Evaluating green supplier development programs with a grey-analytical network process-based methodology

Yijie Dou, Qinghua Zhu, Joseph Sarkis

1. Introduction

Environmental sustainability has gained greater notoriety amongst organizations as industrial environmental impacts resoundingly occur at local, regional, and global levels. The industrial response has not just been reactive to these environmental concerns, but has included organizational search for competitive advantage (Sarkis, 2001; Seuring et al., 2008; Zhu et al., 2008; Bryson and Lombardi, 2009; Teunter and Flapper, 2011; Liu et al., 2012). These responses have also reverberated through organizational supply chains. One dimension of this important green supply chain response by organizations is the introduction of green supplier development (GSD) programs. Integrating environmental sustainability into supplier development has become a necessary measure for the long-term competitiveness and operations of focal companies and their supply chains (Nagel, 2003; Bai and Sarkis, 2010a; Fu et al., 2012; Tang and Zhou, 2012).

Competitive advantages can be accrued from GSD programs, but these programs can require significant organizational resources for their implementation. Not all GSD programs contribute equally to supplier’s operational performance and environmental improvement. This heterogeneous performance and limited resource situation gives rise to the need for evaluating and selecting GSD programs by focal companies. Unfortunately very little research, empirical or otherwise, has investigated GSD programs, their characteristics, management or efficacy (Reuter et al., 2010). Formal models and tools for GSD programs evaluation are even more limited (Bai and Sarkis, 2010a).

GSD programs should be evaluated and examined on supplier performance measurement (Krause et al., 2000). However, key suppliers’ propensity to become involved in GSD programs may be difficult to change.1 Therefore, suppliers’ involvement propensity with GSD programs is a critical consideration when evaluating GSD programs’ effectiveness. In this paper, a dual perspective of supplier performance evaluation factors and suppliers’ propensity to participate in GSD programs will be incorporated into a formal methodological framework for GSD programmatic evaluation.

A viable supplier development program decision needs to cope with uncertain information, simultaneous consideration of

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1 An example is in the case of single sourcing. The single supplier of components may be reluctant to participate in some green supplier development programs. Actually, focal companies faced such issues when they started to promote the EU RoHS directive among their suppliers (Zhu et al., 2010).
multiple factors and their inter-relationships (Paulraj and Chen, 2007; Krause et al., 2007; Wagner, 2011; Bai and Sarkis, 2011). To assist in GSD programs evaluation, we present a formal decision methodology with a joint grey system analytical network process (grey-ANP) based approach. This methodology determines the importance of various GSD programs, how the programs relate to each other and how the uncertainty issues can be addressed. The technique is advantageous when compared to basic optimization or AHP techniques not only considering direct, but interdependence of strategic and operational factors, tangible and intangible factors with allowance for some uncertainty in evaluations. Grey theory (Deng, 1982) will be used in evaluating suppliers' GSD involvement propensity (the willingness to be involved in a specific GSD program) and integrating the involvement propensity into the final results for GSD program attractiveness and ranking.

This paper contributes to the literature by utilizing a formal methodology in an underdeveloped and significant application field, whilst considering uncertainty issues and inter-relationships among factors. The practical outcome of this methodology is to provide insights for focal companies within a supply chain into GSD program management. The management can focus on recommendations for GSD programs in which organizations may conceivably invest their limited financial and human resources.

We begin with the paper by introducing a short discussion of the necessity for GSD programs evaluation. GSD program evaluation factors are then proposed. Further, an overview description of various related models and tools will identify gaps that exist in the literature some of which are addressed with this paper. The following section of the paper shows a real world application of the proposed model. The results are then discussed, with managerial insights, implications, and possible directions for future research.

2. GSD programs evaluation

The greening of a supply chain is critical as organizations compete in markets that have sought stricter environmental requirements (Zhu and Sarkis, 2004; Koplin et al., 2007; Ferretti et al., 2007; Seuring and Muller, 2008; Dekker et al., 2012; Hassini et al., 2012; Zhu et al., 2012). A variety of GSD programs may be available as alternatives for focal companies to green their supply chains. According to the general supplier development research GSD programs may be grouped into three categories (Bai and Sarkis, 2010a): Green Knowledge Transfer and Communication (GKTC); Investment and Resource Transfer (IRT); Management and Organizational Practices (MOP). GKTC can broadly include programs such as training suppliers on the issues of environmental and cost controls, training suppliers on stakeholder expectations, providing green technological advice to suppliers, giving eco-design product development related advice to suppliers, setting environmental improvement targets for suppliers, information sharing on environmental topics, and joint and team problem solving on environmental issues. IRT characteristic programs include transferring supplier employees with environmental expertise to buying firm, transferring employees with environmental expertise to suppliers, supplier rewards for better environmental performance, finance supplier major capital environmental expenditures, and investment in supplier capacity building. MOP programs may comprise such GSD programs as requiring ISO14000 certification for suppliers, setting long-term contracts with environmental dimensions incorporated, building top management commitment for suppliers for green supply practices, and a formal process for supplier development.

Since not all these programs contribute equally to suppliers' performance improvement and given that the organizational resources targeting GSD programs are limited for most focal companies (Narasimhan et al., 2008), the evaluation and selection of GSD programs is a critical managerial decision for focal companies (Dunn and Young, 2004; Humphreys et al., 2004).

2.1. Factors for evaluation

According to Krause et al. (1998, p. 40), supplier development is "any set of activities undertaken by a buying firm to identify, measure and improve supplier performance and facilitate the continuous improvement of the overall value of goods and services supplied to the buying company's business unit." Thus, we can apply supplier performance metrics to evaluate and measure GSD programs' supplier performance.

Key suppliers' GSD involvement propensity may be difficult to alter, especially with suppliers who are not willing to be involved. Hence, the comprehensive evaluation of GSD programs needs to consider suppliers' programmatic involvement propensity (Bai and Sarkis, 2010a), which will be described in detail in Sections 3.3 and 4.7. In this section we focus only on GSD programs' supplier performance factors, and not their involvement propensity, which will be integrated at later stages.

Two classes of supplier performance factors, supplier operational performance and supplier environmental performance, are introduced to evaluate GSD programs' supplier performance. Supplier operational performance factors can be grouped into two clusters (Sarkis and Talluri, 2002): strategic operational performance metrics and organizational factors. The strategic operational performance metrics refer to six major metrics including: cost (CT), quality (QY), time (TE), flexibility (FY), innovativeness (IS), and process management (PM). Operations strategic supplier performance metrics, often being identified as competitive priorities, are frequently applied to evaluate suppliers (Ho et al., 2010). Of these factors, cost and quality are the most common supplier evaluation factors along with on-time delivery and flexibility (Huang and Keskar, 2007; Chiu, 2011). Innovativeness and process management have also been regarded as crucial operational performance metrics for evaluating suppliers (Chan, 2003; Lau, 2011; Azadeegan, 2011).

Organizational factors may include three sets of sub-factors: culture (CE), technology (TY), and relationships (RP). However, these more qualitative and intangible organizational factors, focusing on the capabilities of forming the mutual partnership, can be even more significant than some of the more tangible factors due to increasing strategic supplier relationship practices (Nudurupati et al., 2011). For example, a suitable cultural atmosphere can foster a better collaboration and communication environment between buyers and suppliers, which may further improve manufacturers' quality, delivery, and flexibility, especially in sustainable supply chain relationships (Vachon and Klassen, 2008; Parmigiani et al., 2011). Researchers have emphasized the significance of environmental factors in depicting suppliers' performance (Noci, 1997; Handfield et al., 2002; Humphreys et al., 2003; Sarkis, 2006; Dou and Sarkis, 2010; Tang and Zhou, 2012). For example, practitioners and researchers put forward green vendor rating frameworks for the evaluation of suppliers' environmental performance (Noci, 1997; Handfield et al., 2002). In some green vendor rating systems, green competence, green image, life cycle cost, and environmental efficiency categories are used to evaluate suppliers. These are similar to the value adding dimensions of environmental supply chain management activities such as cost improvements, revenue generation, improved reputation and image, and business continuity (Sarks, 2009). Further, environmental factors such as green design, environmental management systems and environmental competencies have also been utilized in supplier evaluation (Humphreys et al., 2003). An individual firm's sustainable operational strategies
would have more opportunities of gaining success when the strategies are aligned with suppliers (Tang and Zhou, 2012). This strategic fit argument across organizational boundaries further supports the necessity of evaluating suppliers’ environmental performance.

Supplier environmental performance factors may be grouped into many clusters. This paper presents one general environmental group with factors integrating categorizations from Klassen and Whybark (1999) and Gauthier (2005): Pollution Controls (PCs), Pollution Prevention (PP), Environmental Management System (EMS), Resource Consumption (RC), and Pollution Production (PP).

2.2. Models

Formal models for GSD programs evaluation are quite limited. Previous extant studies (e.g. Krause et al., 1998; Humphreys et al., 2004; Watts and Hahn, 2006) sought to determine which programs significantly contribute to general supplier development, however, most of the studies are broadly empirical or conceptual introductory discussions. Opportunities for formal models of general supplier development decisions exist and are fertile areas for additional investigation (Simatupang and Sridharan, 2004; Bai and Sarkis, 2010a).

In one of the few formal models investigating GSD decisions, rough set theory was used to evaluate incomplete and intangible information in GSD decisions (Bai and Sarkis, 2010a). That specific formal model is limited due to the lack of an ultimate managerial decision to be made. It was developed and applied only for formal evaluation of the effectiveness of GSD programs. Surprisingly given the many quantitative decision tools and techniques that exist, ranging from simple scoring and matrix methods to more advanced mathematical programming and game theoretic modelling approaches, none have sought to further investigate application for GSD programs decision making and management.

ANP, which we utilize as the basis for our formal decision and management methodology, is capable of incorporating inter-relationships of factors into the decision model. In addition, ANP does not demand complicated mathematical modelling and computational power, but provides a more robust solution than simple scoring methods (Sarkis and Sundarraj, 2000; Kahraman et al., 2006). To help expand the boundaries of ANP application we also integrate grey system theory allowing for the inclusion of incomplete and uncertain information.

Since human judgment about preferences are often unclear and hard to estimate using deterministic numerical values, grey system theory (Deng, 1982) is helpful for situations characterized by vagueness, uncertainty and imprecision (Bai and Sarkis, 2010b). Superior to conventional statistical modelling tools, grey system models require only a limited amount of data to evaluate the activities of unknown systems (Deng, 1989). Grey methodology has been applied in many areas such as agriculture (e.g. Sun, 1991), environmental protection (e.g. Huang et al., 1995; Pai et al., 2007; Pao et al., 2012), industry (e.g. Tien and Chen, 1997; Hsu and Wen, 2000), and enterprise management (e.g. Wu et al., 2004; Li et al., 2007; Rahimnia et al., 2011). The literature has shown that grey-based approaches can achieve good performance characteristics. Grey system theory provides a relatively flexible, no parametric and distribution assumptions, and general way to integrate fuzziness into a problem. Grey models are more robust with respect to noise and lack of modelling information when compared to conventional methods (Kayacan et al., 2010). Thus, by allowing the inclusion of uncertain information and enabling evaluating inter-relationships among factors, the integration of grey theory and ANP generates a robust and easy-to-use modelling tool for GSD program evaluation.

To this end, the paper proposes a formal model that applies grey theory and ANP to evaluate GSD programs.

3. The grey-ANP based approach

3.1. Grey system theory

Grey system theory (Deng, 1982) can help evaluate outcomes in cases with incomplete and indeterminate information (Li et al., 1997). Fields researched by grey theory contain systems analysis, data processing, modelling, prediction, as well as decision making and control (Hsu and Wen, 2000). In this paper, a grey aggregation method, which has been recognized as an effective tool (Opricovic and Tzeng, 2003) will be utilized.

To introduce some fundamental aspects of grey system theory some general notation and operations for grey systems are first proposed. x is denoted as a closed and bounded set of real numbers. A grey number, , is defined as an interval with known upper and lower bounds but unknown distribution information for x (Deng, 1989). That is,

\[ x = [\underline{x}, \overline{x}] = [\min x, \max x] \]  \hspace{1cm} (1)

where \( \underline{x} \) and \( \overline{x} \) are the lower and upper bounds of \( x \), respectively.

Expressions (2)–(5) demonstrate some basic grey number mathematical operations:

\[ x_1 + x_2 = [\min (x_1 + x_2), \max (x_1 + x_2)] \]  \hspace{1cm} (2)

\[ x_1 - x_2 = [\min (x_1 - x_2), \max (x_1 - x_2)] \]  \hspace{1cm} (3)

\[ x_1 \times x_2 = [\min (x_1 \times x_2), \max (x_1 \times x_2)] \]  \hspace{1cm} (4)

\[ \frac{1}{x} = \left[ \frac{1}{\max x}, \frac{1}{\min x} \right] \]  \hspace{1cm} (5)

For decision making problems within a grey environment, we apply a grey aggregation method – a variation of the CFCSs (Converting Fuzzy data into Crisp Scores) defuzzification method, which has been deemed as an effective method to arrive at crisp values (Opricovic and Tzeng, 2003). The grey aggregation method will be used in the stage of evaluating suppliers’ involvement propensity in various GSD programs (see Section 4.7).

We define \( x^i_j \) as the grey number for a decision maker k, that will evaluate the involvement propensity of a supplier i in a GSD program j, \( \overline{x}^i_j \) and \( \underline{x}^i_j \) are respectively the lower and upper grey values by a decision maker k for the relationship evaluation of a supplier i and a GSD program j. That is:

\[ x^i_j = [\underline{x}^i_j, \overline{x}^i_j] \]  \hspace{1cm} (6)

The modified-CFCS method includes three-step steps as follows:

Step 1: normalization

\[ \overline{x}^i_j = \frac{\underline{x}^i_j - \min \underline{x}^i_j}{\Delta_{\min}} \]  \hspace{1cm} (7)

\[ \underline{x}^i_j = \frac{\overline{x}^i_j - \min \overline{x}^i_j}{\Delta_{\max}} \]  \hspace{1cm} (8)

where \( \Delta_{\min} = \max \overline{x}^i_j - \min \underline{x}^i_j \) \hspace{1cm} (9)

Step 2: calculate total normalized crisp value
The ANP methodology is introduced in the following steps:

3.2.1. Step 1: Formulating a decision network

Initial discussion with decision makers or an evaluation of the previous literature is required to create a decision network. Some tools such as interpretative structural modelling (Sarkis et al., 2008) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) approach (Gabus and Fontela, 1973; Fontela and Gabus, 1976) can be applied to determine these structures.

3.2.2. Step 2: Eliciting pairwise comparisons

The pairwise comparison questions are asked to obtain the relative importance of clusters and factors that compose the ANP decision network. The comparison questions involve two types: inter-cluster comparisons and inter-factor comparisons.

3.2.3. Step 3: Calculating relative importance of factors

The solution for relative importance weights may be calculated through Web HIPRE3+ (Mustajoki and Hämäläinen, 1999), an Internet interactive software available for decision analysis (http://www.hipre.hut.fi/). This software uses standard eigenvalue matrix calculations to arrive at appropriate relative importance scores for a group of factors.

3.2.4. Step 4: Formulating supermatrix from the weights

The ANP approach requires that interdependencies in the evaluations among factors and clusters be completed through a formation of a ‘supermatrix’. The supermatrix concept is similar to the Markov chain process (Saaty, 1996). The relative weights obtained in Step 3 are aggregated into a supermatrix based upon influence from one cluster to another, or from one factor to another within a cluster itself. The supermatrix formation incorporates four elements: (1) relationships to the final objective; (2) comparisons among factors and clusters; (3) comparisons of alternative relationships with respect to the factors; and (4) an identity matrix for all alternatives (unless the alternatives influence each other).

3.2.5. Step 5: Calculating long-term (‘stable’) weights from the supermatrix

The stable weights of alternatives can be determined by raising the supermatrix elicited in Step 4 to a high enough power until the weights in the supermatrix have converged and stabilized.

3.2.6. Step 6: Completing a sensitivity analysis

A sensitivity analysis can be conducted to determine the robustness of the alternatives weights and relationships.

3.3. A grey-ANP based model

The grey-ANP based approach in this paper is composed of the following eight major steps (see also Fig. 1):

(a) Formulate a decision network.

(b) Elicit pairwise comparisons.

(c) Calculate the relative importance of the factors (“weights”).

(d) Formulate the supermatrix from the weights.

(e) Calculate the long-term ("stable") weights for the supermatrix.

(f) Evaluate suppliers’ involvement propensity for various GSD programs.

(g) Calculate suppliers’ final comprehensive performance scores.

(h) Complete a sensitivity analysis.

The approach will be proposed in detail in the illustrative case (Section 4).

4. Case

To detail the presented grey-ANP based approach, a real world case of Company A is provided here. Company A, located in Northeast China, is a leading manufacturer in China’s pivot irrigation equipment industry. As a new emerging industry, the industry of pivot irrigation equipment plays a significant role in corporate sustainability measures by conserving water and raising crop yields in Chinese farming. In recent years, Company A’s business has expanded rapidly. New markets have been gained, mainly in the Middle East and Africa. Consistent with the rapid growth of business and the intense market competitiveness, as well as the marketing of their product as an enabler of sustainability, there is increasing focus of this company on green supplier development. A centre pivot machine is constructed of almost one hundred components and accessories. More than fifty suppliers cooperate with Company A. Under the environmental pressures from markets, Company A is currently encouraging suppliers to provide more energy efficient drives, light and robust pipes and spans, efficient automatic control system, and other durable, low noise, easy disassembly and recyclable units, in order to keep and improve its own market competitiveness. To ensure the high-quality provision of green components and accessories, Company A is planning to conduct some GSD programs. Many GSD programs such as training critical suppliers on the issues of materials reduction and energy efficiency improvement, providing green technological advice to critical suppliers, and building top management commitment for suppliers for green supply practices are available for Company A. However, considering resource limitations, Company A cannot implement all the GSD programs simultaneously. Therefore, the necessity of evaluating and selecting GSD programs is evident. From a number of possibilities, twelve GSD programs have been identified by Company A for evaluation in this illustration:

(a) Setting long-term contracts with environmental dimensions incorporated (P1).

(b) Transferring employees with environmental expertise to suppliers (P2).

(c) Providing green technological advice to suppliers (P3).

(d) Supplier rewards for better environmental performance (P4).

(e) Transferring supplier employees with environmental expertise to buying firm (P5).

(f) Setting environmental improvement targets for suppliers (P6).

(g) Training suppliers on the issues of environmental and cost controls (P7).

(h) Information sharing on environmental topics (P8).

(i) Building top management commitment for suppliers for green supply practices (P9).

(j) Formal process for supplier development (P10).
The general manager of Company A chose nine critical suppliers (S1, S2, S3, S4, S5, S6, S7, S8 and S9) to involve into the decision process. Company A has determined these nine suppliers due to their products’ high potential of environmental performance improvement. Initially Company A evaluates the supplier performance contribution to each GSD program.

Company A utilizes a variety of performance factors including operational metrics such as cost, quality, delivery time, and flexibility. It has recently emphasized the emergent significance of suppliers’ environmental improvement. Therefore, company A also utilizes contribution to environmental improvement efforts (factors) such as Pollution Controls (PCs), Pollution Prevention (PPE), and Environmental Management System (EMS) when evaluating GSD programs. According to the experience of the general manager of Company A, suppliers will have differing degrees of propensity to be involved in various GSD programs due to issues of business confidentiality, additional investments, or strategic orientation. Consequently, the evaluation of GSD programs will be based upon suppliers’ strategic operational performance and environmental performance, and also suppliers’ propensity to be involved in these programs. The nine suppliers’ involvement propensity for the twelve GSD programs will be evaluated through a grey scale method at a later stage.

4.1. Completing an initial filtering process

A filtering process to reduce the number of alternative GSD programs is completed to obtain an “alternatives” set. This step is conducted to help keep the number of pairwise comparisons in latter steps to a manageable level. In this case the general manager applies a simple scoring method to yield the nine programs of P1, P2, P3, P4, P5, P6, P7, P8 and P9. Due to the reason of cost saving, P10 and P12 are eliminated. P11 is assigned a low score because the general manager worries that suppliers only pay attention to the approval of ISO14001 rather than the perfection of their environmental management systems. Thus, we will not consider P10, P11 and P12 in the following sections.

4.2. Formulating a decision network

Relationships amongst and within each cluster need to be determined for the decision network formulation. An initial discussion with the general manager is required (or previous literature may be used) to help determine the relationships. There are also formal tools available to aid in determining these structures and relationships such as interpretative structural modelling (Sarkis...

(k) Requiring ISO14001 certification for suppliers (P11).
(l) Support supplier major capital environmental expenditures (P12).

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**Fig. 1.** The steps of a grey-ANP based methodology.
The general manager, with the help of a research team member, proposes a high-level ANP decision network, shown in Fig. 2. On the right-hand side of this figure is the objective which is to evaluate GSD programs influence on supplier performance. Two sets of clusters, supplier environmental factors and supplier strategic operational performance factors, form the core of this decision network.

Notice that in the supplier operational cluster set of Fig. 2, an internal interdependency (a curved arrow) is assumed to exist within the strategic performance metrics cluster, indicating that factors within this cluster will influence each other and the impact of these factors amongst themselves need to be taken into account in the evaluation process. For instance, cost may be influenced by other strategic metrics such as quality and time.

Each program alternative in the GSD program alternatives cluster is evaluated on the supplier strategic operational and environmental factors. Their relationships are depicted by the one-way arrows between the programs evaluation set and the other clusters in Fig. 2. A more detailed set of factors within the decision network is delineated in Fig. 3.

4.3. Eliciting pairwise comparisons

Pairwise comparisons need to be completed for this procedure. Example pairwise comparison questions to elicit the weights would include:

- for significance of the factors on the decision objective, an example pairwise comparison question would be: “With respect to the overall decision, how much more important is ‘Culture (CE)’ when compared to ‘Technology (TY)’?”
- for determining an interdependent influence of components within a cluster set such as a strategic operational performance metric relative importance on other strategic operational performance metrics, “How much more influence does ‘Cost (CT)’ have on ‘Time’ when compared to ‘Quality (QY)’?”
- One example of pairwise comparison questions regarding the relative performance of GSD program alternatives on the various factors is: “With respect to ‘Technology (TY)’, how much better does green supplier development program P1 perform (or contribute to) when compared to P2?”

These questions are answered in an anchored range of descriptions from Extremely more (a value of 9) to Extremely less (a value of 1/9) (see Saaty, 1980).

An example of pairwise comparisons conducted for organizational factor items based on the overall objective GSD programs evaluation is shown in Table 1. An example pairwise comparison question for this matrix is: “How much more important is ‘Culture (CE)’ than ‘Relationship (RP)’ for the relative performance of GSD programs?” In this example, the general manager put in the value “3” in Table 1 which means that he responded with ‘TY’ as moderately more important than ‘CE’.
To arrive at the final solution, a set of stable weights need to be obtained. To achieve this goal we initially have to normalize the supermatrix to the 28th power, are 

\[
W = \lambda_{\text{max}} W, 
\]

where \( \lambda_{\text{max}} \) is the largest eigenvalue of pairwise comparison matrix \( A \). The solution for the eigenvalues and relative importance weights may be calculated from Web HIPRE3+ (Mustajoki and Hämäläinen, 1999), an Internet interactive software available for decision analysis (http://www.hipre.hut.fi/).

The results of the pairwise comparison matrix for the organizational cluster (Table 1) reveal that ‘Technology (TY)’ was perceived to be the most important organizational factor (0.547). The relative importance weights of this matrix are then introduced into the supermatrix in the next stage.

4.4. Calculating the relative importance of the factors (“weights”)

After the pairwise comparisons are completed, the local priority vector \( w \) (defined as the eigenvector) is computed as the unique solution to:

\[
Aw = \lambda_{\text{max}} W, 
\]

where \( \lambda_{\text{max}} \) is the largest eigenvalue of pairwise comparison matrix \( A \). The solution for the eigenvalues and relative importance weights may be calculated from Web HIPRE3+ (Mustajoki and Hämäläinen, 1999), an Internet interactive software available for decision analysis (http://www.hipre.hut.fi/).

Table 2 demonstrates the supermatrix structure for the illustrative ANP decision network. In Table 2, the second row (and column) represents the objective or “decision” element (i.e. GSD program alternatives set). The next 14 rows (and columns) represent the factors of supplier environmental performance and supplier strategic operational performance, and the last nine rows (and columns) represent 9 GSD programs of the alternatives cluster. To facilitate convergence (Section 4.6 below), Saaty (1996) recommends the addition of the interdependence of each program alternative on itself. Thus an identity matrix (I) is included in the supermatrix for the program alternatives cluster.

All the factors in this decision network (24 total factors in all) and their respective relative importance weights are shown in Table 2. Note that the bolded numbers in Table 2 are the same as the relative importance weights for the organizational factors on the overall decision objective in Table 1. Table 2 is the original unadjusted supermatrix that will be applied in the evaluation of the program alternatives.

4.5. Formulating the supermatrix from the weights

The pairs of rows and columns represent 9 GSD programs of the alternatives cluster. The next 14 rows (and columns) represent the factors of supplier environmental performance and supplier strategic operational performance, and the last nine rows (and columns) represent 9 GSD programs of the alternatives cluster.

All the factors in this decision network (24 total factors in all) and their respective relative importance weights are shown in Table 2. Note that the bolded numbers in Table 2 are the same as the relative importance weights for the organizational factors on the overall decision objective in Table 1. Table 2 is the original unadjusted supermatrix that will be applied in the evaluation of the program alternatives.

4.6. Calculating the long-term (“stable”) weights from the supermatrix

To arrive at the final solution, a set of stable weights need to be obtained. To achieve this goal we initially have to normalize the supermatrix in Table 2. We divide each element by its column sum so that each column adds to one to make the supermatrix “column stochastic.” This matrix property guarantees convergence to a stable set of weights. Next, the normalized supermatrix is raised to a significantly large power. This procedure produces the converged (or stable) weights of the elements of the network on each other, similar to a Markovian analysis. The numbers of interest in the resulting supermatrix are weights of the program alternatives on the decision objective, i.e., the last 9 rows of the first column. The final weights of the nine program alternatives, which were obtained by raising the supermatrix to the 28th power, are 

\[
W^{28} = (0.087, 0.109, 0.133, 0.082, 0.134, 0.088, 0.127, 0.107, 0.113). 
\]

The scores are further normalized by dividing each value by the largest score (0.134), and are shown in Table 3.
The original grey decision making matrix on involvement propensity needs to be initially elicited. We need to determine suppliers’ involvement propensity for each GSD program. The way of conducting this assessment here is to assign perception scores ranging from “No propensity to be involved in the GSD program” to “Very high propensity to be involved in the GSD program” for each supplier and for each GSD program. A five level of grey scale transformation is used in this case is shown in Table 4. The original grey decision making matrix for suppliers’ propensity of involvement into GSD programs is shown in Table 5. As seen in Table 5, S1’s propensity of involvement score for P1 is [0,0] (lower = 0, upper = 0), which, according to the belief of the general manager, indicates that S1 of involvement score for P1 is [0,0] (lower = 0, upper = 0), which, used in this case is shown in Table 4. The grey linguistic scale for the respondents’ assessments. No propensity of involvement (N) [0,0] Low propensity of involvement (L) [0.25,0.5] High propensity of involvement (H) [0.5,0.75] Very high propensity of involvement (VH) [0.75,1]

4.7. Evaluating suppliers’ involvement propensity for various GSD programs

The evaluation of suppliers’ involvement propensity for the various GSD programs utilizes grey-set evaluations. The original grey decision making matrix on involvement propensity needs to be initially elicited. We need to determine suppliers’ involvement propensity for each GSD program. The way of conducting this assessment here is to assign perception scores ranging from “No propensity to be involved in the GSD program” to “Very high propensity to be involved in the GSD program” for each supplier and for each GSD program. A five level of grey scale transformation is used in this case is shown in Table 4. The original grey decision making matrix for suppliers’ propensity of involvement into GSD programs is shown in Table 5. As seen in Table 5, S1’s propensity of involvement score for P1 is [0,0] (lower = 0, upper = 0), which, according to the belief of the general manager, indicates that S1 has a very low propensity to be involved with GSD program P1.

Using expressions (6)-(11), the modified-CFCS method, in Section 3.1, we arrive at the final crisp values of nine suppliers’ propensity of involvement into the nine GSD programs (see Table 6).

4.8. Calculating programs’ final comprehensive performance scores

Nine GSD programs’ final comprehensive performance scores are obtained through product sum calculations to values from column 3 to column 11 in Table 7. For example, the final score for P1 is calculated as:

Table 3
Evaluation of the values of GSD programs for supplier performance.

<table>
<thead>
<tr>
<th>GSD programs</th>
<th>Final values</th>
<th>Normalized values</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0.087</td>
<td>0.651</td>
</tr>
<tr>
<td>P2</td>
<td>0.109</td>
<td>0.812</td>
</tr>
<tr>
<td>P3</td>
<td>0.133</td>
<td>0.987</td>
</tr>
<tr>
<td>P4</td>
<td>0.082</td>
<td>0.615</td>
</tr>
<tr>
<td>P5</td>
<td>0.134</td>
<td>1</td>
</tr>
<tr>
<td>P6</td>
<td>0.088</td>
<td>0.661</td>
</tr>
<tr>
<td>P7</td>
<td>0.127</td>
<td>0.952</td>
</tr>
<tr>
<td>P8</td>
<td>0.107</td>
<td>0.800</td>
</tr>
<tr>
<td>P9</td>
<td>0.113</td>
<td>0.843</td>
</tr>
</tbody>
</table>

Table 4
The grey linguistic scale for the respondents’ assessments.

<table>
<thead>
<tr>
<th>Linguistic terms</th>
<th>Grey numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>No propensity of involvement (N)</td>
<td>[0,0]</td>
</tr>
<tr>
<td>Very low propensity of involvement (VL)</td>
<td>[0.25,0.5]</td>
</tr>
<tr>
<td>Low propensity of involvement (L)</td>
<td>[0.25,0.5]</td>
</tr>
<tr>
<td>High propensity of involvement (H)</td>
<td>[0.5,0.75]</td>
</tr>
<tr>
<td>Very high propensity of involvement (VH)</td>
<td>[0.75,1]</td>
</tr>
</tbody>
</table>

Table 5
The original grey decision making matrix for nine suppliers’ involvement propensity for the nine GSD programs.

<table>
<thead>
<tr>
<th>Suppliers</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S2</td>
<td>0.75</td>
<td>1</td>
<td>0.75</td>
<td>1</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S3</td>
<td>0.75</td>
<td>1</td>
<td>0.25</td>
<td>0.25</td>
<td>0.5</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S4</td>
<td>0.75</td>
<td>1</td>
<td>0.5</td>
<td>0.25</td>
<td>0.75</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S5</td>
<td>0.75</td>
<td>1</td>
<td>0.75</td>
<td>0.5</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S6</td>
<td>0.75</td>
<td>1</td>
<td>0.75</td>
<td>0.5</td>
<td>0.75</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S7</td>
<td>0.75</td>
<td>1</td>
<td>0.75</td>
<td>0.5</td>
<td>0.75</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S8</td>
<td>0.75</td>
<td>1</td>
<td>0.75</td>
<td>0.5</td>
<td>0.75</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S9</td>
<td>0.75</td>
<td>1</td>
<td>0.75</td>
<td>0.5</td>
<td>0.75</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6
The crisp values of suppliers’ involvement propensity for GSD programs.

<table>
<thead>
<tr>
<th>Suppliers</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.000</td>
<td>1.083</td>
<td>0.950</td>
<td>0.650</td>
<td>0.081</td>
<td>0.350</td>
<td>0.950</td>
<td>0.083</td>
<td>0.050</td>
</tr>
<tr>
<td>S2</td>
<td>0.950</td>
<td>1.083</td>
<td>0.050</td>
<td>0.950</td>
<td>0.083</td>
<td>0.050</td>
<td>0.000</td>
<td>0.417</td>
<td>0.350</td>
</tr>
<tr>
<td>S3</td>
<td>0.350</td>
<td>1.083</td>
<td>0.350</td>
<td>0.950</td>
<td>0.083</td>
<td>0.650</td>
<td>0.650</td>
<td>0.083</td>
<td>0.050</td>
</tr>
<tr>
<td>S4</td>
<td>0.950</td>
<td>0.750</td>
<td>0.050</td>
<td>0.650</td>
<td>0.000</td>
<td>0.000</td>
<td>0.350</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>S5</td>
<td>0.950</td>
<td>1.083</td>
<td>0.650</td>
<td>0.050</td>
<td>0.000</td>
<td>0.050</td>
<td>0.050</td>
<td>0.000</td>
<td>0.350</td>
</tr>
<tr>
<td>S6</td>
<td>0.000</td>
<td>1.000</td>
<td>0.050</td>
<td>0.050</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>S7</td>
<td>0.050</td>
<td>1.083</td>
<td>0.350</td>
<td>0.050</td>
<td>0.417</td>
<td>0.650</td>
<td>0.000</td>
<td>0.000</td>
<td>0.417</td>
</tr>
<tr>
<td>S8</td>
<td>0.950</td>
<td>0.750</td>
<td>0.650</td>
<td>0.050</td>
<td>0.083</td>
<td>0.050</td>
<td>0.950</td>
<td>0.000</td>
<td>0.050</td>
</tr>
<tr>
<td>S9</td>
<td>0.050</td>
<td>0.750</td>
<td>0.000</td>
<td>1.000</td>
<td>0.083</td>
<td>0.650</td>
<td>0.050</td>
<td>0.950</td>
<td>0.083</td>
</tr>
</tbody>
</table>

4.7. Evaluating suppliers’ involvement propensity for various GSD programs

The evaluation of suppliers’ involvement propensity for the various GSD programs utilizes grey-set evaluations. The original grey decision making matrix on involvement propensity needs to be initially elicited. We need to determine suppliers’ involvement propensity for each GSD program. The way of conducting this assessment here is to assign perception scores ranging from “No propensity to be involved in the GSD program” to “Very high propensity to be involved in the GSD program” for each supplier and for each GSD program. A five level of grey scale transformation is used in this case is shown in Table 4. The original grey decision making matrix for suppliers’ propensity of involvement into GSD programs is shown in Table 5. As seen in Table 5, S1’s propensity of involvement score for P1 is [0,0] (lower = 0, upper = 0), which, according to the belief of the general manager, indicates that S1 has a very low propensity to be involved with GSD program P1.

Using expressions (6)-(11), the modified-CFCS method, in Section 3.1, we arrive at the final crisp values of nine suppliers’ propensity of involvement into the nine GSD programs (see Table 6).

4.8. Calculating programs’ final comprehensive performance scores

Nine GSD programs’ final comprehensive performance scores are obtained through product sum calculations to values from column 3 to column 11 in Table 7. For example, the final score for P1 is calculated as:
first observe that P2, P3, P4 and P7 in Table 7 are the most effective
programs. In Table 3, we indeed observe that GSD program P4 has the lowest performance outcome score of 0.615. Table 3 also reveals that GSD program P5 (with score of 1) is the best program only evaluating programs’ supplier performance outcome. When integrating suppliers’ GSD program involvement propensity, P4 becomes the third best program overall and P5 becomes the worst program with the smallest score of 0.917 (see Table 7). The general manager did recognize that GSD programs’ supplier performance evaluation and suppliers’ involvement propensity should be simultaneously considered, to arrive at a more accurate portrayal of program success and adoption.

5. Interpretations and discussions

Tables 3 and 7 are the outputs of the methodology that provide useful analytical information for Company A in managing green supply chains. Interpreting these results appropriately can effectively provide managers and researchers with research or practical applications and insights.

In response to market and regulatory pressures focal companies in a supply chain need to, and do, recognize the importance of GSD programs. However, not all programs generate equally good operational and environmental outcomes and programs are rarely implemented simultaneously due to the limited resources and management capabilities. Thus, the necessity for formally evaluating GSD programs is evident.

In terms of specific analysis and interpretation of the results, we first observe that P2, P3, P4 and P7 in Table 7 are the most effective programs. P5 and P8 are relatively less effective, with the lowest scores (around 1). These results surprised the general manager. In his mind, P5 is pretty significant to improve suppliers’ environmental performance, while P4 is regarded as infeasible. In Table 3, programs’ supplier performance evaluation scores. That way, greater probability for success and adoption. One interpretation here is that supply chain focal company may seek to eliminate some programs to conserve limited resources, while still achieving good performance outcomes by initially executing the GSD programs with higher scores among suppliers. Before the evaluation process, the general manager paid much attention to P5. But after evaluating the programs holistically, P5 was eliminated.

The prioritization may not necessarily focus on eliminating programs, but for building ‘buy-in’ to certain GSD programs overall. That is, the management who realizes that some programs are more likely to give larger overall benefits, may seek to implement these more likely to be successful programs initially. In this way, organizational support for such programs may be larger due to early successes. Given that the final high scores of P2 and P7, the general manager of Company A planned to provide more support on the two programs. Thus, the results provide opportunities for order of implementation or exclusion of possibly non-performing GSD programs.

From a strategic viewpoint, Company A, aiming to improve suppliers’ performance in a green supply chain, could focus its attention on encouraging suppliers to be more greatly involved, especially in GSD programs with high supplier performance evaluation scores. That way, greater probability for success and adoption may occur. In this case, according to the experiences of the general manager, P3 (providing green technological advice to suppliers) is quite helpful for the performance improvement of suppliers (see Table 7). The general manager intended to encourage suppliers to be more involved in P3.

In terms of the capability of the ANP model, the general manager mentioned that the process was tough and cumbersome with so many pairwise comparisons. Separating the discussion into multiple phases over several days or by various groups may mitigate some of the fatigue. And the general manager informed that the interdependent consideration was a significant and valuable
trait for managers to make decision for GSD programs. Also the
general manager felt that ANP method is not difficult to learn.
Overall, the general manager regarded ANP model as an interesting
and useful approach.

6. Managerial Implications

A number of useful managerial implications could be derived
from the proposed technique, its general application to GSD, and
specific application in the real world case.

Firstly, the technique is very practical by providing a general
decision framework. Managers can more effectively structure their
decision and planning and determine the relative significance of
their GSD programs. The resulting outcomes of this methodology
would help managers prioritize their GSD programs focusing on
programs delivering greater supplier performance and higher sup-
pliers’ involvement propensity. This prioritization would help in
resource and investments allocations. Conversely, managers within
in a focal company may exclude or eliminate GSD programs with
low supplier performance outcome and low involvement propen-
sity of suppliers.

The sensitivity analysis allows managers to test the robustness
(stability) of their decisions. The practical implications of sensitivity
analysis may also present insights into what factors play a role
in how a project will ultimately perform. This may allow managers
to emphasize various performance or other factors in their analy-
sis. For example if some factors provide greater sensitivity to a final
solution, these factors may be put under greater scrutiny and re-
quire more rigorous and thoughtful evaluation.

Secondly, in order to effectively implement GSD programs that
may improve supplier performance, managers need to explicitly
and simultaneously consider suppliers’ involvement propensity
with respect to the GSD program. Some incentives (e.g. financial
support, prioritized order allocation) may be adopted by focal com-
panies to guarantee deeper involvement of suppliers in these pro-
grams. After all, without higher involvement propensity from
suppliers, a GSD program can wither and be much less effective.

Thirdly, as demonstrated in the real world case, suppliers that
intend to be highly participative in GSD programs (highly moti-
vated suppliers) require less effort or investments. Or at least there
may be greater returns on GSD investments with greater supplier
involvement propensity. In many cases, when compared with focal
companies, suppliers are smaller, and lack resources (tangible and
intangible) to implement such programs. Hence, it is easily under-
stood why P2 (transferring employees with environmental exper-
tise to suppliers) is highly rated by suppliers while P5 (transferring supplier employees with environmental expertise to
buying firm) is poorly rated. This result implies that focal compa-
nies should seek to lower the involvement cost of suppliers for
the viable implementation of GSD programs.

Another important managerial implication is that results will
vary depending on the case situation. A practical application of this
tool should be carefully conceived. The results of this case study may
not be generalizable. A careful analysis will need to be considered gi-
ven the competitive and organizational contexts of managers who
seek to apply this tool. The preference structure and modelling effort
is capable of taking uncertainties into consideration, and users of
this methodology should realize that the uncertainties also exist in
what factors should be included and managerial perceptions associa-
ted with the factors and their relationships.

7. Conclusions

In this paper, using ANP and grey system theory, we introduce a
novel multi-stage grey-ANP based methodological approach for
evaluating green supplier development programs. The introduction of
a grey-ANP based methodology represents one of the few formal
models developed for evaluating GSD programs. ANP is used to
evaluate the programs’ supplier performance. The grey method
encompasses and integrates the uncertainties associated with
evaluating suppliers’ GSD program involvement propensity. Jointly,
the ANP and grey method are valuable not only because of the final
results, but in providing a structured process for exploring the
alternative GSD programs and determining the relationships of
clusters and factors. The efficacy of the method is also testified by
a real world case.

This methodology can act as a valuable decision support tool for
supply chain managers. It can also aid focal companies in supply
chains to effectively plan, design and manage their GSD programs.
Various GSD programs may exist as alternatives for focal com-
npanies. The evaluation and selection of the programs can contribute
to organizational resources saving for both focal companies and
their suppliers.

With significant practical and theoretical advantages, the study has limitations. The supplier–buyer relationships here are
regarded as isolated dyads. We do not fully integrate the network
relationships among suppliers and buyers in supply chains in the
current model. For example, reasons for involvement propensity
in GSD programs may arise to existing relationships in suppliers’
other networks. In addition, the programs’ supplier performance
measurement in the paper only considers operational and environ-
mental factors. Broader social factors, expanding into other dimen-
sions of sustainability, such as child labour and gender
discrimination should be further integrated, as international com-
panies are increasingly acknowledging the significance of social is-
sues like human rights, labour and corruption (Rivoli, 2003). Expansion of the ANP model to integrate a more extensive bene-
fits/costs/opportunities/risk (BCOR) set of decision networks may
also provide greater insights for managers.

Another extension of the methodology is to more fully consider
other possible inter-relationships that may exist. For example, an-
other consideration is that implementation success of some GSD
programs may influence other GSD programs. A more thorough
relationship analysis to determine influence of GSD programs on
each other and other programs can be completed through another
methodological stage utilizing tools such as DEMATEL (Gabus and
Fontela, 1973; Fontela and Gabus, 1976). All these limitations and
extensions provide ample opportunity for future research in eval-
uation and implementation of GSD programs.

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