This

SSCM approach was omitted in prior studies (Seuring et al., 2008; Carter and Rogers, 2008; Lin and Tseng, in press; Tseng et al., in press).

In the literature on SSCM, greening the supply chain encourages efficiency and synergy between partners and facilitates environmental performance, minimal waste, and cost savings (Rao and Holt, 2005; Linton et al., 2007). Therefore, SSCM requires the incorporation of the economic, environmental, and social perspectives of business practices and theory (Carter and Rogers, 2008; Hassini et al., 2012; Ahi and Searcy, 2015). Many studies propose comprehensive SSCM frameworks, for instance, Srivastava (2007) made a significant attempt to address SSCM, including product design, material source and selection, manufacturing process, final product delivery to the consumer, and end-of-life product management after its useful life. Carter and Rogers (2008) presented an SSCM framework and developed propositions based on resource dependence theory, transaction cost economics, population ecology and the resource-based view of the firm to consider key supporting facets that are posited as requisites for implementing SSCM practices. Liu et al. (2012) proposed a new hub-and-spoke integration model to integrate green marketing and SSCM from six dimensions: product, promotion, planning, process, people, and project. Manzini and Accorsi (2013) proposed an integrated approach to control the quality, safety, sustainability, and logistics efficiency of food products and processes throughout the entire supply chain. However, previously noted studies focus the discussion to determine the aspects and criteria in the hierarchical structure (Caniato et al., 2012; Lin and Tseng, in press; Tseng et al., in press; Seuring and Gold, 2013). Few studies in the MCDM field have addressed the building of the hierarchical structure with interrelationships and incomplete information with validity and reliability.

Moreover, for Zhu and Geng (2001), environmental components of supplier selection is a key competitive issue for large and medium-sized enterprises and thus should be considered to maintain long-term relationships with suppliers. Hsu and Hu (2009) applied the analytic network process to construct an evaluation model of supplier selection; the model included five main criteria: procurement management, research and development management, process management, quality control and a management system. Govindan et al. (2013) integrated a number of sustainability aspects into the supplier selection analytical model. Kannan et al. (2014) propose supplier selection based on the supplier's adoption of green supply chain management practices. However, the interrelationships have not been addressed in certain studies, and others do not address the hierarchical issues (Gold et al., 2010; Hsu et al., 2013). The literature presents the suppliers, customers and manufacturers that maintain a long-term relationship and present interrelationships within operational functions (Chang et al., 2011; Lee et al., 2009; Mafakheri et al., 2011; Punniyamoorthy et al., 2011). In summary, in the supplier selection, the analytical method should address the SSCM hierarchical structure simultaneously with interrelationships and incomplete information.

### 2.2. Methods applied in the literature

Moreover, SSCM has achieved social and environmental touchstones within supply chain networks that may increases competitiveness. However, supplier selection involves an important issue: the selection of toxic-free raw materials or parts outsourcing without hazardous materials (Amindoust et al., 2012; Bai and Sarkis, 2010; Büyüközkan and Çifçi, 2011; Seuring and Muller, 2008). In addition, SSCM aspects and criteria play a critical role in filtering suppliers; this may induce more social, economic and environmental interrelationships simultaneously (Kahraman et al., 2003; Lee et al., 2009; Mafakheri et al., 2011; Punniyamoorthy et al., 2011; Sarkis and Talluri, 2002). There are studies that utilize the DEMATEL method to address the interrelationships. For instance, Hsu et al. (2013) presented a carbon management model for supplier selection in green supply chain management with interrelationships among the supplier selection evaluation criteria. Chang et al. (2011) proposed fuzzy numbers and DEMATEL in supplier selection under a well-designed supply chain management system. However, this method continues to lack the ability to address the hierarchical structure in the analysis. In recent studies, Kannan et al. (2014) use this fuzzy technique for order preference to simulate an ideal solution (TOPSIS) for selecting green suppliers based on green supply chain management practices. Govindan et al. (2013) presented qualitative performance evaluation to rank suppliers utilizing fuzzy TOPSIS. However, the prior studies omit discussion of the interrelationships and hierarchical structure in decision-making. Thus, proposing a mathematical analytical approach to address the interrelationships, hierarchical structure and incomplete information remains a challenge.

In the mathematical models, Michelsen et al. (2006) applied eco-efficiency as an instrument to measure all processes in the product life cycle and to measure the relative environmental sustainability and value performance in extended supply chains. Tseng (2009a) proposed a cause and effect decision-making model using the grey-fuzzy DEMATEL approach that omits the hierarchical structure. Tseng (2009a) proposed an analytical network process and DEMATEL to address hierarchical structure; however, this still omits incomplete information. Bai and Sarkis (2010) utilized the grey system and the rough set theory to explicitly consider sustainability attributes; in addition, they introduced a multi-stage grey system and rough set approach that considers economic, environmental, and social factors for selecting sustainable suppliers. Shaverdi et al. (2013) applied the fuzzy analytic hierarchy process approach to evaluate sustainability in supply chain management. Tseng and Hung (2014) applied the proposed linear model to facilitate the understanding of optimal supply chain strategies by considering emissions' social costs in decision-making processes. Chardine-Baumann and Botta-Genoulaz (2014) proposed a multi-level analytical assessment model for SSCM performance, which can be easily implemented by practitioners that employ the proposed framework to positively emphasize the impact of sustainable performance. This discussion leads to the issue of which criteria are commonly applied in the SSCM model with interrelationships; in addition, this discussion leads to the building of a comprehensive hierarchical structure model for incomplete information that exists in the analytical process.

### 2.3. Proposed criteria

SSCM allows firms to implement corporate sustainability practices and achieve a higher efficiency in operational performance and resource usage while pursuing the three sustainability perspectives, i.e., economic, social and environment perspectives (Linton et al., 2007; Tseng et al., in press). Sustainability is the use of natural resources. Sustainability factors into the firm's strategic environmental plan, economic performance, and life cycle assessment (C12) to systemically coordinate internal business processes to improve the long-term performance of the individual firm and its supply chains. The comparisons of profit margin between pre- and post-SSCM practices measure the success of the implementation (C2). The firm thus increases its competitive advantage by being proactive with regard to SSCM. In this context, firms must integrate sustainable practices with supplier management (Linton et al., 2007; Bai and Sarkis, 2010).

In a supply chain, firms emphasize their sustainability and outsource activities to their suppliers. Suppliers play an essential

**Table 1**
Linguistic scales for the importance relation of criteria.

| Linguistic variable | Corresponding grey ($\otimes$v) |
|---|---|
| Very low (VL) | (0.0, 0.3) |
| Low (L) | (0.3, 0.5) |
| Medium (M) | (0.3, 0.7) |
| High (H) | (0.5, 0.9) |
| Very high (VH) | (0.7, 1.0) |

Note: this table is the linguistic scale and their corresponding get numbers (Chen, 2000).

role in sustainability development; thus, suppliers must be carefully evaluated and selected (Tseng et al., 2008). Hence, supplier selection requires various key criteria (Gupta and Palsule-Desai, 2011; Koplin et al., 2007). Preuss (2005) outlined the environmental benefits from partners in the supply chain; this indicates that the upstream and downstream partners play a key role in supply chain performance such as monitoring the following: total supply chain cycle time (C21), supplier environmental standards (C10) and supplier's operational procedures (C11). Firms depend on suppliers to enhance their environmental standards and integrate operational procedures into entire supply chain networks. Lambert et al. (2006) wrote that SSCM refers to "the integration of key business processes from end-user through original suppliers that provides products, services, and information that add value for customers and others".

Nonetheless, assessing the corporate sustainability plan in detail, e.g., considering which metrics are suitable for capturing sustainability attributes in informal SSCM and which criteria are used in a holistic SSCM, would identify which avenues could help further integrate holistic measures and the resulting social performance impacts. Consequently, a firm typically prioritizes the evaluation of the business' social impact (C8), such as community investment in sustainability (C9) and signing a code of conduct or voluntary initiatives (C6). Moreover, customers are aware of their personal environmental impact and environmental friendliness (C1); they are willing to pay more for green purchases (C13) (Rao, 2002; Rao and Holt, 2005). A firm must increase employee awareness as a precondition for overall SSCM success (C20). The employees are educated when firms are in an environmental certification application process such as ISO14001 and carbon footprint (C22).

For internal business processes, reducing the environmental impact puts great emphasis on corporate sustainability development in a competitive and sustainable market (C7). The environmental dimension includes the consumption of natural resources and waste and pollution emissions (C5) (Tang and Zhou, 2012). Specifically, Tseng et al. (2013) identified the sustainable production indicators for overhauling the production process to achieve the firm's goal of waste elimination (C16), decrease the generation of toxic and hazardous matters (C18), monitor energy consumption (C15), reduce the water consumption percentage (C14) and Recycle/Reuse/Reduce to increase the material savings percentage. Moreover, a green design is characterized by a key rule: it should be designed to close the material loops to minimize the impact on the environment (C17) (Tseng et al., 2013; Wang et al., 2014). Hence, green design in operations and products is primarily influenced by the fact that green products can be disassembled, reused or recycled for raw materials and are free from hazardous materials (C4) (Tang and Zhou, 2012; Wang et al., 2014). The revenues from green products must be measured as economic performance (C3) (Tseng and Hung, 2014).

To understand corporate sustainability development, research and development for green technology improvements (C19), friendly management systems, and environmental certificates are needed. As noted, the proposed criteria are derived from the literature, including the business activities, components and characteristics that are found to be associated with these proposed measures. Table 2 presents the criteria. This study applies exploratory factor analysis to acquire the hierarchical structure for further decision-making analysis.

## 3. Method

This session discusses the definitions of grey theory and DEMATEL and proposes hierarchical grey-DEMATEL as follows:

**Table 2**
Validity and reliability tests for measures.

| Named aspects | Criteria | | Loading | Reliability coefficient |
|---|---|---|---|---|
| Sustainable plan | C1 | Encourage customers to be environmentally friendly in the property. | 0.841 | 0.916 |
| | C2 | Comparisons of profit margin between after and before SSCM implementation (Quantitative Scale) | 0.816 | |
| | C3 | Revenues from green products (Quantitative Scale) | 0.796 | |
| | C4 | Recycle/Reuse/Reduce for material saving percentage (Quantitative Scale) | 0.783 | |
| | C5 | Reduce carbon emissions per quarter (Quantitative Scale) | 0.739 | |
| Communities for sustainability | C6 | Signing the code of conducts or voluntary initiatives | 0.817 | 0.782 |
| | C7 | Corporate sustainability development | 0.735 | |
| | C8 | Evaluates the social impact of the business. | 0.721 | |
| | C9 | Community investment in sustainability | 0.694 | |
| | C10 | Supplier environmental standards | 0.652 | |
| | C11 | Supplier's booking in operational procedures | 0.606 | |
| Sustainable operational process controlling | C12 | Life cycle assessment performed | 0.856 | 0.852 |
| | C13 | Green purchasing | 0.824 | |
| | C14 | Reduced percentage of water consumption (Quantitative Scale) | 0.792 | |
| | C15 | Monitoring energy consumption | 0.756 | |
| | C16 | Waste volume decreases by percentage (Quantitative Scale) | 0.732 | |
| | C17 | Green design in operations and products | 0.707 | |
| | C18 | Decrease the generation of toxic and hazardous matters (Quantitative Scale) | 0.658 | |
| Sustainable certificates and growth | C19 | Research & development for green technologies | 0.895 | 0.768 |
| | C20 | Employee awareness | 0.836 | |
| | C21 | Total supply chain cycle time (Quantitative Scale) | 0.785 | |
| | C22 | Environmental certificates (ISO 14000, carbon footprint etc) | 0.736 | |

Note: percentage of total variance is 75.3% and KMO = 0.63.

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### 3.1. Transformation of the quantitative data

The crisp values derived from the operational measures are characterized by various units that cannot be directly compared to quantitative scales. The crisp values must be transformed to achieve comparable unit-free criteria values. The transformed crisp values of $C_{ij}$ are calculated using Eq. (1) (Tseng et al., 2009, 2013).

$$T_{ij} = \left(t_{ij}^{N} - \min t_{ij}^{N}\right) \Big/ \left(\max t_{ij}^{N} - \min t_{ij}^{N}\right)\ T_{ij} \in (0,1); \quad N = 1, 2, \ldots n, \tag{1}$$

where $\max T_{ij}^{N} = \max\{t_{ij}^{1},\ t_{ij}^{2}, \ldots t_{ij}^{N}\}$ and $\min T_{ij}^{N} = \min\{t_{ij}^{1}, t_{ij}^{2}, \ldots . t_{ij}^{N}\}$.

### 3.2. Grey theory

Grey theory is a mathematical theory derived from the grey set (Deng, 1982). It is an effective method for solving uncertainty problems with discrete data. This study applies basic grey definitions and a grey number (Zhang et al., 2005; Chen and Tzeng, 2004). Let $S$ be the universal set.

**Definition 1.** A grey set $X$ of $S$ is denoted by its two mappings $\widehat{\sigma}_X(s)$ and $\breve{\sigma}_X(s)$.

$$\begin{cases} \widehat{\sigma}_X(s) \\ \breve{\sigma}_X(s) \end{cases}, s \to [0,1], \quad \text{where } \widehat{\sigma}_X(s) \geq \breve{\sigma}_X(s), s \in S, S = R. \tag{2}$$

**Definition 2.** The $\widehat{\sigma}_X(s)$ and $\breve{\sigma}_X(s)$ represent the upper and lower membership functions in the grey set $X$. If $\widehat{\sigma}_X(s) = \breve{\sigma}_X(s)$, the grey set $X$ can consider a fuzzy condition and address the flexibility of the uncertain status. The criteria ratings are described by the grey number $\otimes X(\otimes X = X|_{\breve{\sigma}}^{\widehat{\sigma}})$.

**Definition 3.** The lower and upper limits of $X$ can be estimated; $X$ is defined as a lower limit grey number.

$$\left(-\infty, \widehat{X}\right] = \otimes X = \left[\breve{X}, \infty\right) \tag{3}$$

**Definition 4.** The $X$ lower and upper limits can be estimated and defined as an interval grey number.

$$\otimes X = \left[\breve{X}, \widehat{X}\right] \tag{4}$$

**Definition 5.** The grey numbers are presented as $\otimes X_a = [\breve{X}_a, \widehat{X}_a]$ and $\otimes X_b = [\breve{X}_b, \widehat{X}_b]$ on intervals in which the basic operations on the grey interval represent the exact range of the corresponding operation.

$$\begin{cases} \otimes X_a + \otimes X_b = \left[\breve{X}_a + \breve{X}_b, \widehat{X}_a + \widehat{X}_b\right] \\ \otimes X_a - \otimes X_b = \left[\breve{X}_a - \breve{X}_b, \widehat{X}_a - \widehat{X}_b\right] \end{cases} \tag{5}$$

**Definition 6.** The interval of the grey number $\otimes X$ is defined as

$$\mu(\otimes X) = \left[\breve{X} - \widehat{X}\right] \tag{6}$$

**Definition 7.** For the two grey numbers $\otimes X_a = [\breve{X}_a, \widehat{X}_a]$ and $\otimes X_b = [\breve{X}_b, \widehat{X}_b]$, the possible degree of $\otimes X_a \leq \otimes X_b$ can expressed as follows

$$p\{\otimes X_a \leq \otimes X_b\} = \frac{\left(\max\left(0, \mu' - \max\left(0, \widehat{X}_a - \breve{X}_b\right)\right)\right)}{\mu'} \tag{7}$$

where $\mu' = \mu(\otimes X_a) + \mu(\otimes X_b)$; the positive relation between $\otimes X_a$ and $\otimes X_b$ is determined as follows:

1. If $\breve{X}_a = \breve{X}_b$ and $\widehat{X}_a = \widehat{X}_b$, that is, $\otimes X_a = \otimes X_b$, then $p\{\otimes X_a \leq \otimes X_b\} = 0.5$.
2. If $\breve{X}_b > \widehat{X}_a$, that $\otimes X_b > \otimes X_a$, then $p\{\otimes X_a \leq \otimes X_b\} = 1$.
3. If $\widehat{X}_b < \breve{X}_a$ and $\widehat{X}_a > \widehat{X}_b$, that is $\otimes X_b < \otimes X_a$, then $p\{\otimes X_a \leq \otimes X_b\} = 0$.
4. If an intercrossing part exists when $p\{\otimes X_a \leq \otimes X_b\} > 0.5$, then $\otimes X_b > \otimes X_a$. When

$$p\{\otimes X_a \leq \otimes X_b\} < 0.5, \quad \text{then } \otimes X_b < \otimes X_a. \tag{8}$$

### 3.3. DEMATEL

The Decision Making Trial and Evaluation Laboratory (DEMATEL) method is particularly practical and useful for visualizing the structure of complicated causal relations with matrices or digraphs (Fontela and Gabus, 1976). The matrices or digraphs portray a contextual relation between system elements, in which a numeral represents the strength of influence. Thus, this method can be used to convert the relations between criteria's causes and effects into a structural mapping model. The essentials of the DEMATEL method assume that a system contains a set of criteria $C = \{C_1, C_2, \cdots, C_j\}$ and that the particular pairwise relations are determined for modeling with respect to a mathematical relation. In a real situation, a hierarchical structure with incomplete information always exists (Tseng, 2009a; b; c). This study proposes a hybrid approach named the hierarchical grey-DEMATEL.

### 3.4. Proposed hierarchical grey-DEMATEL

A grey system is a system that contains uncertain information represented by a grey number. A grey possibility degree is proposed for ordering the preference ranking (Tseng, 2010). The ranking of a decision-making problem is uncertain. Assume that $At = \{At_1, At_2, \cdots, At_i\}$ is a discrete set of m alternatives. $C = \{C_1, C_2, \cdots, C_j\}$ is a set of n criteria. The criteria are additively independent, and $\otimes \nu = \{\otimes \nu_1, \otimes \nu_2, \cdots, \otimes \nu_j\}$ is the vector of criteria relations. The concept of a grey-DEMATEL system is shown in Fig. 1.

The criteria and ratings of alternative relations, which are considered the number scale and criteria relations, can be expressed in grey numbers, as shown in Table 1 (Chen and Tzeng,

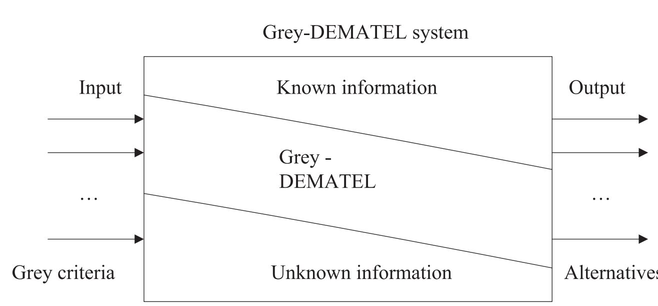


**Fig. 1.** The concept of a grey-DEMATEL system.

2004). The expert opinions with TFNs can be constructed based on Eq. (1). The procedures are summarized as follows:

Step 1. A sample group of experts identified the criteria relations. Assume that a decision group has $h$ respondents; the criteria relations $\nu_n$ can be calculated as

$$\otimes \nu_n = \frac{1}{h}\left(\otimes \nu_j^1 + \otimes \nu_j^2 + \cdots + \otimes \nu_j^h\right), \tag{9}$$

where $\otimes \nu_n^h$ $(n = 1, 2, \cdots, j)$ is the criteria relation of $h$th experts, which can be described as $\otimes \nu_n^h = [\underset{n}{\overset{h}{\breve{\nu}}}, \widehat{\nu}_n^h]$.

Step 2. Use the grey number for the rating to create a criteria rating value. The rating value can be calculated as

$$\otimes X_{ij} = \frac{1}{h}\left[\otimes X_{ij}^1 + \otimes X_{ij}^2 + \cdots + \otimes X_{ij}^h\right], \tag{10}$$

where $\otimes X_{ij}^h (i = 1, 2, \cdots m;\ j = 1, 2, \cdots n)$ is the criteria relation of $h$th experts, which can be described by grey number $\otimes X_j^h = [\otimes \underset{j}{\overset{h}{\breve{X}}}, \otimes \widehat{X}_j^h]$.

Step 3. Establish the grey direct relation decision matrix ($G$), in which $i$ affects the criteria $j$.

$$G = \begin{bmatrix} \otimes X_{11} & \otimes X_{12} & \cdots & \otimes X_{1j} \\ \otimes X_{21} & \otimes X_{22} & \cdots & \otimes X_{2j} \\ \vdots & \vdots & \cdots & \vdots \\ \otimes X_{i1} & \otimes X_{i2} & \cdots & \otimes X_{ij} \end{bmatrix}_{m \times n}, \tag{11}$$

where $\otimes X_{ij}$ are based on the grey number.

Step 4. Normalized the grey relation decision matrix ($G'$)

$$G' = \begin{bmatrix} \otimes X'_{11} & \otimes X'_{12} & \cdots & \otimes X'_{1j} \\ \otimes X'_{21} & \otimes X'_{22} & \cdots & \otimes X'_{2j} \\ \vdots & \vdots & \cdots & \vdots \\ \otimes X'_{i1} & \otimes X'_{i2} & \cdots & \otimes X'_{ij} \end{bmatrix}_{m \times n}. \tag{12}$$

For the benefit criteria, $\otimes X_{ij}^b$ is expressed as

$$\otimes X_{ij}^b = \left[\frac{\underset{ij}{\breve{X}}}{X_j^{max}}, \frac{\widehat{X}_{ij}}{X_j^{max}}\right], X_j^{max} = \max_{1 \le i \le m}\left\{\widehat{X}_{ij}\right\}. \tag{13}$$

For the cost criteria, $\otimes X_{ij}^c$ is expressed as

$$\otimes X_{ij}^c = \left[\frac{X_j^{min}}{\widehat{X}_{ij}}, \frac{X_j^{min}}{\underset{ij}{\breve{X}}}\right], \quad X_j^{min} = \min_{1 \le i \le m}\left\{\underset{ij}{\breve{X}}\right\}, \tag{14}$$

where $x_j^{max} = \max_i\{x_{ij}, i = 1 \cdots x\}$ and $x_j^{min} = \min_i\{x_{ij}, i = 1 \cdots x\}$. However, the decision group contains $t$ respondents, and the normalization preserves the property that enables the ranges of the normalized grey number to belong to $[0, 1]$

The reference series can be acquired as follows:

$$R_{max} = (1, 1), (1, 1) \cdots, (1, 1)$$

$$R_{min} = (0, 0), (0, 0) \cdots, (0, 0)$$

$$\delta_{ij}^{(max)} = \sqrt{\frac{1}{2}\left(\frac{\underset{ij}{\breve{X}}}{X_j^{max}} - 1\right)^2 + \left(\frac{\widehat{X}_{ij}}{X_j^{max}} - 1\right)^2}$$

$$\delta_{ij}^{(min)} = \sqrt{\frac{1}{2}\left(\frac{X_j^{min}}{\widehat{X}_{ij}} - 0\right)^2 + \left(\frac{X_j^{min}}{\underset{ij}{\breve{X}}} - 0\right)^2} \tag{15}$$

The distance $\delta_{ij}$ between the reference value and each comparison value can be formulated. This study for transforming the grey weights into the crisp weights applies the average method, which is a simple and practical method to calculate the best non-grey performance (BNP) value of the grey weights of each aspect.

Step 5. Establish the relation normalized grey-DEMATEL decision matrix($M^*$). Considering the different importance of each criterion, the relation normalized grey decision matrix can be established as

$$M^* = \begin{bmatrix} \otimes \delta_{11} & \otimes \delta_{12} & \cdots & \otimes \delta_{1j} \\ \otimes \delta_{21} & \otimes \delta_{22} & \cdots & \otimes \delta_{2j} \\ \vdots & \vdots & \cdots & \vdots \\ \otimes \delta_{i1} & \otimes \delta_{i2} & \cdots & \otimes \delta_{ij} \end{bmatrix}_{m \times n}, \tag{16}$$

where $\otimes \delta_{ij} = \otimes X'_{ij} \times \tau$, $\tau = \frac{1}{(\max_{1 \le i \le m} \sum_{j=1}^{n} \delta_{ij})}$.

Step 6. The normalized direct-relation matrix $M^*$ is obtained, and the total relation matrix $T$ can be acquired by Eq. (17)

$$T = M^*\left(I - M^*\right)^{-1}, \tag{17}$$

where $I$ is denoted as the identity matrix.

The sum of the rows and columns, which are separately obtained, are denoted as vectors D and R, respectively, using Eqs. (18)–(19). The causal diagram is composed by (D, R)

$$T = [t_{mn}]_{\ell \times \ell}, \quad m, n = 1, 2, \cdots, \ell \tag{18}$$

$$\begin{cases} D = \left[\sum_{i=1}^{m} t_{mn}\right]_{\ell \times 1} = [r_i]_{\ell \times 1} \\ R = \left[\sum_{j=1}^{n} t_{mn}\right]_{1 \times \ell} = [r_j]_{1 \times \ell} \end{cases} \tag{19}$$

Step 7. Use the ideal alternative $(\delta_{ij}^{(max)}, \delta_{ij}^{(min)})$ as a referential alternative. For $i$ possible alternatives set $At = \{At_1, At_2, \cdots, At_i\}$ as the ideal referential alternative $At^{max} = \{\otimes X_1^{max}, \otimes X_2^{max}, \cdots, \otimes X_n^{max}\}$ can be obtained by

$$At^{max} = \left\{\left|\max_{1 \le i \le m} \underset{i1}{\breve{\delta}}, \max_{1 \le i \le m} \widehat{\delta}_{i1}\right|, \left|\max_{1 \le i \le m} \underset{i2}{\breve{\delta}}, \max_{1 \le i \le m} \widehat{\delta}_{i2}\right|, \cdots, \left|\max_{1 \le i \le m} \underset{in}{\breve{\delta}}, \max_{1 \le i \le m} \widehat{\delta}_{in}\right|\right\}. \tag{20}$$

Step 8. Calculate the grey-DEMATEL possibility degree among the compared alternatives; set $At = \{At_1, At_2, \cdots, At_i\}$ and the ideal alternative $At^{max}$.

$$p\{At_i \leq At^{max}\} = \frac{1}{n}\sum_{i=1}^{n} p\{\otimes\delta_{ij} \leq \otimes X_i^{max}\} \tag{21}$$

Step 9. Rank the order for alternatives. When $p\{At_i \leq At^{max}\}$ is smaller, the ranking order of $At_i$ is better.

## 4. Results

This section presents the case's background and addresses how the SSCM is important to the case study; in addition, the analytical results are presented in the sub-section. This section focuses on case background and analytical results.

### 4.1. Case background

A Taiwanese electronic manufacturing focal firm is used to evaluate SSCM measurement. This firm is globally famous for producing mobile phones and computer pads and exports electronic products throughout the world. Hence, the SSCM is relatively important for this focal firm. This firm has been continuously making product innovation; it has remarkable green products and incorporates social responsibility into its supply chain network. The evaluation aspects and criteria are extracted from the firm's operational process and literature. This firm continuously enhances its competitiveness, completely satisfying the market and customer demands by developing a global and systematic supply chain.

This evaluation is challenging because of the relevant quantity of operational information. This study needs to transform real data into a comparable scale. In recent years, initial green practices adhere to regulatory green requirements. Recently, social responsibility has received greater exposure. This firm utilizes corporate social responsibility to enhance its social image. This study is evaluated by an expert group, which includes ten professors and ten industrial practitioners with extensive experience. This study applies grey theory to address incomplete information in the operations and uses the DEMATEL to evaluate the criteria performance in SSCM.

In addition, this study employs factor analysis to test the framework's validity and reliability. This study tests the appropriateness of proposed analytical tools and applies a proposed hybrid method to evaluate the SSCM aspects and criteria for a hierarchical structure in incomplete information. The aspects and criteria innately exhibit a hierarchical structure; in addition, interrelationships exist among the criteria. Table 2 presents the proposed evaluation and the aspects, criteria and exploratory factor analysis results.

### 4.2. Proposed measures

The evaluation measures were pre-tested for content validity in two stages: (1) Six experienced experts were requested to critique the questionnaire for ambiguity, clarity and appropriateness of the items used to operationalize each aspect and to enhance the clarity and appropriateness of the measures purporting. (2) These industrial and academic experts were requested to review the structure, readability, ambiguity and completeness of the measures. The exploratory factor analysis is anticipated in the initial stage to confirm the Validity and reliability tests for aspects and criteria. This process yielded a survey instrument that was determined to exhibit high validity (percentage of total variance is 75.3% and KMO = 0.63) and reliability ($\alpha > 0.7$). Table 2 is presented a hierarchical structure. The aspects and criteria are used to construct the theoretical hierarchical structure based on an extensive review of related literature.

This approach was proposed for ordering supplier preference by human preferences. Four alternatives-$At_i$ (i = 1,2, …,4)-were evaluated utilizing 22 criteria $C_j$ (j = 1,2,3 … .,22), which include four suppliers. The criteria are additively independent. The criteria weights and alternative ratings are considered linguistic preferences and incomplete information. The criteria rating $\otimes v$ is expressed in grey numbers, and the definitions are presented in definitions (1)–(6) and Eqs. (2)–(6). The proposed computational procedures are summarized as follows.

Step 1. Qualitative and quantitative scales are derived from the grey numbers and operational information. Therefore, this study must transform the quantitative scales into comparable scales using Eq. (1). In addition, this study tested the validity and reliability of measures and applied factor analysis to acquire four aspects, as shown in Table 2. These aspects are named Sustainable plan (As1), Communities for sustainability (As2), Sustainable operational process control (As3) and Sustainable certificates and growth (As4). The weights of the criteria were $C_j$ (j = 1,2,3 … ,22). The experts expressed their preferences to select the proposed supplier. From Eq. (9), the evaluation criteria weights can be obtained, and the results are summarized and shown in Table 3.
Step 2. Weighting the criteria rating for aspects by applying Eq. (10), the results of the criteria rating value can be transformed from the linguistic preferences. This transformation is shown in Table 1. Twenty experts reflect on the relations among the aspects and the criteria. Table 4 presents the grey direct relation decision matrix.
Step 3. Based on Eq. (11), the grey relation decision matrix of the criteria to the aspects can be obtained, as shown in Table 5.
Step 4. Based on Eq. (12), the normalized grey decision matrix can be obtained. The grey normalized decision table is shown in Table 6. For example, 0.421 × 0.483 = 0.203 and 0.920 x 0.810 = 0.745.

In addition, the cost and benefit distance computations need to contract with the reference values using Eqs. (13) and (14). The distance values between the benefit and the cost matrices are acquired from Eq. (15). The sequence of aspect BNP value is as follows: As1 (0.357), As3 (0.348), As4 (0.158), As2 (0.137). Table 7 presented

**Table 3**
Criteria weights.

| $C_j$ | $Exp_1$ | $Exp_2$ | … | $Exp_{19}$ | $Exp_{20}$ | $\otimes v_n$ | $\otimes X_{ij}$ |
|---|---|---|---|---|---|---|---|
| C1 | M | H | … | M | M | [0.445, 0.800] | [0.438, 0.810] |
| C2 | H | VH | … | M | H | [0.472, 0.837] | [0.466, 0.858] |
| C3 | M | M | … | M | M | [0.350, 0.725] | [0.354, 0.734] |
| C4 | M | H | … | H | L | [0.425, 0.800] | [0.430, 0.820] |
| C5 | H | H | … | M | H | [0.500, 0.887] | [0.506, 0.799] |
| C6 | H | VH | … | M | H | [0.600, 0.950] | [0.608, 0.951] |
| C7 | H | H | … | M | H | [0.425, 0.825] | [0.430, 0.842] |
| C8 | H | H | … | H | H | [0.475, 0.875] | [0.481, 0.886] |
| C9 | M | M | … | VH | VH | [0.400, 0.750] | [0.405, 0.759] |
| C10 | H | H | … | M | M | [0.375, 0.775] | [0.380, 0.785] |
| … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … |
| C21 | M | M | … | H | M | [0.375, 0.750] | [0.380, 0.759] |
| C22 | H | VH | … | VH | VH | [0.675, 0.988] | [0.684, 1.000] |

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**Table 4**
Grey direct relation decision matrix.

| $C_i$ | $As_l$ | $Exp_1$ | $Exp_2$ | … | $Exp_{19}$ | $Exp_{20}$ | $G$ |
|---|---|---|---|---|---|---|---|
| C1 | As1 | F | G | … | F | F | [5.25, 8.50] |
| | As2 | G | G | … | G | G | [4.75, 9.25] |
| | As3 | G | G | … | G | G | [5.25, 9.00] |
| | As4 | F | G | … | G | G | [4.75, 8.75] |
| C2 | As1 | G | F | … | F | F | [4.25, 8.50] |
| | As2 | G | G | … | F | F | [4.00, 8.75] |
| | As3 | VG | G | … | VG | VG | [6.50, 9.75] |
| | As4 | G | G | … | P | P | [4.25, 8.50] |
| C3 | As1 | G | F | … | F | F | [4.75, 7.75] |
| | As2 | G | F | … | F | F | [4.25, 8.00] |
| | As3 | F | G | … | F | F | [3.00, 7.25] |
| | As4 | G | F | … | F | F | [3.25, 8.25] |
| C4 | As1 | G | G | … | F | F | [3.50, 7.50] |
| | As2 | G | G | … | P | P | [3.25, 7.25] |
| | As3 | G | G | … | P | P | [3.50, 7.50] |
| | As4 | F | G | … | P | P | [3.25, 8.25] |
| C5 | As1 | F | G | … | F | F | [3.50, 8.50] |
| | As2 | F | P | … | P | P | [1.75, 5.75] |
| | As3 | G | G | … | F | F | [4.75, 8.62] |
| | As4 | F | G | … | F | F | [3.50, 7.50] |
| … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … |
| C21 | As1 | G | G | … | G | G | [4.00, 8.00] |
| | As2 | VG | G | … | P | P | [5.00, 8.75] |
| | As3 | F | G | … | F | F | [6.00, 9.50] |
| | As4 | G | G | … | G | G | [4.25, 9.25] |
| C22 | As1 | G | G | … | G | G | [4.00, 8.00] |
| | As2 | VG | G | … | P | P | [5.00, 8.75] |
| | As3 | G | G | … | F | F | [6.00, 9.50] |
| | As4 | G | F | … | G | G | [4.25, 9.25] |

the distance between each reference value and each comparison value among the aspects and criteria. The computational process is repeated to obtain the distance between the reference value and each comparison value among the criteria and alternatives, as shown in Table 8, as for the grey number (0.203, 0.745) of alternative At1 with respect to criteria C1 (refer to Table 8), where $0.690 \times 0.685 = 0.407$ and $0.930 \times 0.987 = 0.917$.

Step 5. Based on Eq. (16), the weighted relation normalized grey decision matrix can be obtained. Table 9 is derived from Table 7. This means that the hierarchical structure is computed from aspects of the criteria.

Step 6. The total relation matrix ($T$) is computed and applied to Eq. (17), and the vectors D and R are presented in Table 10 using Eqs. (18) and (19). Fig. 2 shows the Grey-causal diagram. The top 5 criteria are as follows: 1. C4 (Recycle/Reuse/Reduce to increase the material saving percentage); 2. C7 (Corporate sustainability development); 3. C11 (Supplier integration in operational procedures) 4. C13 (Green purchasing); and 5. C12 (Life Cycle Assessment performed).

Step 7. Make the ideal alternative $At^{max}$, which is a referential alternative based on Eq. (20); the ideal alternative $At^{max}$ is shown as follows: $At^{max}$ = {[0.225, 0.810], [0.304,0.848], [0.262, 0.736], [0.276, 0.810], [0.341, 0.937], [0.288, 0.899], [0.354, 0.962], [0.371, 0.862], [0.284, 0.802], [0.322, 0.882], [0.338, 0.822], [0.330, 0.882], [0.371, 0.902], [0.322, 0.962], [0.384, 0.962], [0.384, 0.882], [0.384, 0.922], [0.384, 0.962], [0.354, 0.944], [0.384, 0.957], [0.264, 0.852], [0.284, 0.822]}.

Step 8. Calculate the grey possibility degree between the 4 compared alternatives $At_i$ (i = 1,2,3,4) and the ideal referential alternative $At^{max}$. Define Eqs. (7) and (8), and Eq. (21), and the results of the grey-DEMATEL possibility degree are as follows:

$$P(At_1 \leqq At^{max}) = 0.474; \quad P(At_2 \leqq At^{max}) = 0.477; \quad P(At_3 \leqq At^{max}) = 0.427; \quad P(At_4 \leqq At^{max}) = 0.431.$$

**Table 7**
The distance of reference value and each comparison values (Aspects to Criteria).

| | As1 | | As2 | | As3 | | As4 | |
|---|---|---|---|---|---|---|---|---|
| | $\delta_{ij}^{(max)}$ | $\delta_{ij}^{(min)}$ | $\delta_{ij}^{(max)}$ | $\delta_{ij}^{(min)}$ | $\delta_{ij}^{(max)}$ | $\delta_{ij}^{(min)}$ | $\delta_{ij}^{(max)}$ | $\delta_{ij}^{(min)}$ |
| C1 | 0.709 | 0.832 | 0.917 | 0.504 | 0.608 | 0.506 | 0.550 | 0.563 |
| C2 | 0.429 | 0.429 | 0.465 | 0.578 | 0.662 | 0.401 | 0.456 | 0.613 |
| C3 | 0.551 | 0.623 | 0.610 | 0.467 | 0.459 | 0.555 | 0.606 | 0.943 |
| C4 | 0.342 | 0.457 | 0.469 | 0.633 | 0.554 | 0.513 | 0.697 | 0.503 |
| C5 | 0.655 | 0.471 | 0.465 | 0.441 | 0.471 | 0.536 | 0.546 | 0.370 |
| C6 | 0.608 | 0.402 | 0.581 | 0.351 | 0.374 | 0.650 | 0.729 | 0.584 |
| C7 | 0.695 | 0.786 | 0.899 | 0.501 | 0.558 | 0.411 | 0.451 | 0.400 |
| C8 | 0.628 | 0.773 | 1.000 | 0.455 | 0.546 | 0.629 | 0.762 | 0.453 |
| C9 | 0.550 | 0.387 | 0.375 | 0.399 | 0.465 | 0.516 | 0.465 | 0.642 |
| C10 | 0.435 | 0.514 | 0.426 | 0.429 | 0.470 | 0.488 | 0.443 | 0.359 |
| C11 | 0.686 | 0.615 | 0.630 | 0.379 | 0.419 | 0.569 | 0.673 | 0.379 |
| C12 | 0.421 | 0.775 | 0.595 | 0.578 | 0.687 | 0.485 | 0.623 | 0.528 |
| C13 | 0.656 | 0.352 | 0.419 | 0.517 | 0.594 | 0.513 | 0.532 | 0.406 |
| C14 | 0.703 | 0.555 | 0.711 | 0.444 | 0.452 | 0.466 | 0.575 | 0.452 |
| C15 | 0.481 | 0.501 | 0.485 | 0.407 | 0.565 | 0.463 | 0.479 | 0.771 |
| C16 | 0.469 | 0.396 | 0.390 | 0.542 | 0.664 | 0.430 | 0.521 | 0.400 |
| C17 | 0.430 | 0.547 | 0.665 | 0.440 | 0.449 | 0.355 | 0.477 | 0.540 |
| C18 | 0.470 | 0.527 | 0.464 | 0.515 | 0.583 | 0.402 | 0.497 | 0.506 |
| C19 | 0.548 | 0.502 | 0.590 | 0.448 | 0.455 | 0.494 | 0.510 | 0.449 |
| C20 | 0.599 | 0.675 | 0.743 | 0.423 | 0.536 | 0.422 | 0.559 | 0.503 |
| C21 | 0.473 | 0.443 | 0.535 | 0.498 | 0.548 | 0.481 | 0.526 | 0.411 |
| C22 | 0.534 | 0.548 | 0.683 | 0.494 | 0.545 | 0.633 | 0.736 | 0.566 |

**Table 5**
Grey relation decision matrix.

| | C1 | C2 | C3 | C4 | C5–19 | | C20 | C21 | C22 |
|---|---|---|---|---|---|---|---|---|---|
| As1 | [0.472, 0.917] | [0.436, 0.846] | [0.400, 0.827] | [0.387, 0.903] | … | … … | [0.313, 0.813] | [0.353, 0.824] | [0.406, 0.870] |
| As2 | [0.556, 1.000] | [0.410, 0.821] | [0.427, 0.853] | [0.419, 0.935] | … | … … | [0.344, 0.844] | [0.353, 0.824] | [0.203, 0.667] |
| As3 | [0.556, 1.000] | [0.667, 1.000] | [0.320, 0.747] | [0.452, 0.968] | … | … … | [0.344, 0.844] | [0.500, 0.971] | [0.551, 1.000] |
| As4 | [0.528, 0.972] | [0.436, 0.833] | [0.347, 0.773] | [0.419, 0.935] | … | … … | [0.344, 0.844] | [0.529, 1.000] | [0.406, 0.870] |

**Table 6**
Grey weighted normalized decision.

| | C1 | C2 | C3 | C4 | C5–19 | | C20 | C21 | C22 |
|---|---|---|---|---|---|---|---|---|---|
| As1 | [0.203, 0.745][5] | [0.225, 0.748] | [0.182, 0.607] | [0.257, 0.732] | … | … … | [0.214, 0.792] | [0.236, 0.815] | [0.358, 0.899] |
| As2 | [0.252,0.815] | [0.188, 0.756] | [0.185, 0.726] | [0.275, 0.758] | … | … … | [0.214, 0.792] | [0.118, 0.624] | [0.358, 0.872] |
| As3 | [0.252, 0.815] | [0.345, 0.848] | [0.165, 0.748] | [0.183, 0.784] | … | … … | [0.304, 0.934] | [0.321, 0.937] | [0.378, 0.899] |
| As4 | [0.275, 0.888] | [0.190, 0.737] | [0.154, 0.868] | [0.270, 0.758] | … | … … | [0.322, 0.962] | [0.236, 0.815] | [0.343, 0.819] |

**Table 8**
The distance of reference value and each comparison values (Criteria to alternatives).

| | C1 | C2 | C3 | C4 | C5–C18 | C19 | C20 | C21 | C22 |
|---|---|---|---|---|---|---|---|---|---|
| At1 | [0.472 0.917 ][7] | [0.436 0.846 ] | [0.400 0.827 ] | [0.387 0.903 ] | … | [0.485 0.779 ] | [0.236 0.667 ] | [0.313 0.813 ] | [0.412 0.882 ] |
| At2 | [0.528 0.972 ] | [0.410 0.821 ] | [0.427 0.853 ] | [0.419 0.935 ] | … | [0.471 0.941 ] | [0.361 0.778 ] | [0.344 0.844 ] | [0.382 0.853 ] |
| At3 | [0.556 1.000 ] | [0.667 1.000 ] | [0.320 0.747 ] | [0.452 0.968 ] | … | [0.382 0.853 ] | [0.278 0.722 ] | [0.344 0.844 ] | [0.500 0.971 ] |
| At4 | [0.528 0.972 ] | [0.436 0.833 ] | [0.347 0.773 ] | [0.355 0.839 ] | … | [0.441 0.912 ] | [0.611 1.000 ] | [0.344 0.844 ] | [0.529 1.000 ] |

**Table 9**
The weighted relation normalized grey decision matrix.

| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 | C12 | C13 | C14 | C15 | C16 | C17 | C18 | C19 | C20 | C21 | C22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C1 | 0.279 | 0.230 | 0.225 | 0.206 | 0.243 | 0.204 | 0.249 | 0.213 | 0.187 | 0.231 | 0.211 | 0.202 | 0.186 | 0.201 | 0.210 | 0.204 | 0.194 | 0.187 | 0.188 | 0.200 | 0.207 | 0.204 |
| C2 | 0.241 | 0.161 | 0.161 | 0.148 | 0.167 | 0.127 | 0.128 | 0.127 | 0.113 | 0.151 | 0.135 | 0.147 | 0.104 | 0.121 | 0.127 | 0.158 | 0.120 | 0.111 | 0.125 | 0.138 | 0.169 | 0.358 |
| C3 | 0.254 | 0.154 | 0.153 | 0.149 | 0.168 | 0.138 | 0.152 | 0.128 | 0.116 | 0.151 | 0.128 | 0.126 | 0.118 | 0.133 | 0.146 | 0.143 | 0.122 | 0.138 | 0.143 | 0.130 | 0.147 | 0.143 |
| C4 | 0.432 | 0.239 | 0.235 | 0.223 | 0.252 | 0.239 | 0.259 | 0.266 | 0.250 | 0.285 | 0.243 | 0.243 | 0.233 | 0.251 | 0.257 | 0.208 | 0.251 | 0.178 | 0.233 | 0.249 | 0.224 | 0.208 |
| C5 | 0.237 | 0.166 | 0.179 | 0.172 | 0.201 | 0.191 | 0.196 | 0.176 | 0.144 | 0.182 | 0.158 | 0.186 | 0.165 | 0.162 | 0.164 | 0.169 | 0.155 | 0.144 | 0.153 | 0.155 | 0.168 | 0.169 |
| C6 | 0.236 | 0.163 | 0.169 | 0.151 | 0.187 | 0.139 | 0.150 | 0.149 | 0.165 | 0.172 | 0.139 | 0.129 | 0.164 | 0.151 | 0.147 | 0.169 | 0.149 | 0.155 | 0.148 | 0.129 | 0.177 | 0.178 |
| C7 | 0.299 | 0.213 | 0.201 | 0.200 | 0.247 | 0.200 | 0.213 | 0.233 | 0.177 | 0.259 | 0.206 | 0.190 | 0.200 | 0.230 | 0.237 | 0.205 | 0.211 | 0.214 | 0.202 | 0.209 | 0.221 | 0.235 |
| C8 | 0.230 | 0.154 | 0.161 | 0.151 | 0.190 | 0.140 | 0.194 | 0.167 | 0.165 | 0.159 | 0.177 | 0.183 | 0.122 | 0.147 | 0.149 | 0.128 | 0.145 | 0.116 | 0.124 | 0.153 | 0.148 | 0.128 |
| C9 | 0.229 | 0.171 | 0.169 | 0.151 | 0.194 | 0.196 | 0.174 | 0.151 | 0.142 | 0.155 | 0.128 | 0.129 | 0.148 | 0.139 | 0.148 | 0.127 | 0.149 | 0.158 | 0.144 | 0.156 | 0.183 | 0.167 |
| C10 | 0.264 | 0.195 | 0.191 | 0.202 | 0.221 | 0.164 | 0.168 | 0.169 | 0.203 | 0.232 | 0.152 | 0.209 | 0.175 | 0.201 | 0.191 | 0.168 | 0.160 | 0.166 | 0.164 | 0.153 | 0.167 | 0.158 |
| C11 | 0.263 | 0.194 | 0.196 | 0.194 | 0.223 | 0.210 | 0.186 | 0.175 | 0.171 | 0.192 | 0.210 | 0.185 | 0.171 | 0.161 | 0.186 | 0.196 | 0.144 | 0.174 | 0.158 | 0.164 | 0.162 | 0.196 |
| C2 | 0.265 | 0.208 | 0.188 | 0.196 | 0.231 | 0.160 | 0.181 | 0.203 | 0.154 | 0.191 | 0.169 | 0.163 | 0.179 | 0.190 | 0.202 | 0.163 | 0.203 | 0.172 | 0.210 | 0.194 | 0.224 | 0.173 |
| C13 | 0.262 | 0.200 | 0.188 | 0.188 | 0.223 | 0.189 | 0.225 | 0.195 | 0.158 | 0.230 | 0.163 | 0.154 | 0.140 | 0.151 | 0.158 | 0.181 | 0.183 | 0.165 | 0.138 | 0.196 | 0.163 | 0.181 |
| C14 | 0.205 | 0.160 | 0.153 | 0.150 | 0.181 | 0.143 | 0.144 | 0.120 | 0.128 | 0.141 | 0.112 | 0.136 | 0.114 | 0.115 | 0.115 | 0.123 | 0.114 | 0.127 | 0.118 | 0.152 | 0.130 | 0.293 |
| C15 | 0.237 | 0.172 | 0.177 | 0.142 | 0.200 | 0.160 | 0.187 | 0.157 | 0.132 | 0.214 | 0.161 | 0.144 | 0.123 | 0.154 | 0.144 | 0.194 | 0.159 | 0.133 | 0.126 | 0.168 | 0.146 | 0.194 |
| C16 | 0.240 | 0.180 | 0.181 | 0.141 | 0.209 | 0.193 | 0.158 | 0.174 | 0.142 | 0.175 | 0.139 | 0.200 | 0.158 | 0.167 | 0.155 | 0.155 | 0.139 | 0.188 | 0.164 | 0.151 | 0.143 | 0.275 |
| C17 | 0.220 | 0.163 | 0.161 | 0.130 | 0.190 | 0.134 | 0.178 | 0.174 | 0.136 | 0.141 | 0.150 | 0.129 | 0.110 | 0.169 | 0.147 | 0.123 | 0.123 | 0.119 | 0.113 | 0.168 | 0.140 | 0.153 |
| C18 | 0.194 | 0.146 | 0.142 | 0.126 | 0.169 | 0.129 | 0.124 | 0.108 | 0.110 | 0.131 | 0.110 | 0.123 | 0.102 | 0.101 | 0.144 | 0.117 | 0.103 | 0.092 | 0.131 | 0.118 | 0.111 | 0.317 |
| C19 | 0.254 | 0.195 | 0.173 | 0.178 | 0.225 | 0.149 | 0.185 | 0.193 | 0.157 | 0.222 | 0.162 | 0.208 | 0.162 | 0.156 | 0.209 | 0.167 | 0.159 | 0.138 | 0.182 | 0.168 | 0.173 | 0.467 |
| C20 | 0.228 | 0.169 | 0.157 | 0.152 | 0.200 | 0.182 | 0.188 | 0.139 | 0.120 | 0.187 | 0.139 | 0.154 | 0.129 | 0.130 | 0.163 | 0.137 | 0.163 | 0.136 | 0.150 | 0.139 | 0.139 | 0.137 |
| C21 | 0.248 | 0.185 | 0.172 | 0.166 | 0.202 | 0.187 | 0.191 | 0.201 | 0.162 | 0.191 | 0.147 | 0.148 | 0.136 | 0.176 | 0.185 | 0.153 | 0.188 | 0.154 | 0.127 | 0.161 | 0.210 | 0.153 |
| C22 | 0.124 | 0.229 | 0.130 | 0.131 | 0.228 | 0.231 | 0.230 | 0.228 | 0.232 | 0.130 | 0.127 | 0.228 | 0.230 | 0.128 | 0.131 | 0.129 | 0.328 | 0.229 | 0.233 | 0.125 | 0.030 | 0.129 |

**Table 10**
The sum of rows and columns for grey-causal diagram (Aspect to Criteria).

| | D (Sum) | R (Sum) | (D + R) | (D − R) |
|---|---|---|---|---|
| C1 | 4.457 | 5.317 | 9.774 | −0.860 |
| C2 | 2.979 | 3.818 | 6.797 | −0.839 |
| C3 | 3.037 | 3.732 | 6.769 | −0.695 |
| C4 | 5.250 | 3.516 | 8.766 | 1.734 |
| C5 | 3.623 | 4.323 | 7.946 | −0.700 |
| C6 | 3.338 | 3.574 | 6.912 | −0.236 |
| C7 | 4.567 | 3.830 | 8.397 | 0.737 |
| C8 | 3.303 | 3.618 | 6.921 | −0.315 |
| C9 | 3.341 | 3.232 | 6.573 | 0.109 |
| C10 | 3.915 | 3.992 | 7.907 | −0.077 |
| C11 | 3.915 | 3.339 | 7.254 | 0.576 |
| C12 | 4.046 | 3.488 | 7.534 | 0.558 |
| C13 | 3.850 | 3.139 | 6.989 | 0.711 |
| C14 | 2.881 | 3.406 | 6.287 | −0.525 |
| C15 | 3.430 | 3.584 | 7.014 | −0.154 |
| C16 | 3.552 | 3.388 | 6.940 | 0.164 |
| C17 | 3.118 | 3.334 | 6.452 | −0.216 |
| C18 | 2.631 | 3.165 | 5.796 | −0.534 |
| C19 | 3.815 | 3.241 | 7.056 | 0.574 |
| C20 | 3.301 | 3.451 | 6.752 | −0.150 |
| C21 | 3.690 | 3.552 | 7.242 | 0.138 |
| C22 | 3.811 | 4.487 | 8.298 | −0.676 |

Step 9. Rank the order of four alternative suppliers $At_i$ ($i = 1,2,3,4$). Using step 8, the result of the ranking order is as follows (Table 11):

$At_2 > At_1 > At_4 > At_3$

This study shows that supplier 2 ($At_2$) is the best supplier subject to the SSCM aspects and criteria.

## 5. Theoretical and managerial implications

SSCM for a firm involves implementing the design for the environment and involves the monitoring of all environmental activities with the objectives of creating value from related communities, building a competitive infrastructure and measuring performances. SSCM is dynamic and resilient, enabling change in a timely manner with the appropriate mechanisms. This study determines that firms must plan and improve their corporate sustainability development (C7) and life cycle assessment (LCA) (C12) performance, address the supplier's operational procedure integration (C11) and focus on green purchasing (C13) as an entire system to enhance the three Rs (recycle/reuse/reduce) to increase the material saving percentage (C4). Usually, the product designs are based on three Rs to increase the material saving percentage; compliance with legal requirements and environmental auditing programs avoid or reduce toxic or hazardous material use (Kannan et al., 2014). In particular, LCA analysis is a fundamental requirement that enables a firm to produce environmentally friendly products, and an MCDM approach prioritizes the supplier that follows the firms' SSCM requirements.

From the theoretical perspective, this study develops a SSCM hierarchical structure from the focal firm. This study fills the focal firm's supply selection and interrelationships gap presented by Seuring and Gold (2013). In reality, there are many firms lacking such a structure; practical decision-making tools may help set priorities and help make both financially and environmentally sound decisions. There is a rich opportunity for researchers and practitioners to collaborate in understanding the prioritization and holistic SSCM structure that can treat these complex trade-offs and serve as decision support tools for management (Lin and Tseng, in press). In particular, the sustainable plan and sustainable operational process control are presented as the top two aspects for firms to involve more resources. These aspects can be applied by general means for corporate sustainable development. For example, sustainable operational process control is a basic function of a manufacturing firm that integrates green technology into operational process control. Indeed, the environmental practice and performances should be simultaneously tightened; in addition, the sustainable indicators can be implemented in the operational and controlling processes (Tseng et al., 2008; Tseng, 2013).

From a strategic perspective, corporate sustainability development focuses on the management process. The main purpose is

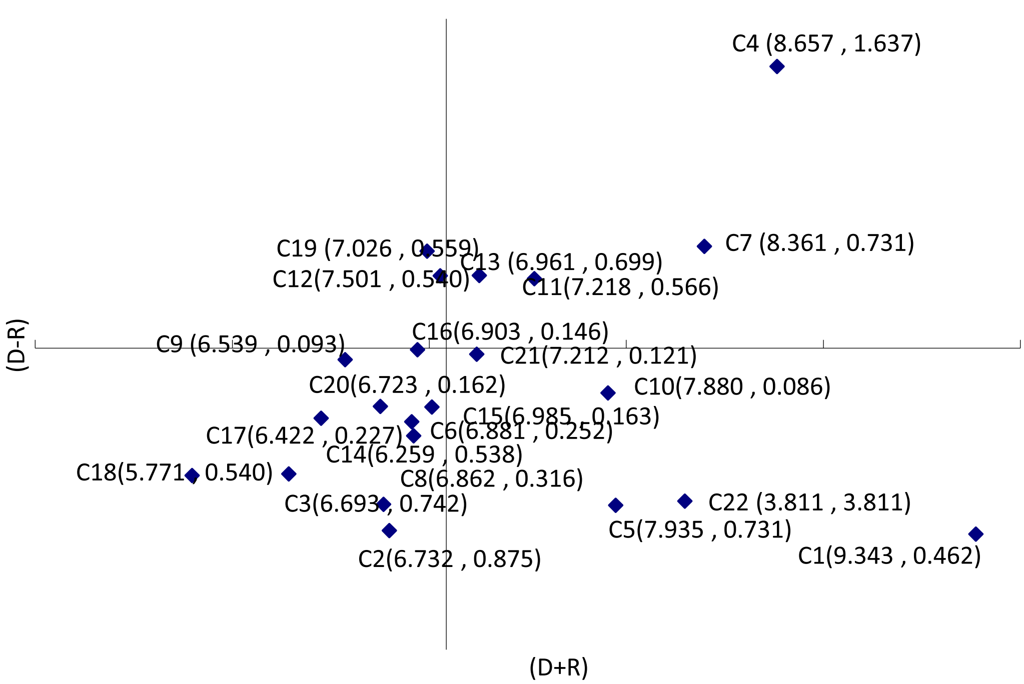


**Fig. 2.** Grey-causal diagram.

**Table 11**
Grey-DEMATEL possibility degree of 4 alternatives.

| G = (U − L) | C1 | | C2 | | C3 | | C4 | | C5−C18 | C19 | | C20 | | C21 | | C22 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.560 | | 0.482 | | 0.475 | | 0.000 | | | 0.578 | | 0.000 | | 0.000 | | 0.000 | |
| At1 Final Rate | 0.539 | 1.100 | | | 0.465 | 1.026 | 0.565 | 1.126 | … | 0.426 | 0.987 | 0.462 | 1.023 | 0.550 | 1.110 | 0.558 | 1.118 |
| 0.474 | 0.515 | | | | 0.607 | | 0.732 | | … | 0.691 | | 0.258 | | 0.720 | | 0.782 | |
| | 0.584 | | | | 0.419 | | 0.394 | | … | 0.296 | | 0.765 | | 0.390 | | 0.336 | |
| | 0.531 | | 0.5 | | 0.408 | | 0.350 | | … | 0.300 | | 0.748 | | 0.352 | | 0.301 | |
| At2 Final Rate | | | 0.473 | 0.955 | 0.475 | 0.958 | 0.577 | 1.060 | … | 0.578 | 1.156 | 0.493 | 0.975 | 0.561 | 1.043 | 0.548 | 1.030 |
| 0.477 | | | 0.372 | | 0.626 | | 0.758 | | … | 0.834 | | 0.357 | | 0.748 | | 0.756 | |
| | | | 0.583 | | 0.331 | | 0.302 | | … | 0.322 | | 0.618 | | 0.295 | | 0.274 | |
| | 0.500 | | 0.610 | | 0.346 | | 0.285 | | … | 0.278 | | 0.634 | | 0.283 | | 0.266 | |
| At3 Final Rate | 0.571 | 1.053 | | | 0.435 | 0.917 | 0.590 | 1.072 | … | 0.548 | 1.030 | 0.489 | 0.971 | 0.561 | 1.043 | 0.588 | 1.070 |
| 0.427 | 0.583 | | | | 0.548 | | 0.784 | | … | 0.756 | | 0.307 | | 0.748 | | 0.860 | |
| | 0.470 | | | | 0.369 | | 0.288 | | … | 0.274 | | 0.664 | | 0.295 | | 0.210 | |
| | 0.447 | | 0.500 | | 0.402 | | 0.269 | | … | 0.266 | | 0.684 | | 0.283 | | 0.196 | |
| At4 Final Rate | 0.560 | 1.043 | 0.472 | 0.955 | 0.445 | 0.927 | 0.527 | 1.009 | … | 0.568 | 1.050 | | | 0.561 | 1.043 | 0.598 | 1.080 |
| 0.431 | 0.560 | | 0.382 | | 0.568 | | 0.679 | | … | 0.808 | | | | 0.748 | | 0.886 | |
| | 0.482 | | 0.573 | | 0.359 | | 0.330 | | … | 0.242 | | | | 0.295 | | 0.194 | |
| | 0.463 | | 0.600 | | 0.388 | | 0.327 | | … | 0.231 | | 0.500 | | 0.283 | | 0.180 | |

to identify and demonstrate the connectivity, continuous production or process flow among the many environmental impacts, tools and resources and to assess how they are applied to develop sustainability. Corporate sustainability development resembles a filter that considers all inputs and stakeholder output that defines a particular issue's materiality and prioritizes corporate sustainability development into actions. For instance, the input stage focuses on green purchasing, LCA and supplier selection, the process stage focuses on the 30 Rs to increase the material saving percentage and the supplier's integration of operational procedures; in addition, the output stage controls the LCA design stage.

In practice, the LCA is performed to assess the total environmental impact of electronic products, which is common for reducing the scope of an LCA to target specific life cycle stages, such as the end of life, or specific environmental issues, such as energy consumption, resource consumption, return products or the product end life cycle. Many regulations and policies constrain the raw material used in electronic production; these regulations include the Restriction of Hazardous Substances Directive, Waste Electrical and Electronic Equipment Directive and the Registration, Evaluation, Authorization and Restriction of Chemicals Directive in European countries. In addition, the environment directives regulate the focal electronic manufacturer; the strategic plan's target is the LCA analysis for the product, cradle-to-grave. In particular, ISO 14000 is a common practice of Taiwanese electronic manufacturers and helps manufacturers minimize their operations to reduce environmental impacts. There are a series of norms to promote effective and efficient environmental management and to provide useful and usable tools to attain cost-effective, system-based, efficient, and operationally flexible, continuous improvements; these also communicate environmentally relevant information and regulations.

In terms of MCDM analysis, the use of the SSCM hierarchical structure guides management and resource allocation, which supports management's development and implementation. The SSCM performance is composed of the aspects and criteria devised to address and prevent the impacts or potential impacts of related issues. This study closely analyzes the criteria for supplier selection and expands the resource allocation efficiency. This study's objective is to develop an integrated SSCM hierarchical structure for supplier selection and fill the gap in the existing literature (Bai and Sarkis, 2010; Seuring and Gold, 2013; Tseng et al., 2009). This novel approach simultaneously combines both qualitative and quantitative criteria and integrates grey theory and DEMATEL. Specifically, the suppliers in electronic SSCM need to focus on their significant criteria relations with the supplier because suppliers perform different activities in the supply chain network. The case study firm must employ compatible interfaces for environmental management to enable a supplier's integration of operational procedures.

## 6. Concluding remarks

This study concentrated on the development of a SSCM hierarchical structure in the initial stage and a novel approach using grey and DEMATEL to address hierarchical structure and incomplete information to obtain the relation between the critical criteria and a specific supplier. The insightful and practical implications of this study can be interpreted as follows: There are many methodology applications that currently require rapid processing on the MCDM. The grey-DEMATEL can be used to simultaneously process the incomplete information without significantly reducing the quality of the results. Few studies utilize the exploratory factor analysis to explore the hierarchical structure and merge the hierarchal structure into the decision-making process. In reality, this study considers two types of data, quantitative and qualitative information. To assist practitioners, this proposed method could be efficient for SSCM. Last, the theoretical contribution could expand the research direction with regard to the hierarchical structure utilized in this study.

The results presented the suppliers' decision-making process using the SSCM aspects and criteria hierarchical structure. The analytical method shows the proposed hierarchical structure and the supplier selection needing justification in this grey-DEMATEL method with incomplete information. This analysis emphasized the critical aspects and criteria using exploratory factor analysis to construct a hierarchical structure that critically affects SSCM and uses the hierarchical structure to make decisions regarding supplier selection. Subsequently, an analytical solution is recommended for effective management under hierarchical structure interrelationships and incomplete information. If these aspects and criteria can be improved in the supply chain network, the current SSCM could be enhanced. In addition, management should focus on improving long-term perspectives to address the SSCM issue and improve performance. This can guide a firm to recommend operational aspects and criteria to select suppliers for future operations.

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Limitations of the mathematical MCDM method exist; these are independent of our study's peculiarities. In the decision-making process, one or more equally suitable method may exist; these require thorough understanding and appropriate use. The proposed method should enable adjustments for alignment with the paradigms on which they are based, improve business performance and permit consistent application with a well-structured method for electronic manufacturing firms. This novel method can complement and refine the results by providing consecutive filters. Future studies may include more firms to develop a comparative study or an entire industrial-based study. From this insightful study, future studies could achieve the following objectives: (i) extend the input information in the context of the proposed method; (ii) incorporate this proposed grey-DEMATEL in an industrial study; (iii) apply this proposed method to other decision-making problems; and (iv) utilize this method and these results to develop a detailed practical indicator for government policy-making processes.

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