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RESEARCH ARTICLE

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Green supplier selection for sustainable development of the automotive industry using grey decision-making

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Abstract

Sustainable development is a common global theme of the 21st century. Global environmental issues have attracted increasing public attention in recent years. As one of the most important industries in Taiwan, the automotive industry needs to implement green supply chain management to comply with current trends, and the selection of suppliers of green parts is particularly important in this regard. Supplier selection is a classic case of multiple-criteria decision-making (MCDM). A traditional method, called the decision-making trial and evaluation laboratory (DEMATEL)-based analytical network process (ANP) (DANP), is appropriate to solve the problem of supplier selection. This study proposes a novel variant of DANP, called grey DANP, to effectively reduce the huge problem arising from pairwise comparisons. An empirical study was used to demonstrate the usefulness of the proposed grey DANP. It contributes to finding the key factors of selecting green suppliers for Taiwan's automotive industry, including technology, delivery time, environmental management system and pollution control. The cause–effect relationships among key factors indicate that the environmental management system should be given more attention by manufacturers in the selection of green suppliers.

KEYWORDS

analytical network process, DEMATEL, green supplier, grey relational analysis, MCDM, sustainable development

1 | INTRODUCTION

The automotive industry in Taiwan has emerged as one of the country's most important industries in recent decades. Because automotive parts are sourced from several industries (e.g., mechanical, electronic, chemical and information industries), growth in the automotive industry can promote the development of others (Huang & Hu, 2013). However, the Taiwanese automotive industry is facing an unprecedented challenge. Greater public consciousness of issues related to environmental protection worldwide has prompted several countries to set up green barriers to restrict international trade. Thus, Taiwanese automotive vehicles exported to the international market must comply with environmental protection standards. Green supply chain management (GSCM), which is a powerful weapon to break down the green barriers of the international market (Sharma, Chandna, & Bhardwaj, 2017; Vachon, 2010; Vermeulen & Ras, 2006), has emerged as the focus of attention in the automotive industry.

Srivastava (2007) described GSCM as a combination of environmental thinking and SCM that encompasses product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumer, and end-of-life management of the product (Tseng & Chiu, 2013). In general, GSCM is understood to involve screening suppliers based on environmental performance, and doing business only with those that meet certain environmental regulations or standards (Rao, 2002). This complex management problem—supplier selection and evaluation—is a classic case of multiple-criteria decision-making (MCDM) (Huang & Keskar, 2007; Liao & Rittscher, 2007), and the decision criteria have interdependent impacts (Hu, Chiu, Hsu, & Chang, 2015).

Methods based on MCDM are often used to address problems characterized by several incommensurable and conflicting (competing) criteria, where no one solution satisfies all criteria simultaneously Ou Yang, Shieh, & Tzeng, 2013). An increasing number of studies have addressed issues related to green supplier selection using MCDM methods. Tsai et al. (2015) applied Fuzzy DEMATEL (decision-making trial and evaluation laboratory) to examine the environmental performance of manufacturers. Dweiri, Kumar, Khan, and Jain (2016) proposed a decision support model for supplier selection based on the analytical hierarchy process (AHP) using the case of the automotive industry in Pakistan. Sarkis (2003) applied the analytical network process (ANP) to identify the key components and elements of GSCM, and explored its applicability for decision-making within the green supply chain. Using DEMATEL, Hsu, Kuo, Chen, and Hu (2013) recognized influential criteria for carbon management in the green supply chain, which can improve the overall performance of suppliers in terms of carbon management. To accommodate the vagueness of human perception, Lin (2013) used fuzzy set theory and DEMATEL to form a structural model to determine the cause-and-effect relationships among criteria. Tseng and Chiu (2013) used a Taiwanese printed circuit board manufacturer as an example to identify appropriate criteria for supplier selection through fuzzy theory. Kuo, Hsu, and Li (2015) applied a hybrid MCDM method called the DEMATEL-based ANP (DANP) (Ou Yang, Shieh, Leu, & Tzeng, 2008) to determine both the importance of evaluation criteria in selecting suppliers for an electronics company and the causal relationships between them.

However, the methods proposed in previous research on green supplier selection have some limitations. First, the AHP method requires that aspects and criteria be independent of one another, which is not common in practice (Saaty, 1980). Second, ANP can accommodate interdependence and feedback among criteria and alternatives (Saaty, 1996), but a serious problem is that consistent pairwise comparisons are not easy to achieve (Hu & Tsai, 2006), especially for a matrix with high order, because of limitations in human cognition and shortcomings in the typically used one-to-nine scale (Xu & Wei, 1999). Moreover, either DEMATEL or the original DANP must generate a direct influence matrix involved in pairwise comparisons. Another problem is that the greater the number of factors, the greater the extent to which a respondent needs to finish an initial direct influence matrix. Therefore, the quality of the outcome may be influenced to a greater or lesser degree as respondents become bored, tired or inattentive while completing a long and complex questionnaire.

Thus, an MCDM technique is needed to automatically generate the direct influence matrix for multiple criteria. Grey relational analysis (GRA) proposed by Deng (1982) can be used to effectively measure the degree of relationships between the given data sequences or patterns (Hu, 2008, 2013, 2014, 2016; Hu, Chen, Hsu, & Tzeng, 2002; Liu & Lin, 2006). Therefore, in this study, we propose a grey DANP (GDANP) decision model that combines GRA and DANP to solve the aforementioned problems. The main difference between DANP and GDANP is that the latter employs GRA to automatically generate the direct influence matrix from a Delphi questionnaire, instead of asking respondents to complete the direct influence matrix.

A few grey-based decision-making models have been proposed in the literature. Li, Yamaguchi, and Nagai (2007) and Golmohammadi and Mellat-Parast (2012) used grey numbers to describe linguistic variables to obtain the weights of each attribute. Some grey DEMATEL-based methods have also been proposed (Liang et al., 2016; Rajesh & Ravi, 2015; Su et al., 2016; Xia, Govindan, & Zhu, 2015), but they use a specific grey number to describe each element in the direct influence matrix. In addition, a new method combining D-number theory and DEMATEL, namely D-DEMATEL, was proposed by Zhou, Shi, and Deng (2017). This technique was used to identify the critical success factors in emergency management. In this method, direct relations of influential factors evaluated by multiple experts are presented as intuitionistic fuzzy numbers. Thereafter, the intuitionistic fuzzy numbers are converted into D-numbers, using the combination rule of D-numbers to fuse group opinions. Herein, the proposed method, namely GDANP, differs from these grey-based methods in two main ways: first, it uses the GRA to generate the direct influence matrix and, second, it then combines DEMATEL and ANP to provide the final decision structure.

The remainder of this paper is organized as follows. Section 2 reviews the related literature on green supplier selection and establishes the prototype decision structure, and Section 3 introduces the proposed GDANP model. Section 4 applies the proposed method to identify key factors for green supplier selection for the Taiwanese automotive industry using the outcomes of the Delphi method. Section 5 discusses the various outcomes, and provides the conclusions of this study.

2 | ESTABLISHING THE DECISION STRUCTURE

Automotive manufacturers and their suppliers form an industrial symbiosis. Industrial symbiosis makes a major contribution to achieving a win-win status in supply-chain networks (Tseng & Bui, 2017). The relationships between automotive manufacturers and suppliers have changed over the years, from a vertical integration model into the development of partnerships (Liu & Chen, 2013). Manufacturers outsource a large number of automotive parts to form a complex and competitive supply chain consisting of several suppliers operating synergistically (Ghodsypour & O'Brien, 2001; Yang, Lai, Wang, Rauniar, & Xie, 2015). Therefore, the process of selecting a suitable automotive parts supplier has become a top priority for automotive manufacturers (Baraldi, Proença, Proença, & de Castro, 2014).

A large number of studies dedicated to supplier selection based on conventional criteria have been published. Weber, Current, and Benton (1991) proposed that the ability to establish long-term relationships with direct or indirect suppliers is a key factor when selecting suppliers; they considered price, delivery time and quality as the top three factors in order of importance. Choi and Hartley (1996) summarized a series of criteria that affect supplier selection, such as consistency, relationships, flexibility, technology, customer service, reliability and price. A large number of similar studies have been conducted (Barbarosoglu & Yazgac, 1997; Chen, 2012; Chopra & Meindl, 2006; Ghodsypour & O'Brien, 2001; Hsu, Kannan, Keong

Leong, & Tan, 2006; Huang & Hsu, 2008; Nepal, Lassan, Drow, & Chelst, 2009; Pernot & Roodhooft, 2014; Schmitz & Platts, 2004; Tuli, Kohli, & Bharadwaj, 2007; Ulaga & Reinartz, 2011). Traditional supplier assessment indicators have become the basis of supplier assessment modes.

However, in some cases, there is a trade-off between environmental criteria and traditional economic criteria when selecting suppliers. Indeed, an increasing number of authors have addressed supplier selection issues in green supply chains viewed from the environmental perspective (Sarkis, 2003). Lee, Kang, Hsu, and Hung (2009) used the high-tech industry as an example and claimed that quality, environmental management, pollution control, technical ability, green product characteristics and green competitiveness are the key factors for supplier selection. Kannan, Khodaverdi, Olfat, Jafarian, and Diabat (2013) proposed that logistics costs be regarded as a key indicator in evaluating green suppliers. Yazdani (2014) formulated ten green factors for automotive manufacturers in supplier selection: green production capacity, green price, green quality, green design, green materials, green environmental management system, green talent cultivation, green waste management plan, recycling rate of green products, and green product recovery rate. Govindan, Khodaverdi, and Vafadarnikjoo (2015) identified internal management support, and green procurement and certification of ISO 14001 as the most significant factors in the practices of green suppliers. They also claimed that quality, price and delivery time are factors that should engage Taiwanese automotive manufacturers.

It is reasonable to consider both economic and environmental aspects in selecting suppliers of products because this closely mirrors management practices. The prototype framework of this study is based on the research by Hashemi, Karimi, and Tavana (2015). Other factors that were integrated into the framework were based on a literature review, according to similarities in definitions and semantics. The prototype framework considers two aspects and 23 criteria, as shown in Tables 1 and 2.

3 | GREY DEMATEL-BASED ANP (GDANP)

The proposed GDANP consists of DEMATEL and the ANP, but the main difference between DANP and GDANP is that the latter employs GRA to automatically generate the direct influence matrix from the Delphi questionnaire instead of asking respondents to complete the direct influence matrix. Therefore, we organize this section as follows. Section 3.1 introduces the Delphi method and its outcomes. Section 3.2 presents the framework of the DANP method, and Section 3.3 explains how to generate the direct influence matrix

TABLE 1 Economic aspects in prototype framework

Aspect	Criteria	References
Economic aspect	Cost	Dickson (1966), Weber et al. (1991), Choi and Hartley (1996), Kannan et al. (2013), Yazdani (2014), Hashemi et al. (2015).
	Quality	Dickson (1966), Weber et al. (1991), Choi and Hartley (1996), Lee et al. (2009), Kannan et al. (2013), Yazdani (2014), Hashemi et al. (2015).
	Delivery time	Dickson (1966), Weber et al. (1991), Choi and Hartley (1996), Kannan et al. (2013), Hashemi et al. (2015).
	Technology	Dickson (1966), Weber et al. (1991), Choi and Hartley (1996), Lee et al. (2009), Kannan et al. (2013), Hashemi et al. (2015).
	Flexibility	Dickson (1966), Weber et al. (1991), Choi and Hartley (1996), Hashemi et al. (2015).
	Culture	Dickson (1966), Weber et al. (1991), Choi and Hartley (1996), Hashemi et al. (2015).
	Innovative relationships	Dickson (1966), Weber et al. (1991), Choi and Hartley (1996), Hashemi et al. (2015).
	Financial situation	Dickson (1966), Weber et al. (1991), Choi and Hartley (1996);
	Geographical position	Dickson (1966), Weber et al. (1991), Choi and Hartley (1996);
	Supplier performance award	Choi and Hartley (1996).

TABLE 2 Environmental aspects in prototype framework

Aspect	Criteria	References
Environmental aspect	Green production	Lee et al. (2009), Hashemi et al. (2015).
	Pollution control	Lee et al. (2009), Hashemi et al. (2015).
	Resource consumption	Lee et al. (2009), Yazdani (2014), Hashemi et al. (2015).
	Ecological design	Lee et al. (2009), Kannan et al. (2013), Yazdani (2014), Govindan et al. (2015), Hashemi et al. (2015).
	Environmental management system	Lee et al. (2009), Kannan et al. (2013), Yazdani (2014), Govindan et al. (2015), Hashemi et al. (2015).
	Green image	Lee et al. (2009), Hashemi et al. (2015).
	Green competitiveness	Lee et al. (2009), Govindan et al. (2015), Hashemi et al. (2015).
	Green product	Lee et al. (2009), Govindan et al. (2015), Hashemi et al. (2015).
	Staff environmental training	Lee et al. (2009), Yazdani (2014), Govindan et al. (2015), Hashemi et al. (2015).
	Management commitment	Lee et al. (2009), Govindan et al. (2015), Hashemi et al. (2015).
	Carbon management	Hsu et al. (2013), Govindan et al. (2015).
	Supplier environmental cooperation	Govindan et al. (2015).
	Customer environmental cooperation	Govindan et al. (2015).

using GRA. Section 3.4 highlights the advantages of the proposed GDANP.

3.1 | Delphi method

The Delphi method was proposed by the RAND Corporation in the 1950s (Schmidt, 1997). The objective was to develop a technique to obtain the most reliable consensus of a group of experts (Dalkey & Helmer, 1963; Devaney & Henchion, 2018). Researchers applied this method primarily to cases where judgmental information was indispensable, and typically used a series of questionnaires interspersed with controlled feedback (Rowe, Wright, & Bolger, 1991). Ou Yang et al. (2008) indicated that the Delphi method depends on experts' experience, instincts and values to determine outcomes. In practice, experts from different fields are usually expected to provide varying perspectives on a topic. They can understand one another's perspectives in one round of the questionnaire, and adjust their own perspectives in the next round to attain consistency (Hu et al., 2015). Briefly, this process avoids direct confrontation among the experts (Okoli & Pawlowski, 2004). The Delphi method has been successfully used in a wide variety of situations as a tool for expert group decision-making (Hu et al., 2015; Keil, Lee, & Deng, 2013; Nevo & Chan, 2007; Ou Yang et al., 2008).

Okoli and Pawlowski (2004) proposed a “ranking-type” Delphi method to develop group consensus about the relative importance of issues. The consensus deviation index (CDI) was applied to indicate the degree of common consensus. The greater the CDI, the weaker the common consensus (Hu et al., 2015).

The procedure of the Delphi method as explained by Hu et al. (2015) is briefly summarized in Figure 1. For the proposed model, we assume that there are u ($u \geq 2$) aspects that can be defined beforehand, where each factor can be categorized into a single aspect. Let factor l in aspect p be represented as x_{pl} ($1 \leq l \leq c_p$), and factor i in aspect q be represented as x_{qi} ($1 \leq i \leq c_q$), where c_p and c_q denote the number of factors in aspects p and q, respectively, $c_1 + c_2 + .. . + c_u = n$, and a_{plt} represents the necessity for factor x_{pl} to be included in the research structure according to expert t. The general outcomes of the Delphi method are displayed as the decision matrix shown in Table 3.

3.2 | DEMATEL-based ANP (DANP)

The traditional ANP faces a thorny problem: due to the limitations of human cognition, especially for questionnaires of a high order, it is difficult to achieve consistency (Xu & Wei, 1999). A hybrid MCDM method called DANP can effectively solve this problem as it is free of the consistency test (Ou Yang et al., 2008). The DANP method directly uses the total influence matrix generated by DEMATEL as an

TABLE 3 The general decision matrix of Delphi outcomes

		Expert				
Aspect	Criteria	E_1	E_2	E_3	...	E_t
X_p	x_{p1}	a_{p11}	a_{p12}	a_{p13}	...	a_{p1t}
	x_{p2}	a_{p21}	a_{p22}	a_{p23}	...	a_{p2t}
	x_{p3}	a_{p31}	a_{p32}	a_{p33}	...	a_{p3t}
	x_{pl}	a_{pl1}	a_{pl2}	a_{pl3}	...	a_{plt}

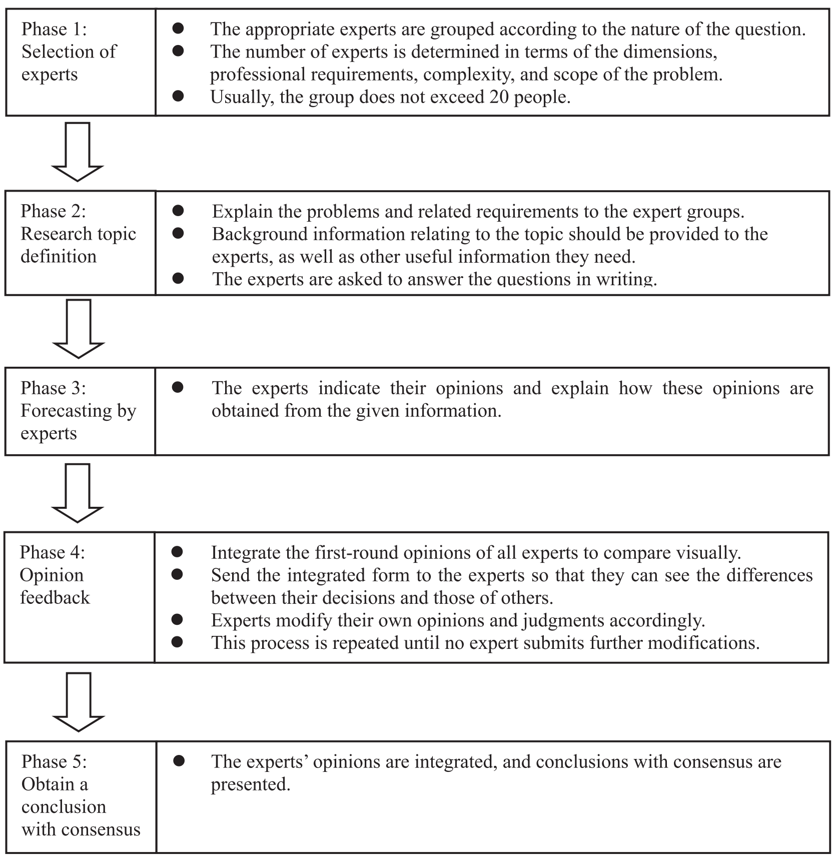

FIGURE 1 Procedure of the Delphi method

unweighted supermatrix of the ANP to avoid troublesome pairwise comparisons (Tzeng & Huang, 2011). Moreover, Hu et al. (2015) proposed a variant of DANP with some distinctive features. The details of DANP are given by Hu et al. (2015) and Tzeng and Huang (2011).

3.3 | Generating the direct influence matrix by GRA

According to grey theory proposed by Deng (1982), certain relationships exist between any two objects (Hu et al., 2002). Therefore, in multiple-criteria decision-making problems, each alternative takes the form of a data sequence, and certain relationships exist between any two data sequences (Hu, 2008; Liu & Lin, 2006). However, comparative sequences exist simultaneously with multiple reference sequences in some cases. Undoubtedly, the grey relational matrix is an appropriate approach for analyzing relationships among comparative sequences and multiple reference sequences (Liu & Lin, 2006). Unlike statistical correlation analysis, which measures the relationship between any two random variables, GRA can find the relationships between a given reference sequence and several comparative sequences by viewing the reference sequence as the desired goal (Hu et al., 2002). This motivates us to use GRA to find relationships among criteria to automatically generate the direct influence matrix.

Let x_{pl} = (x_{pl1}, x_{pl2}. .. x_{pls}) ($1 \leq l \leq c_p$) be a reference pattern, and x_{qi} = (x_{qi1}, x_{qi2}. .. x_{qis}) ($1 \leq i \leq c_q$) be a comparative pattern. The operation procedure using the grey relational matrix is then as follows.

Step 1: Grey relational coefficient calculation

Let ξ_k (x_{qi}, x_{pl}) denote a grey relational coefficient, which indicates the relationship between x_{qi} and x_{pl} on attribute k ($1 \leq k \leq s$). Then,

$$\xi_k(x_{qi}, x_{pl}) = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\Delta_{isk} + \rho\Delta_{\max}}, \tag{1}$$

where ρ is the discriminative coefficient ($0 \leq \rho \leq 1$) and usually ρ = .5:

$$\Delta_{min} = \min_{i=1..c_q} x_{plj} - x_{qij} \,|\,; \tag{2}$$

$$\Delta_{max} = \max_{i=1..c_q} |x_{plj} - x_{qij}|; \tag{3}$$

and

$$\Delta_{ilk} = |\, x_{plk} - x_{qik} \,| \tag{4}$$

Step 2: Grey relational grade calculation

The grey relational grade (GRG) indicates the grade of the relationship between x_{qi} and x_{pl}, and can be represented in this implementation as:

$$z\,(xqi, xpl) = \sum_{k=1}^{s} w_k \xi_k(x_{qi}, x_{pl}), \tag{5}$$

where w_k is the relative importance of attribute k, z (x_{qi}, x_{pl}) ranges from 0 to 1, and the sum of w_1, w_2. .. w_n is 1.

Step 3: Obtaining the grey relational matrix

The direct influence matrix $\boldsymbol{Z}$ is a partitioned matrix consisting of u^2 segments, where each segment represents a relationship between two aspects of a system, and the segment related to the relationship between aspects p and q is

$$Z_{qp} = \begin{bmatrix} z(x_{q1}, x_{p1}) & z(x_{q1}, x_{p2}) & \dots & z(x_{q1}, x_{pc_p}) \\ z(x_{q2}, x_{p1}) & z(x_{q2}, x_{p2}) & \dots & z(x_{q2}, x_{pc_p}) \\ \vdots & \vdots & \ddots & \vdots \\ z(x_{qc_q}, x_{p1}) & z(x_{qc_q}, x_{p2}) & \dots & z(x_{qc_q}, x_{pc_p}) \end{bmatrix}, \text{for } 1 \leq p, q \leq u. \tag{6}$$

When p = q, the corresponding segment is called a grey self-relational matrix. Then, z (x_{qi}, x_{qi}) in Z_{qq} can be set to zero to conform to the requirement of DEMATEL. Instead of requiring respondents to complete the direct influence matrix, in the proposed GDANP we use the GRA to directly generate this matrix using responses from the Delphi questionnaire.

The flowchart of the proposed GDANP is shown as Figure 2.

First, a few methods that are easier to use (such as normalization and the weighted average approach) may be used to solve the decision problem stated in Table 3. However, these simple techniques cannot identify relationships among factors; thus, we cannot apply them to derive Z from Table 3. Instead, GRA is an appropriate method for this task because it can measure certain relationships among patterns. In fact, GRA can find relationships between a given reference sequence and several comparative sequences (Deng, 1982) by viewing the reference sequence as the desired goal (Hu et al., 2002).

Second, consistent pairwise comparisons (e.g., as measured using a consistency index, CI) are not easy to achieve, especially for a matrix with high order (Xu & Wei, 1999). However, a consistency-like test, CDI, proposed by Okoli and Pawlowski (2004) is still needed in the proposed method. However, there are many differences between CDI and CI, as summarized in Table 4. As shown in Table 4, CI and CDI are different from each other.

Third, to illustrate the better performance of the proposed method, three DEMATEL-related methods are addressed, namely the combination of DEMATEL with the ANP (DEMATEL + ANP), the DANP and the GDANP, respectively (Jiang, 2017). Furthermore, we analyze the complexity of these methods.

Assuming that n factors have been collected before the Delphi survey, we analyze the number of items that a respondent can be asked to complete.

Delphi survey: Assume m rounds are required for the survey. Then, each expert can be asked to rate n items in each round. After m rounds are finished, each expert has provided input on mn items. In the worst case, m = 3 is sufficient to complete a whole Delphi survey.

Initial direct influence matrix: Each respondent can be asked to complete $n^2 - n$ items.

Pairwise comparisons: In the worst case, C_2^n pairwise comparisons can be performed for each factor. Therefore, nC_2^npairwise comparisons should be completed by each respondent.

Consequently, if a respondent participates in the aforementioned three types of surveys, the respondent will be asked to complete (mn + ($n^2 - n$) + nC_2^n) items. Letting m = 3, a comparison with different values of n is depicted in Figure 3. Evidently, the great advantage of the GDANP over the other DEMATEL-related methods is that

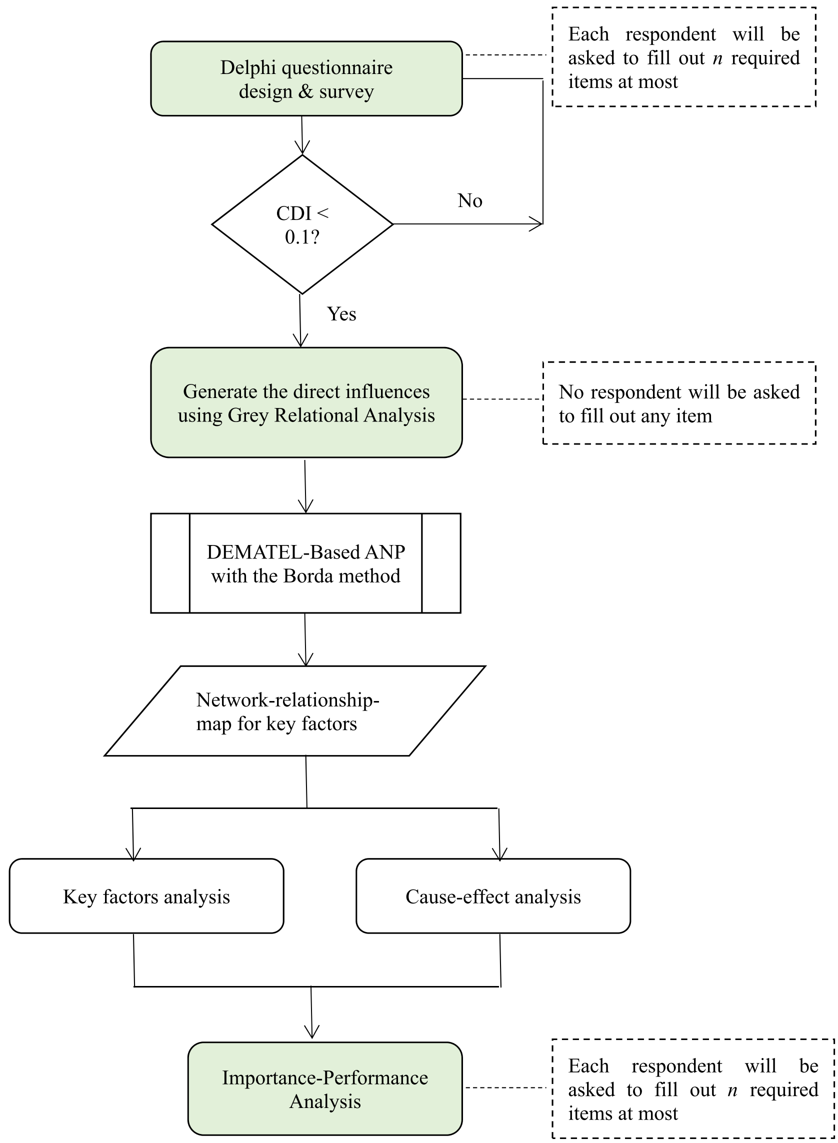

FIGURE 2 Flowchart of the proposed GDANP using the Delphi method [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Comparisons between consensus deviation index (CDI) and consistency index (CI)

	CDI	CI
Meaning	The CDI is used to indicate the degree of common consensus, especially in the Delphi process (Hu et al., 2015). The CDI test is a consensus test for a single item. CDI is not affected by the number of items.	The CI test is one of the critical components in traditional analytical network process (Kwiesielewicz & Van Uden, 2004). CI is used to judge the accuracy and reliability of a comparison pairwise matrix. CI is hugely affected by the number of items.
Scale	CDI is concerned with differences in expert ratings. The ratings could be various, such as 1–5, 0–100, etc.	CI is used to measure the degree of interaction for pairwise comparison of a 17-point scale,i.e., 9:1, 8:1, 7:1,. .. 1:9.
Formula	CDI = (standard deviation)/(mean value)	CI = $(\lambda_{max} - n)/(n - 1)$
Criterion for judgment	The judgment standard is set as 0.1; if CDI < 0.1, the item should be included in the formal decision structure.	The judgment standard is set as 0.1; if CI < 0.1, the weights obtained from the comparison pairwise questionnaire are reliable.

considerable time can be saved because the GDANP does not include a survey for the initial direct influence matrix and pairwise comparisons. This time-saving method may well result in better expert evaluations by avoiding respondent fatigue that can occur during the completion of long and complex questionnaires.

One of the greatest contributions of this paper is successfully changing the tasks involved in executing the DANP from a higher complexity class to a lower complexity class. This change can improve such combination work in both the best and the worst cases, as shown in Table 5.

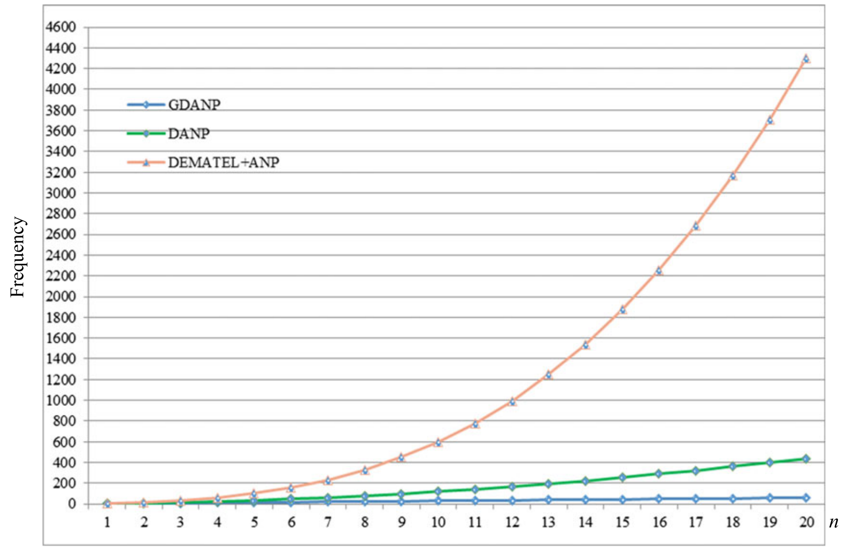

FIGURE 3 The maximum number of items for each model that a respondent is asked to fill out [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 The number of items for each model that a respondent is asked to fill out in the best and worst case

Method	Best case (m = 1)	Worst case (m = 3)
DEMATEL + ANP	$n^2 + nC_2^n$	$2n + n^2 + nC_2^n$
DANP	n^2	$2n + n^2$
GDANP	n	$3n$

4 | EMPIRICAL STUDY

4.1 | Determining the formal decision structure

Most decision-makers make decisions based on subjective opinion and experience, but this approach can lead to wrong decisions. The Delphi method is an appropriate choice for decision-makers to attain consensus in decision-making (Okoli & Pawlowski, 2004). In this study, an expert group consisting of eight managers, Experts A–H in Table 6, each of whom had worked for more than 10 years in Taiwan's automotive industry, was selected. The professional backgrounds of the eight experts are shown in Table 6.

Two aspects and 23 criteria (Tables 1 and 2) were identified from a literature review. After the first round of the Delphi survey, all these indicators were integrated according to similarities in definition and semantics by the eight experts, from which two aspects and 12 criteria (Table 7) were selected for the prototype research architecture. As indicated in Table 7, the CDI in the Delphi method of each factor was lower than 0.1 after the third round, which meant that all eight experts had reached a consensus on the importance of the criteria. Following discussion, the experts agreed to set an average value of 90 points as the threshold value. As a result, criteria whose values were less than 90 were deleted due to insufficient importance. Two aspects and eight criteria were thus considered in the formal decision structure as shown in Table 8. The data required by the construction of the grey relational matrix were obtained as shown in Table 8.

Table 9 summarizes the importance scores of the criteria in the formal framework. The economics aspect (X_1) and the environment

TABLE 6 Professional backgrounds of the selected eight experts for the Delphi survey

Expert	Organization	Duties	Seniority (yr)
A	Technical and Customer Service Department, Commercial Vehicles Service Division, Hotai Motor Co., Ltd.	Specialist	15–20
B	Body Development Division Engineering, Hua-chuang Automobile Information Technical Center Co., Ltd.	Development Engineer	15–20
C	Vehicle Production Engineering Group Production Engineering Department, Yulon, Motor Co., Ltd.	Engineer	10–15
D	Quality Technology Section, China Motor Corporation	Senior Manager	20–30
E	Production Control Management Division, China Motor Corporation	Project Manager	20–30
F	Parts Quality Group TCS (Total Customer Satisfaction Dept.), Yulong Nissan Motor Corporation	Parts Quality Group Manager	20–30
G	Management Department, Fong Yue Automotive Parts Co., Ltd.	Purchasing Manager	20–30
H	Manufacturing department, Lee Na Enterprise Co., Ltd.	Section Manager	20–30
I	Parts Quality Control Section V Quality Control Division, China Motor Corporation	Team Leader	25–30
J	Body Development Division Engineering Development Engineer, Hua-chuang Automobile Information Technical Center Co., Ltd.	Engineer	10–15

TABLE 7 Scores of criteria necessity

Aspects	Criteria	Experts A	B	C	D	E	F	G	H	Average value	SD	CDI
Economics	Cost	90	100	100	90	100	100	100	100	97.500	4.629	0.046
	Quality	100	100	100	100	100	100	100	100	100.000	0.000	0.000
	Technology	80	100	100	100	90	100	100	90	95.000	7.559	0.076
	Delivery time	90	95	100	100	90	100	70	90	91.875	9.978	0.100
	Flexibility	70	90	80	80	80	90	100	80	83.750	9.161	0.092
	Culture	70	80	70	80	80	80	100	80	80.000	9.258	0.093
Environment	Environmental management system	90	95	90	100	90	100	100	90	94.375	4.955	0.050
	Ecological design	80	85	80	100	90	90	100	100	90.625	8.634	0.086
	Pollution control	90	85	90	100	90	90	100	90	91.875	5.303	0.053
	Management commitment	80	90	90	100	90	90	100	90	91.250	6.409	0.064
	Carbon footprint management	80	85	70	90	80	70	70	90	79.375	8.634	0.086
	Cooperative environment	80	75	70	90	80	80	100	80	81.875	9.234	0.092

TABLE 8 Formal decision structure for the case study

Aspects	Criteria	Descriptions
Economics	Cost	Provide customers with reasonable parts, packing and logistics costs, with the option of reducing the cost of products. Have the ability to respond quickly to price changes.
	Quality	Ensure acceptable quality of goods. Produce products that meet the customers' quality consistency and reliability demands. Improve the production process, and reduce the occurrence and reoccurrence of defective products. Establish a comprehensive quality management system. Get third-party professional certification.
	Technology	Have sound product development and organizational capabilities. Have a perspective on market demand for the future. Be innovative in product design, use of raw materials, production processes, and customer collaboration to meet future market demand.
	Delivery time	Provide timely and accurate delivery at the agreed time. Use a delivery management mechanism that responds to market changes.
Environment	Environmental management system	Implement a sound environmental management certification system, such as ISO 14000. Comply with environmental laws and regulations. Implement an internal control process of environmental management.
	Ecological design	Known as green design, life cycle design or environmental design, ecological design includes the environmental factors of design to help determine the direction of design decisions. Eco-design requirements for environmental factors are considered in all stages of product development to reduce the impact of the life cycles of products on the environment, and ultimately lead to more sustainable production and consumption systems.
	Pollution control	Exhibits the ability to manage and control the pollutants produced in the product design, the manufacturing process, etc. Controls pollutants including gas emissions, wastewater, solid waste, etc. Targets emission reductions and proposes an effective improvement plan.
	Management commitment	Support exists from top managers in their commitment to the environment. Managers agree with the concept of green supply chain management. Demonstrates corporate social responsibility.

TABLE 9 Scores of formal criteria necessity

Aspects	Criteria	Experts A	B	C	D	E	F	G	H
Economics (X_1)	Cost (x_{11})	90	100	100	90	100	100	100	100
	Quality (x_{12})	100	100	100	100	100	100	100	100
	Technology (x_{13})	80	100	100	100	90	100	100	90
	Delivery time (x_{14})	90	95	100	100	90	100	70	90
Environment (X_2)	Environmental management system (x_{21})	90	95	90	100	90	100	100	90
	Ecological design (x_{22})	80	85	80	100	90	90	100	100
	Pollution control (x_{23})	90	85	90	100	90	90	100	90
	Management commitment (x_{24})	80	90	90	100	90	90	100	90

aspect (X_2) (i.e., r = 2) consist of four factors each (i.e., $c_1 = c_2 = 4$). Therefore, n = 8. Each factor was assessed by eight experts (i.e., s = 8).

For DANP, the direct influence matrix was obtained from respondents through questionnaires. However, the proposed model generated the direct influence matrix by using GRA to integrate the importance scores of the criteria, where Z can be automatically obtained through partitioning it into four segments (i.e., Z_{11}, Z_{12}, Z_{21}, Z_{22}).

4.2 | Generating the initial direct influence matrix using GRA

Because the measurement scales are identical in this study, there is no need to consider normalization. Thus, the GRGs for Z_{11}, Z_{12}, Z_{21} and Z_{22} were calculated using Equations (1)–(5).

In this case, u = 2, and thus Z has four matrix segments, where each matrix segment represents a relationship between economics and the environment. The partitioned matrix represents the relationships between any two factors, and may be used to generate the initial direct influence matrix. Therefore, z (x_{qi}, x_{qi}) was set to zero to conform to the requirements of DEMATEL, and the segments related to the relationships between economics and the environment were obtained using Equation (6), as shown in Table 10.

4.3 | Determining the total influence matrix

Following the DEMATEL method, the normalized direct influence matrix was obtained by normalizing the initial direct influence matrix. Because $T = X(I - X)^{-1}$, the total influence is as shown in Table 11, and the prominence and relations of each factor are as shown in Table 12. According to Table 12, the environmental management system (x_{21}), ecological design (x_{22}), pollution control (x_{23}) and management commitment (x_{24}) criteria were divided into the "cause group," whereas the "effect group" included the cost (x_{11}), quality (x_{12}), technology (x_{13}) and delivery time (x_{14}) criteria.

4.4 | Identifying key factors

The weighted supermatrix obtained by normalizing the total influence matrix, and Table 13 shows the limiting supermatrix derived from the weighted supermatrix. Table 14 shows the overall ranking of factors, arranged in ascending order of the sum of rankings for each factor.

Given the importance of green supplier selection, as presented in Table 14, the criteria were ranked as $x_3 > x_{21} > x_{14} > x_{24} > x_{12} > x_{11} > x_{22}$, and $x_{14} = x_{23}$ according to the overall ranking obtained using the

TABLE 12 Prominence and relation of each factor

Factor	d	r	$d + r$	$d - r$
x_{11}	9.8829	10.4370	20.3199	−0.5541
x_{12}	10.0756	10.5837	20.6593	−0.5081
x_{13}	11.0424	11.3439	22.3863	−0.3014
x_{14}	10.6369	10.6389	21.2758	−0.0021
x_{21}	10.8876	10.6170	21.5046	0.2706
x_{22}	9.8231	9.4833	19.3064	0.3398
x_{23}	10.7119	10.3325	21.0444	0.3793
x_{24}	10.6154	10.2394	20.8548	0.3761

TABLE 10 The initial direct influence matrix

	x_{11}	x_{12}	x_{13}	x_{14}	x_{21}	x_{22}	x_{23}	x_{24}
x_{11}	0.0000	0.9000	0.8000	0.7354	0.7083	0.5917	0.6125	0.5625
x_{12}	0.9000	0.0000	0.8286	0.7354	0.7083	0.6333	0.6125	0.6042
x_{13}	0.8000	0.8286	0.0000	0.8354	0.8333	0.7167	0.7375	0.8125
x_{14}	0.7354	0.7354	0.8354	0.0000	0.8667	0.6452	0.7667	0.7354
x_{21}	0.7688	0.7688	0.8688	0.8667	0.0000	0.5833	0.8333	0.7708
x_{22}	0.6661	0.6946	0.7661	0.6452	0.5833	0.0000	0.7500	0.7708
x_{23}	0.6875	0.6875	0.7875	0.7667	0.8333	0.7500	0.0000	0.8542
x_{24}	0.6500	0.6786	0.8500	0.7354	0.7708	0.7708	0.8542	0.0000

TABLE 11 The total influence matrix

	x_{11}	x_{12}	x_{13}	x_{14}	x_{21}	x_{22}	x_{23}	x_{24}	d
x_{11}	1.1389	1.2904	1.3589	1.2736	1.2673	1.1267	1.2220	1.2051	9.8829
x_{12}	1.2966	1.1772	1.3867	1.2961	1.2898	1.1526	1.2440	1.2325	10.0756
x_{13}	1.3937	1.4153	1.3816	**1.4230**	**1.4201**	1.2657	**1.3722**	1.3707	11.0424
x_{14}	1.3383	1.3554	1.4581	1.2487	1.3776	1.2135	1.3302	1.3151	10.6369
x_{21}	1.3717	1.3892	**1.4939**	1.4095	1.2760	1.2315	1.3676	1.3481	10.8876
x_{22}	1.2345	1.2544	1.3465	1.2536	1.2430	1.0280	1.2350	1.2281	9.8231
x_{23}	1.3397	1.3571	1.4610	1.3750	1.3815	1.2362	1.2214	1.3401	10.7119
x_{24}	1.3235	1.3446	1.4571	1.3594	1.3618	1.2292	1.3400	1.1998	10.6154
r	10.4370	10.5837	11.3439	10.6389	10.6170	9.4833	10.3325	10.2394	

The use of bold words is to highlight the greatest influence.

TABLE 13 The limited supermatrix for factors

	x_{11}	x_{12}	x_{13}	x_{14}	x_{21}	x_{22}	x_{23}	x_{24}
x_{11}	0.1181	0.1181	0.1181	0.1181	0.1181	0.1181	0.1181	0.1181
x_{12}	0.1204	0.1204	0.1204	0.1204	0.1204	0.1204	0.1204	0.1204
x_{13}	0.1320	0.1320	0.1320	0.1320	0.1320	0.1320	0.1320	0.1320
x_{14}	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271
x_{21}	0.1301	0.1301	0.1301	0.1301	0.1301	0.1301	0.1301	0.1301
x_{22}	0.1174	0.1174	0.1174	0.1174	0.1174	0.1174	0.1174	0.1174
x_{23}	0.1280	0.1280	0.1280	0.1280	0.1280	0.1280	0.1280	0.1280
x_{24}	0.1268	0.1268	0.1268	0.1268	0.1268	0.1268	0.1268	0.1268

TABLE 14 The overall ranking for the factors

Factor	DEMATEL	DANP	Sum of rankings	Overall rankings
x_{11}	7	7	14	7
x_{12}	6	6	12	6
x_{13}	1	1	2	**1**
x_{14}	3	4	7	**3**
x_{21}	2	2	4	**2**
x_{22}	8	8	16	8
x_{23}	4	3	7	**3**
x_{24}	5	5	10	5

Bold text is used to highlight the top three key factors.

Borda score. After discussing the results with experts, the key criteria (sum of rankings ≤7) were identified: technology (x_{13}), delivery time (x_{14}), environmental management system (x_{21}) and pollution control (x_{23}).

4.5 | Importance performance analysis (IPA)

An industry's resources are always limited; thus, it is necessary to decide how to deploy these limited resources to the industry's best advantage. IPA is an effective means to effectively configure resource priority (Matzler, Bailom, Hinterhuber, Renzl, & Pichler, 2004). To assess the performance of the criteria using IPA, experts are invited to give a performance score for each criterion. During the IPA survey in our empirical study, three of the former eight experts (A, B and C) identified in Table 6 were used by suppliers and distributors, and were not deemed suitable to objectively evaluate supplier performance. Therefore, these three experts were excluded from the process of performance assessment of suppliers, and two new experts, Experts I and J, were invited to join the five remaining original experts to give their performance scores. The professional backgrounds of the seven selected managers are also shown in Table 6.

The relationship between rating and performance is shown in Table 15. The average values of the eight criteria are shown in Table 16.

After consultation, all experts agreed to use a value of 75 as the threshold to distinguish criteria with acceptable performance (≥75) from those with unacceptable performance (<75). Each criterion with its rank and performance value is shown in Figure 4, and these were used in the IPA to determine the key factors on which to concentrate.

Figure 4 shows that in addition to delivery time (x_{14}) and pollution control (x_{23}), the other two key criteria, namely technology (x_{13}) and the environmental management system (x_{21}), were located in the upper-right grid. Taiwanese automotive manufacturers determined that the key factors in this position on the grid should receive

TABLE 15 Relationship between rating and performance

Rating	0	25	50	75	100
Performance	Very dissatisfied	Dissatisfied	Medium	Satisfied	Very satisfied

TABLE 16 Performance assessment of eight criteria

		Experts							
Aspects	Criteria	D	E	F	G	H	I	J	Average value
Economics (X_1)	Cost (x_{11})	65	75	60	75	70	65	60	67
	Quality (x_{12})	95	70	65	80	70	65	80	75
	Technology (x_{13})	90	75	95	95	80	95	100	90
	Delivery time (x_{14})	75	60	60	90	75	75	80	74
Environment (X_2)	Environmental management system (x_{21})	75	65	65	75	80	70	100	76
	Ecological design (x_{22})	75	55	25	75	65	55	75	61
	Pollution control (x_{23})	85	55	70	80	70	56	100	74
	Management commitment (x_{24})	85	65	65	55	70	80	90	73

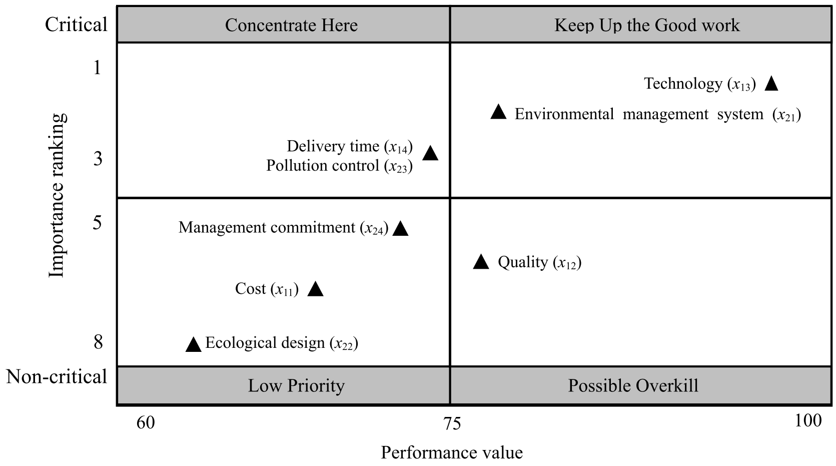

FIGURE 4 Importance-performance analysis [Colour figure can be viewed at wileyonlinelibrary.com]

continual focus to ensure good performance. They also expected parts suppliers to ensure timely delivery of components and improve pollution control, both of which were located in the upper-left grid. However, the quality criterion (x_{12}) that was located in the lower-right grid would have been better employed elsewhere, and it was not necessary to focus additional effort on cost (x_{11}), ecological design (x_{22}) and management commitment (x_{24}). Therefore, according to the empirical results, this study identified four key factors that Taiwanese automotive manufacturers most cared about when they selected green parts suppliers: namely, technology (x_{13}), delivery time (x_{14}), environmental management system (x_{21}) and pollution control (x_{23}). According to the total influence matrix in Table 11, a causal diagram is shown in Figure 5.

5 | MANAGERIAL IMPLICATIONS

Among many industries, GSCM has recently emerged as a proactive approach to enhance environmental performance (Lin, 2013). As proactive firms adopt GSCM, their economic performance and environmental performance improve (Hashemi et al., 2015). This study identified the key factors that Taiwanese automotive manufacturers use to select green suppliers. According to the empirical results, technology and the environmental management system are the most influential criteria. However, only the environmental management system belongs to the “cause group”; technology does not. As shown in Figure 5, technology has the greatest impact on delivery time, the environmental management system and pollution control, whereas the environmental management system has a significant impact only on technology. Because causal factors have an impact on the entire system, their performance can influence the overall goal (Lin, 2013), and hence among the key factors, the environmental management system should be given more attention by manufacturers in the selection of green suppliers.

5.1 | Environmental management system (EMS)

As Experts D and G said, “an environmental management system (EMS) is the core of the successful implementation of GSCM by an enterprise.” Parts suppliers should work on improving the performance of their EMSs to satisfy manufacturers and to facilitate the other key factors. Indeed, Taiwanese automotive manufacturers should establish a sound EMS, which includes several components. First, parts suppliers should strive to achieve ISO 4001 certification for their products, which is crucial to entering the global market. Second, parts suppliers should continually monitor and regulate compliance throughout the production process to find and solve problems quickly, hence avoiding pollution. Moreover, parts suppliers should unswervingly implement a government's environmental policy. Further still, they should strengthen green process planning to obtain green competitiveness. Finally, parts suppliers should optimize their internal control processes to ensure green quality. According to the results of the IPA analysis, EMS was allocated to the quadrant “Keep up the good work,” which indicates that Taiwanese automotive manufacturers were quite satisfied with the EMS of their parts suppliers.

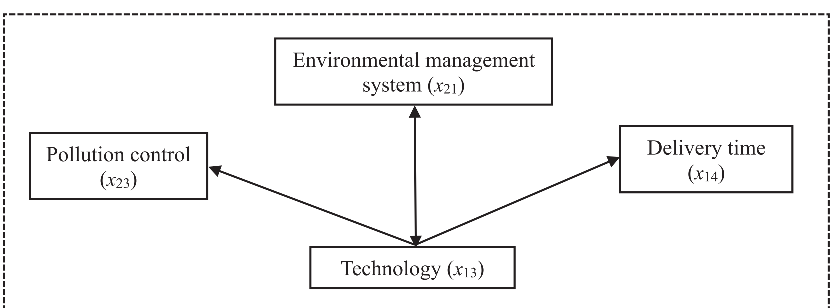

FIGURE 5 The causal diagram for key factors

5.2 | Technology

In general, technology is the core competitiveness of an enterprise. In this study, technology was regarded as a key factor of concern for Taiwanese automotive manufacturers when they selected parts suppliers; hence, parts suppliers should attend to the use of technology in their enterprises. In Expert G's opinion, "suppliers should first have full control over the manufacturing facilities and capabilities, because this control is directly related to both production efficiency and corporate image." Suppliers should also focus on technological development to meet the current and future demands of the firm. Moreover, parts suppliers should have research and development capability and novel product design. In addition, Expert B also stressed that technological compatibility and speed of development were necessary for parts suppliers. According to the study results presented in Figure 5, technology should be the continual focus of parts suppliers to ensure good performance.

5.3 | Delivery time

The remaining two key factors, delivery time and pollution control, were allocated to the quadrant "Concentrate Here," which indicated that these aspects needed to be improved urgently. Delivery time was the most common critical criterion for supplier selection, probably because it seriously affects the customers' production activities. However, in practice, suppliers are not doing well with regards to the timely delivery of parts, a point proved in this study. Delivery time is regarded as an emerging parameter for maintaining long-term collaborative relationships. Parts suppliers should strive to improve their performance in the following areas: appropriateness of delivery date, compliance with due date, delivery delays, delivery efficiency, delivery lead time, delivery reliability, number of shipments arriving on time and wait times.

5.4 | Pollution control

Pollution control was also classified as a key factor allocated to the quadrant "Concentrate Here." In practice, these pollutants included gas emissions, wastewater and solid waste. Pollution control exhibits the ability to manage and control the pollutants produced in the product design, the manufacturing process, and so on. Therefore, parts suppliers should strive to achieve pollution control from two aspects: (i) remediation technology and (ii) end-of-pipe control. Target emission reductions and proposing an effective improvement plan are necessary.

6 | CONCLUDING REMARKS

The purpose of this research was to identify key factors affecting Taiwanese automotive manufacturers in the selection of their parts suppliers. The proposed GDANP can generate the initial direct influence matrix automatically, obviating the requirement for respondents to assign values to numerous items in the initial direct influence matrix. Because the DANP usually requires respondents to complete tedious DEMATEL questionnaires, the experts may become bored, tired and inattentive when assigning values to pairwise comparisons as time passes (Triantaphyllou, 2001), which can cause the values to become inconsistent. The results obtained in this study using the GDANP were consistent with expert opinions. This highlights the effectiveness of the GDANP in SCM practice.

Evidently, the great advantage of the GDANP over the other DEMATEL-related methods is that considerable time can be saved because the GDANP does not include a survey for the initial direct influence matrix and pairwise comparisons. This time-saving method may result in better expert evaluations by avoiding respondent fatigue that can occur during the completion of long and complex questionnaires.

One of the greatest contributions of this paper is successfully changing the tasks involved in executing the DANP from a higher complexity class to a lower complexity class. This change can improve such combination work in both the best and the worst cases, as shown in Table 5.

It is clear that the GRG is defined by an additive set function μ on all singletons $\{x_j\}$ with $\mu(\{x_j\}) = w_j$. That is, like the weighted average method or the Lebesgue integral, the traditional GRG is an additive integral in which noninteraction among the involved attributes is assumed. Nevertheless, an assumption of additivity may not be realistic in numerous applications (Wang et al., 1998) because the variables are not always independent of each other. Therefore, it would be interesting and useful to replace the additive GRG with a nonadditive one (Hu, 2008, 2014; Hu et al., 2015; Tzeng et al., 2002). Future research can examine the performance of the nonadditive GRG in the GDANP.

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