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A fuzzy goal programming approach for green supply chain optimisation under activity-based costing and performance evaluation with a value-chain structure

W.-H. Tsai[a]* and Shih-Jieh Hung[b]

[a]*Department of Business Administration, National Central University, Jhongli, Taoyuan 320, Taiwan;* [b]*Department of Accounting Information, Takming University of Science and Technology, Neihu, Taipei 114, Taiwan*

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Supply chain operation with sustainable consideration has become an increasingly important issue in recent years. However, the decision framework with integrated costing and performance evaluation for green supply chain (GSC) has not been well developed so far in the literature. For this reason, this paper is aimed to propose a fuzzy goal programming (FGP) approach that integrates activity-based costing (ABC) and performance evaluation in a value-chain structure for optimal GSC supplier selection and flow allocation. The FGP approach is particularly suitable for such a decision model which includes flexible goals, financial and non-financial measures, quantitative and qualitative methods, multi-layer structure, multiple criteria, multiple objectives, and multiple strategies. An activity-based example of structural GSC with relevant costs and performances is presented for computing the composite performance indices of the GSC suppliers. A green supply chain of a mobile phone is used as an illustrative case. Several objective structures and their results are compared. The sensitivity analyses show that pure maximisation of financial profit can achieve the highest profit level, which also has the largest Euclidean distance to the multiple aspiration goals. In order to determine the final objective structure, an analytic hierarchy process (AHP) is used. This paper provides a new approach to assess and control a complex GSC based on value-chain activities, and obtain a more precise solution. The establishment of this GSC model not only helps decision-makers to monitor GSC comprehensive performance but also can facilitate further improvement and development of GSC management.

Keywords: activity-based costing (ABC); optimisation; green supply chain (GSC); performance evaluation; fuzzy goal programming (FGP); value-chain structure

1. Introduction

Industrial production can have a great impact and damage on the sustainability of the natural environment and human life. Generally, the impacts include depletive resource use, global environmental impacts, local environmental impacts, health impacts, and safety risks (GEMI 2001). These environmental issues have received more and more attention in recent years. Along with the new environmental legislation of WEEE (Waste from

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*Corresponding author. Email: whtsai@mgt.ncu.edu.tw

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Electronic and Electrical Equipment), RoHS (Restriction on the Use of Hazardous Substances), and EuP (Ecodesign Requirement for Energy-using Product) in the European Union, modern businesses are faced with increasing pressure to make their production or supply chain more environment friendly. Many large companies such as HP, IBM, and Xerox have been aware of the importance of environmental issues and have implemented green supply chain (GSC) (Sarkis 2003). However, the problem of GSC implementation may exist in the costing and performance evaluation system. Lack of a sound evaluation system can mislead a producer into improper production ways.

Many prior researches on GSC optimisation or supply chain evaluation proposed several cost factors and performance measures, while they did not integrate GSC costing and performance evaluation in a systematic and comprehensive way (e.g. Zhou *et al.* 2000, Bullinger *et al.* 2002, Talluri and Sarkis 2002, Kumar *et al.* 2004, Wang *et al.* 2004, Hugo and Pistikopoulos 2005). From the viewpoint of strategy and risk management, environmental management can help modern businesses to grow and keep safe in current environmental protection trends. However, when costing and performance evaluation are not integrated, the meaning of environmental cost or environmental performance will become ambiguous, because the composite effects are unknown.

An activity-based evaluation structure can link GSC costs and performances reasonably. In addition, GSC management not only manages environmental issues but also wastage. Activity-based costing (ABC) is designed to identify and eliminate business wastage, but is still rarely applied to GSC management. Therefore, this paper serves to fill these gaps by providing a fuzzy goal programming (FGP) model for GSC supplier selection and flow allocation under integrated ABC and performance assessment in a value chain structure.

An ABC system measures business costs from the viewpoint of business activities, and further links the cost drivers to the performance measures with respect to a certain object such as product or service (Johnson and Kaplan 1987, Kaplan and Cooper 1998). Cost driver is a characteristic of an activity that results in the incurrence of costs by that activity (Hilton 2005). For example, machine hour as a cost driver for the activity cost pool 'machinery' can be used to describe the machine activities for a certain product. As the ABC system not only views cost as a lump sum of cash outlay but a way of business operation, it is generally used as a managerial tool to analyse the efficiency and effectiveness of businesses, and especially useful for those complicated organisations such as GSC. Fletcher and Smith (2004) used a weighted average method of analytic hierarchy process (AHP) to integrate financial and non-financial performance indices which were calculated from the comparison of targeted and actual values. This paper further applies this methodology to GSC costing and performance evaluation and uses an FGP model to arrange the multiple layers, multiple criteria, and multiple objectives of a GSC. FGP is particularly suitable for the flexible goal cases such as GSC optimisation. This approach is comprehensive and activity-based, so it can result in a more reasonable and precise solution. Traditional supply-chain optimisation has difficulties to respect multiple requirements, while this proposed model is flexible enough to accommodate the complicated criteria and goals. The sensitivity analyses show that pure maximisation of financial profit can make the most profit, but also has the lowest precision from the perspective of the multiple aspiration goals. At last, an AHP is suggested to determine the final objective structure and flow allocation. For such a complicated organisation as GSC, this paper provides a comprehensive evaluation tool and decision model which can help the practitioners to improve the GSC management and make better GSC decisions.

The rest of this paper is organised as follows: Section 2 presents the literature review. Section 3 discusses the proposed FGP model for GSC optimisation followed by an illustrative case study in Section 4. Section 5 concludes this study.

2. Literature review

Supply chain is a modern business organisation that integrates related companies, stages, and possible resources to strengthen business competitiveness, speed and capacity (Hugo and Pistikopoulos 2005). In the literature, the terminology about the supply chain with environmental consideration includes green supply chain (Seuring 2001, Sarkis 2003, Kainuma and Tawara 2006), environmental supply chain (Hugo and Pistikopoulos 2005, Tsoulfas and Pappis 2006), sustainable supply chain (Zhou *et al.* 2000), integrated supply chain, and substance supply chain (Seuring 2004). This paper adopts the term ‘green supply chain’ to express the environment-friendly characteristics of such a supply chain. Green supply chain should include the environmental principle of 3R: reduce, reuse, recycle (Sarkis 2003). A traditional supply chain network often neglects the eco-design of product, packaging, and process; consumption of depletive resources; the treatment of waste and pollution, and recycling/disposal in the end-of-life (EOL) stage; while in the context of green supply chain, these issues will be discussed (Tsoulfas and Pappis 2006).

In the literature of supply chain performance or selection, Talluri and Sarkis (2002) proposed a data envelopment analysis (DEA) model for supplier performance monitoring. Bullinger *et al.* (2002) analysed supply chain performance by a balanced scorecard (BSC) method. GEMI (2001) provided an overview of industrial environmental impacts and supplier evaluation. Sheu and Lo (2005) integrated environment into corporate performance evaluation for a single company. Wang *et al.* (2004) applied the supply chain operations reference (SCOR) model and AHP to supplier selection. Kumar *et al.* (2004) used an FGP approach to solve the vendor selection problem. As for GSC costing, environmental management accounting (EMA) that includes activities such as pollution prevention and waste/emission treatment is widely used for environmental costing (e.g. Jasch 2003, 2006, Gale 2006). Seuring (2001) suggested that direct costs, activity-based costs, and transaction costs are the major cost types of a GSC. There are also some papers investigating GSC optimisation. Zhou *et al.* (2000) proposed a goal programming framework of continuous process industries in sustainable supply chains. Hugo and Pistikopoulos (2005) presented an environmentally conscious design of supply chain networks. Sarkis (2003) proposed a strategic analytic network process (ANP) model to select GSC systems. Some of these papers provide the ways to evaluate GSC performance, and some provide GSC cost measurement, while they do not integrate environmental cost and performance in a comprehensive and systematic way. When a GSC manager wants to make decisions, such scattered and unsystematic information may become another problem (Robbins and Coulter 2001). This point is particularly important to GSC management in which some costs and performances are often hidden traditionally. For these reasons, this paper proposes an activity-based approach that integrates comprehensive costs and performances in the value chain structure derived from the concepts of Porter (1985). After that, an FGP model is used for GSC optimisation.

3. The FGP model for GSC supplier selection and flow allocation

3.1 *Problem formulation*

Allocation of flow quantities to relevant suppliers is one of the focal problems in GSC management (Shih 2001, Hu *et al.* 2002, Hugo and Pistikopoulos 2005). Through the proper allocation and operation in a GSC, raw materials will be efficiently converted into final goods. The GSC optimisation problem in this paper can be stated as follows.

An initiating company (or procurement company) in a GSC selects suppliers of green production, recycling/disposal, logistics, and distribution channels; and allocates suitable flow quantities to them. Certain quantity of product has been planned to be produced during a certain period, which therefore generates relevant cost and performance of the GSC. The cost and performance of the GSC are mainly measured from the standpoint of the initiating company. The cost portion is not limited to the outlay that the initiating company actually pays. The cost and performance of the GSC have a value-chain structure. The cost drivers and performance measures are identifiable and measurable. In the recycling/disposal activities, the scrap only has one type, and the activities can be outsourced. The recycling/disposal cost includes transport and storage cost. The logistics activities (only in component transport) are also outsourced to third party logistics. A logistics supplier can take charge of one or more components, and one or more production suppliers, while each production supplier only has one logistics supplier. The initiating company proposes price quotes first, and then the distribution channels propose their demands. As the total demand is more than the planned production quantity, the initiating company allocates its products to these distribution channels by careful selection. The freight and storage cost of the final products are absorbed by the distribution channels. Several objective structures and their results will be compared. AHP is performed to determine the final objective structure.

3.2 *The composite performance index of supplier cost and performance*

A GSC integrates various suppliers, and operates as a large business organisation to satisfy the demands of the customers with higher speed, higher quality, lower cost, and lower inventory (Hugo and Pistikopoulos 2005). The initiating company (or procurement company) designs and controls the GSC, and serves as a final payer of the GSC cost. In fact, a GSC is operated in an expanded value chain, so the structure of value chain can be applied to GSC with multiple suppliers. This proposed GSC value-chain adds the concepts of green production, recycling/disposal, GSC management information system (MIS) and administration, long-term strategic (LTS) activities, total competitiveness management (TCM), total quality management (TQM), total risk management (TRM), total environmental management (TEM), and non-value-added (NVA) activities to the traditional value chain. Generally, GSC suppliers take charge of the primary activities (production, recycling/disposal, logistics, marketing, and so on) but also have relations with the other layers, i.e. layers of secondary, LTS (including TCM, TQM, TRM, TEM), and NVA activities, so these suppliers also consume the resources of the other layers and contribute performance to the goals of the other layers. For example, a green component supplier who performs the primary activity of the GSC will also use the MIS activity of the GSC (a secondary activity), and affect the performance of MIS sector, in addition to its own costs and performances. Therefore, the evaluation of GSC suppliers and flow allocation should consider not only cost and performance, but also all activity layers.

A GSC is more complicated than a single company, and involves not only primary and NVA activities but also supply chain and LTS activities. This paper uses an integrated ABC and value-chain structure to recover cost and performance of GSC suppliers for further supplier selection. Each unit allocated to the GSC suppliers will be evaluated and given a composite performance index (CPI). Wang *et al.* (2004) used analytic hierarchy process (AHP) to get a similar unit performance score that depends on the judgment of experienced managers. However, they did not provide a methodology for getting the scores systematically from structural measurement in an activity-based value chain. A more precise measurement for GSC suppliers is necessary, especially when the ever increasing environmental requirements not only regulate a single company but also the whole GSC. The procedure to obtain the unit CPIs for GSC suppliers is as follows.

Step 1: Select suitable activity cost pools and their cost drivers in a value chain.

Step 2: Select suitable performance goals and their measures in the value chain.

Step 3: Establish standard values of cost and performance measures according to benchmarking.

Step 4: Compute unit variance rates for the suppliers after comparing the actual values and standard values of the cost drivers (or ABC costs) and performance measures (Hilton 2005). If it is difficult to identify the unit performances of the suppliers, then the performances during the same period are defined to be unit performances for comparison between the suppliers (Kumar *et al.* 2004, Wang *et al.* 2004). Positive unit variance rates mean favourable cases such as cost saving, problem reduction, or higher performance, as compared with the standard values.

Step 5: Treat the unit variance rates vertically and horizontally to obtain the unit CPIs of the suppliers (Liberatore *et al.* 1997, Pineno 2000, Fletcher and Smith 2004). This paper adopts the weighted average approach similar to Fletcher and Smith (2004) to integrate the various variance rates. When treating vertical (or cross-layer) variance rates, the variance rates are weighted averaged. When treating horizontal variance rates across cost and performance, the variance rates are summed up for simplicity.

Step 6: Use the unit CPIs of the suppliers in Step 5 as unit scores, and substitute these scores into the FGP model to solve the optimal flow allocation in the GSC.

3.3 *The FGP model*

A fuzzy goal means an imprecise (or vague) goal that comes from the decision-maker's understanding or flexibility (Arican and Güngör 2001). Sometimes, the goals cannot be simply described as the types of 'not more than' or 'not less than', so using the targeted intervals is necessary (Biswas and Pal 2005). In practice, it is more realistic to adopt flexible fuzzy goals instead of fixed levels when the situation is not so deterministic (Sharma *et al.* 2006). The concept of fuzzy sets developed by Zadeh (1965) was combined with goal programming to form FGP (Narasimhan 1980, Hannan 1981a, b, Rubin and Narasimhan 1984). The practical application of FGP includes agricultural planning (Slowinski 1986, Sinha *et al.* 1988, Pal and Moitra 2002, Biswas and Pal 2005), forestry (Pickens and Hof 1991), stochastic transportation problem (Chalam 1994), portfolio selection (Parra *et al.* 2001), metropolitan solid waste management (Chang and Wang

1997), water quality management (Lee and Wen 1997), and cellular manufacturing system design (Shankar and Vrat 1999). GSC optimisation problem may also involve fuzziness in the goals of composite performance, speed, and budget. However, the application of FGP in GSC problem was still discussed very little in the literature.

We first define the notations used in the FGP model and then present the model.
Subscript:

f	subscript for priority
g	subscript for goal
m	subscript for production suppliers
i	subscript for components
r	subscript for recycling/disposal suppliers
h	subscript for logistics suppliers
s	subscript for distribution channels

Decision variables:

Z	objective function
X	flow quantity of components
E	flow quantity of scrap
Y	flow quantity of component carried
D	flow quantity of finished goods
λ	binary variable indicating if the logistics supplier is chosen ($\lambda = 1$) or not ($\lambda = 0$)
d_g	variables representing deviation from maximum or minimum values
d_g^-	deviation variables representing under-achievements of the targeted goals
d_g^+	deviation variables representing overachievements of the targeted goals

Parameters:

P_f	pre-emptive priority ($P_1 > P_2 > \cdots > P_K$)
ω	weights of the deviation variables
A	aspiration level
u	lower- or upper-tolerance range
α	composite performance index (CPI) for primary activities
β	CPI for secondary activities
γ	CPI for long-term strategic (LTS1) activities (not including total environmental management, TEM)
δ	CPI for TEM activities
ε	CPI for non-value-added (NVA) activities
T	average time for transport
C_{mi}	purchasing cost (not including freight) for component i
C_r	outsourcing cost for recycling/disposal (including freight)
η	unit freight
P	selling price of finished good
σ	unit defect rate
ϕ	unit late delivery rate
ρ	unit flexibility rate
θ	account receivable days for one dollar
Q_i	total flow quantity of component i
Q_R	total flow quantity of scrap

Q_H	total flow quantity of logistics
Q_V	total flow quantity of product
CAP	economic capacity
CAP^e	capacity under environmental regulation (ecological capacity)

0/1 integer variable: λ
Non-negative integer variables: X, E, Y, D
Non-negative variables: d
Non-negative parameters: ω, A, u, α, β, γ, δ, ε, T, C, η, P, σ, ϕ, ρ, θ, Q, CAP

In the problem of GSC flow allocation, the goals of the decision-makers may be fuzzy in order to allow flexibility and vagueness in the preferences. We used an FGP model to describe such GSC decision framework (Biswas and Pal 2005). The advantage of FGP is that this tool can handle priority structure of objectives with fuzzy goals. As for the constraints, the concepts of pecuniary cost, defect rate, late delivery, flexibility, capacity, and fixed flow quantity also have been considered in the literature (e.g. Zhou *et al.* 2000, Kumar *et al.* 2004, Wang *et al.* 2004, Hugo and Pistikopoulos 2005).

If the goal has a lower limit ($A_g - u_g$), then the membership function $\mu_g(\mathbf{x})$ in different intervals is Equation (1).

$$\mu_g(\mathbf{x}) = \begin{cases} 1 & \text{if } f_g(\mathbf{x}) \geq A_g, \\ [f_g(\mathbf{x}) - (A_g - u_g)]/u_g & \text{if } A_g - u_g \leq f_g(\mathbf{x}) < A_g, \\ 0 & \text{if } f_g(\mathbf{x}) < A_g - u_g, \end{cases} \tag{1}$$

where $\mathbf{x}$ is the vector of decision variables.

On the contrary, if the goal has an upper limit ($A_g + u_g$), then the membership function $\mu_g(\mathbf{x})$ in different intervals is Equation (2).

$$\mu_g(\mathbf{x}) = \begin{cases} 1 & \text{if } f_g(\mathbf{x}) \leq A_g, \\ [(A_g + u_g) - f_g(\mathbf{x})]/u_g & \text{if } A_g < f_g(\mathbf{x}) \leq A_g + u_g, \\ 0 & \text{if } f_g(\mathbf{x}) > A_g + u_g, \end{cases} \tag{2}$$

The FGP model of the GSC flow allocation problem can be stated as follows:

Objective function:

$$\text{Minimise}$$
$$Z = \sum_{f=1}^{K} \sum_{g=1}^{10} P_f\left(\omega_{fg} d_g + \omega_{fg}^{-} d_g^{-}\right) \tag{3}$$

In this model, minimisations of under-achievements (d_g^-) of the targeted goals and deviations (d_g) from the extreme values are the objectives that have several priorities (P_f). Minimising deviations d_g means maximising or minimising the goal values. The higher priority objectives must be first satisfied and then the lower priority objectives. The priority f and weight ω are judged by the decision-maker. Weight ω is a 0/1 integer variable used for controlling the objectives; if ω_{fg}^{-} (or ω_{fg}) = 0, then d_g^- (or d_g) in priority f will have no effect.

Constraints:

This model also has the following goals and constraints:

(Primary activity goal):

$$\left[\sum_{m=1}^{Mi}\sum_{i=1}^{N}\alpha_{mi}X_{mi}+\sum_{r=1}^{R}\alpha_r E_r+\sum_{h=1}^{H}\alpha_h Y_h+\sum_{s=1}^{V}\alpha_s D_s-(A_1-u_1)\right]\Big/u_1+d_1^- -d_1^+=1, \quad (4)$$

(Secondary activity goal):

$$\left[\sum_{m=1}^{Mi}\sum_{i=1}^{N}\beta_{mi}X_{mi}+\sum_{r=1}^{R}\beta_r E_r+\sum_{h=1}^{H}\beta_h Y_h+\sum_{s=1}^{V}\beta_s D_s-(A_2-u_2)\right]\Big/u_2+d_2^- -d_2^+=1, \quad (5)$$

(LTS1 activity goal):

$$\left[\sum_{m=1}^{Mi}\sum_{i=1}^{N}\gamma_{mi}X_{mi}+\sum_{r=1}^{R}\gamma_r E_r+\sum_{h=1}^{H}\gamma_h Y_h+\sum_{s=1}^{V}\gamma_s D_s-(A_3-u_3)\right]\Big/u_3+d_3^- -d_3^+=1, \quad (6)$$

(TEM activity goal):

$$\left[\sum_{m=1}^{Mi}\sum_{i=1}^{N}\delta_{mi}X_{mi}+\sum_{r=1}^{R}\delta_r E_r+\sum_{h=1}^{H}\delta_h Y_h+\sum_{s=1}^{V}\delta_s D_s-(A_4-u_4)\right]\Big/u_4+d_4^- -d_4^+=1, \quad (7)$$

(NVA activity goal):

$$\left[\sum_{m=1}^{Mi}\sum_{i=1}^{N}\varepsilon_{mi}X_{mi}+\sum_{r=1}^{R}\varepsilon_r E_r+\sum_{h=1}^{H}\varepsilon_h Y_h+\sum_{s=1}^{V}\varepsilon_s D_s-(A_5-u_5)\right]\Big/u_5+d_5^- -d_5^+=1, \quad (8)$$

Equations (4)–(8) are the membership functions with the activity goals. For green production, there are Mi suppliers for each component i. There are also N types of components, R recycling/disposal suppliers, H logistics suppliers, and V distribution channels. The coefficients $(\alpha, \beta, \gamma, \delta, \varepsilon)$ in Equations (4)–(8) are the unit CPIs. The unit CPIs of each supplier are computed by the steps stated in section 2.1.3. CPIs are regarded as scores for one unit output of the suppliers. Multiplying each unit CPI by the flow quantity of each supplier obtains the CPI value of that supplier. Summing up the CPI values of the suppliers for each goal g obtains the GSC performance value $[f_g(\mathbf{x})]$ from the perspective of that goal. The decision-maker must set the fuzzy goal interval $[A_g-u_g, A_g]$ first for each goal g. When the GSC performance value falls on the aspiration level A_g, the value of the membership function will be one, i.e. $d_g^-=0$ [see Equation (1)]. In order to separate environmental goal from other goals, in Equation (6), LTS1 activities include TCM, TQM, TRM, but exclude TEM activities. It is expected that larger quantity with higher positive CPI will contribute more to total GSC performance, so controlling the GSC performance goals will filter out suitable suppliers and their allocated quantities. Wang *et al.* (2004) and Kumar *et al.* (2004) used similar unit scores, while their scores are not based on value-chain activities. The implementation of ABC and performance evaluation with fuzzy goals can make the GSC solution more precise and flexible.

(Special LTS1 goal for critical component 1):

$$\left[\sum_{m=1}^{Mi} \gamma_{m1} X_{m1} - (A_6 - u_6)\right] \Big/ u_6 + d_6^- - d_6^+ = 1, \tag{9}$$

(Special TEM goal for recycling/disposal):

$$\left[\sum_{r=1}^{R} \delta_r E_r - (A_7 - u_7)\right] \Big/ u_7 + d_7^- - d_7^+ = 1, \tag{10}$$

Equations (9)–(10) are the special goals. When the decision-maker wants to strengthen certain functions or keep certain departments at certain performance levels, these goals can be useful. Equations (9)–(10) can be useful. Equation (9) specifies LTS1 goal, because critical component 1 needs more R&D performance. Equation (10) specifies TEM goal for recycling/disposal activities.

(Speed goal for logistics):

$$\left\{(A_8 + u_8) - \left[\sum_{m=1}^{Mi} \sum_{h=1}^{H} \sum_{i=1}^{N} T_{mhi} \lambda_{mhi}\right]\right\} \Big/ u_8 + d_8^- - d_8^+ = 1, \tag{11}$$

Equation (11) is the time (or speed) goal for logistics. Logistics time T_{mhi} can vary with production suppliers (m), logistics suppliers (h), or components (i). Binary variables λ_{mhi} select the suitable logistics mixes for the fuzzy goal of total logistics time. Less time is preferable, so the fuzzy goal interval for goal 8 becomes $[A_8, A_8 + u_8]$. When the total logistics time falls on the aspiration level A_8, the value of the membership function will be one, i.e. $d_8^- = 0$ [see Equation (2)].

(Purchasing cost & freight goal):

$$\left[(A_9 + u_9) - \left(\sum_{m=1}^{Mi} \sum_{i=1}^{N} C_{mi} X_{mi} + \sum_{r=1}^{R} C_r E_r + \sum_{m=1}^{Mi} \sum_{h=1}^{H} \sum_{i=1}^{N} \eta_{mhi} X_{mi} \lambda_{mhi}\right)\right] \Big/ u_9 + d_9^- - d_9^+ = 1, \tag{12}$$

Equation (12) is the pecuniary cost goal for component production, logistics, and recycling/disposal. According to the problem formulation, component purchasing costs ($C_{mi} X_{mi}$), component freights ($\eta_{mhi} X_{mhi}$), and recycling/disposal cost ($C_r E_r$) are separated. Recycling/disposal freights are included in the outsourcing cost C_r. λ_{mhi} are binary variables for selecting logistics suppliers and freights. The unit freight η_{mhi} is determined according to the weight, size, and attribute of the component; and the distance, difficulty, and transportation mode.

(Revenue goal for the distribution channels):

$$\left[\sum_{s=1}^{V} P_s D_s - (A_{10} - u_{10})\right] \Big/ u_{10} + d_{10}^- - d_{10}^+ = 1, \tag{13}$$

Equation (13) is the revenue goal for the distribution channels. Higher revenue ($P_s D_s$) is preferable, so it has a fuzzy goal interval $[A_g - u_g, A_g]$.

(Defect rates):

$$\sum_{m=1}^{Mi} \sigma_{mi} X_{mi} \leq \sigma_i Q_i, \quad \forall i \tag{14}$$

$$\sum_{r=1}^{R} \sigma_r E_r \leq \sigma_R Q_R, \tag{15}$$

Equations (14)–(15) are the defect rate constraints. For quality assurance, required average defect rate σ_i and σ_R cannot be exceeded (Kumar *et al.* 2004, Wang *et al.* 2004).

(Late delivery rates):

$$\sum_{m=1}^{Mi} \phi_{mi} X_{mi} \leq \phi_i Q_i, \quad \forall i \tag{16}$$

$$\sum_{r=1}^{R} \phi_r E_r \leq \phi_R Q_R, \tag{17}$$

$$\sum_{h=1}^{H} \phi_h Y_h \leq \phi_H \sum_{i=1}^{N} Q_i, \tag{18}$$

Equations (16)–(18) are the late delivery rate constraints. For delivery control, late delivery rates ϕ are limited (Kumar *et al.* 2004) for the component suppliers (*i*), recycling/disposal suppliers (*R*), and logistics suppliers (*H*).

(Flexibility rates):

$$\sum_{m=1}^{Mi} \rho_{mi} X_{mi} \geq \rho_i Q_i, \quad \forall i \tag{19}$$

$$\sum_{r=1}^{R} \rho_r E_r \geq \rho_R Q_R, \tag{20}$$

$$\sum_{h=1}^{H} \rho_h Y_h \geq \rho_H \sum_{i=1}^{N} Q_i, \tag{21}$$

Equations (19)–(21) are the flexibility rate constraints. Quantity flexibility is important for GSC response (Kumar *et al.* 2004). Flexibility rate ρ here controls the quantity flexibility for the component suppliers (*i*), recycling/disposal suppliers (*R*), and logistics suppliers (*H*).

(Account receivable days):

$$\sum_{s=1}^{V} \theta_s P_s D_s \leq \theta_V \sum_{s=1}^{V} P_s D_s \tag{22}$$

Equation (22) limits the account receivable days of the distribution channels. θ refers to the account receivable days, and measures the cash collection period for one dollar of the promised revenue ($P_s D_s$).

(Flow quantities):

$$\sum_{m=1}^{Mi} X_{mi} = Q_i, \quad \forall i \tag{23}$$

$$\sum_{r=1}^{R} E_r = Q_R, \tag{24}$$

$$\sum_{h=1}^{H} Y_h = Q_H = \sum_{i=1}^{N} Q_i, \tag{25}$$

$$\sum_{s=1}^{V} D_s = Q_V, \tag{26}$$

Equations (23)–(26) are the constraints of the flow quantities (Kumar *et al.* 2004, Wang *et al.* 2004) for the component suppliers (*i*), recycling/disposal suppliers (*R*), logistics suppliers (*H*), and distribution channels (*V*).

(Logistics supplier conditions):

$$\sum_{m=1}^{Mi} \sum_{i=1}^{N} X_{mi}\lambda_{mhi} = Y_h, \quad \forall h \tag{27}$$

$$\sum_{h=1}^{H} \lambda_{mhi} = 1, \quad \forall m, i \tag{28}$$

Equations (27)–(28) are designed for the logistics supplier selection. Equation (27) allocates each logistics supplier's capacity to the component suppliers. Equation (28) requires that each component supplier only has one logistics supplier.

(Capacity constraints):

$$0 \le X_{mi} \le \min\{CAP_{mi}, CAP^e_{mi}\}, \quad \forall m, i \tag{29}$$

$$0 \le E_r \le \min\{CAP_r, CAP^e_r\}, \quad \forall r \tag{30}$$

$$0 \le Y_h \le CAP_h, \quad \forall h \tag{31}$$

$$0 \le D_s \le CAP_s, \quad \forall s \tag{32}$$

$$d_g^-, d_g^+ \ge 0. \quad \forall g \tag{33}$$

Equations (29)–(32) are the capacity constraints. For component suppliers (*mi*) and recycling/disposal suppliers (*r*), the capacity can be economic (*CAP*) or ecological (CAP^e). A supplier may have larger economic capacity, but only the smaller capacity under environmental regulation, such as carbon dioxide (CO_2) emission constraint, is actually used (Letmathe and Balakrishnan 2005), so the actual capacity is the smaller one of these two types of capacities. As for logistics suppliers and distribution channels, they only have economic capacities.

4. Illustrative case study and discussion

Company GT is a mobile-phone brand manufacturer that outsources several components and services in its GSC, so it is faced with a supplier selection and flow allocation problem as an initiating company. For parsimony, the supplier selection model is limited to two components, i.e. printed circuit board (PCB) and liquid crystal display (LCD), three component suppliers for each component, three recycling/disposal suppliers, three logistics suppliers, and three distribution channels. The situation that Company GT faces is consistent with the problem formulation stated in Section 3.1. As seen in Figure 1, Company GT holds the brand, product design ability, supply-chain operation ability, and core technology. Other activities in which Company GT has less competitiveness are outsourced, such as components production (PCB, LCD), recycling/disposal, logistics, and distribution (marketing). Although Company GT does not directly choose the upstream suppliers of PCB or LCD, it can still influence them through the contracts with the suppliers of PCB or LCD. For example, the restriction of hazardous substances can be listed in the contracts, which will in turn influence the selection of the upstream suppliers of PCB or LCD. Company GT is responsible for its own industrial scrap and the EOL mobile phones, and the treatment of these scraps is outsourced to the recycling/disposal suppliers. After the prices are proposed, the distribution channels will offer their maximum demands, and then Company GT can select the channels according to their composite performance indices and revenues.

4.1 *Determination of the composite performance indices of the suppliers*

The determination process of the composite performance indices for the suppliers is illustrated in Tables 1 and 2. As the core problem is supplier selection, these

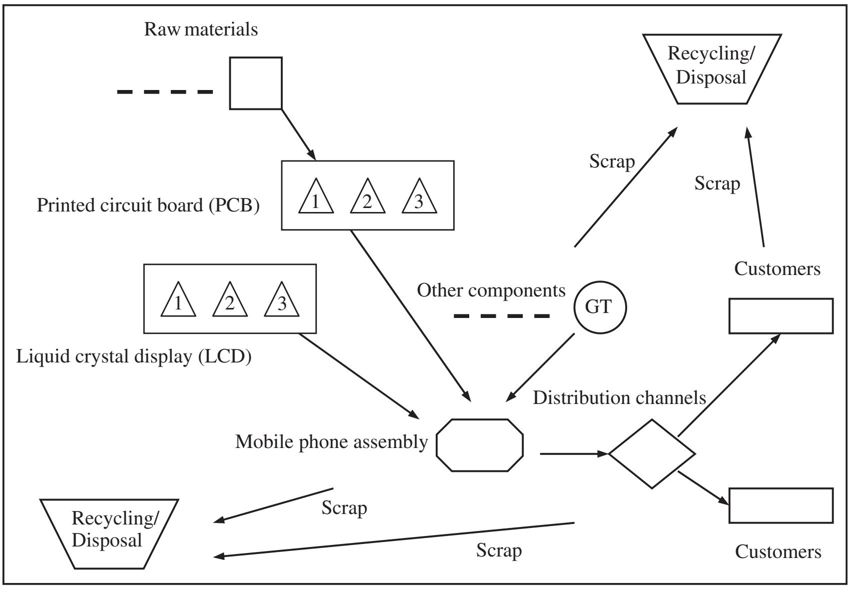

Figure 1. The GSC model of mobile-phone initiating company GT.

Table 1. Cost and performance data of LCD green production suppliers for the illustrative mobile phone GSC.

Supplier-related GSC costs for one unit LCD				Supplier-related GSC performances[a] for one unit LCD			
Green production suppliers	D1	D2	D3	Green production suppliers	D1	D2	D3
Primary activities				*Primary activities*			
Green production cost ($)	11.8	13.3	10.8	Green production	0.12	0.03	−0.08
Logistics related ($)	0.8	0.6	0.5	Logistics related	0.06	0.08	−0.03
Total primary cost ($)	12.6	13.9	11.3	Average primary variance rate[b] of performance	0.09	0.06	−0.06
Standard primary cost ($)	14.5	14.5	14.5				
Primary cost variance rate[b]	0.13	0.04	0.22				
Secondary activities				*Secondary activities*			
Contracting related ($)	0.22	0.20	0.37	Contracting related	0.14	0.27	−0.04
GSC-MIS related ($)	0.73	0.41	0.63	GSC-MIS related	0.08	0.11	−0.17
GSC adm. related ($)	0.62	0.43	0.67	GSC adm. related	0.11	0.16	−0.03
GSC finance related ($)	0.30	0.25	0.23	GSC finance related	0.14	0.14	−0.11
Business sust. related ($)	0.82	0.74	0.67	Business sust. related	0.19	0.16	−0.04
Total secondary cost ($)	2.69	2.03	2.57	Average secondary variance rate of performance	0.13	0.17	−0.08
Standard secondary cost ($)	2.55	2.55	2.55				
Secondary cost variance rate	−0.05	0.20	−0.01				
LTS1 activities				*LTS1 activities*			
TCM related ($)	0.52	0.52	0.48	TCM related	0.11	0.15	−0.19
TQM related ($)	0.3	0.30	0.27	TQM related	0.05	0.1	−0.12
TRM related ($)	0.22	0.23	0.20	TRM related	0.08	0.12	−0.13
Total LTS1 cost ($)	1.04	1.05	0.95	Average LTS1 variance rate of performance	0.08	0.12	−0.15
Standard LTS1 cost ($)	1.05	1.05	1.05				
LTS1 cost variance rate	0.01	0.00	0.10				
TEM activities				*TEM activities*			
TEM related ($)	0.65	0.64	0.52	Average TEM variance rate of performance	0.09	0.16	−0.19
Standard TEM cost ($)	0.63	0.63	0.63				

(*continued*)

Table 1. Continued.

Supplier-related GSC costs for one unit LCD				Supplier-related GSC performances[a] for one unit LCD			
Green production suppliers	D1	D2	D3	Green production suppliers	D1	D2	D3
TEM cost variance rate	–0.03	–0.02	0.17				
Non-value-added activities							
Over waiting time ($)	0.2	0.11	0.25				
Excess capacity ($)	0.23	0.15	0.3				
Over motion ($)	0.26	0.23	0.31				
Rework ($)	0.33	0.31	0.27				
Inventory holding costs ($)	0.31	0.26	0.32				
Total NVA cost ($)	1.33	1.06	1.45				
Standard NVA cost ($)	1.12	1.12	1.12				
NVA cost variance rate	–0.19	0.05	–0.29				

Adm., Administration; LTS1, Long-Term Strategic management excluding TEM; MIS, Management Information System; NVA, Non-value-added; Sust., Sustaining; TCM, Total Competitiveness Management; TEM, Total Environmental Management; TQM, Total Quality Management; TRM, Total Risk Management.

[a] The numbers in the performance columns are the performance variance rates computed by the relevant performance measures.

[b] Positive variance rates indicate 'superior to standard level', e.g. less cost, lower defect rate, less excess expenses, more usage frequency of ERP system,... etc.

Table 2. Unit composite performance indices for the illustrative mobile phone GSC.

Activities	Primary activities	Secondary activities	LTS1 activities	TEM activities	NVA activities
Composite indices	TL[a]	TL	WL[b]	WL	TL
Green production suppliers (LCD)					
Suppliers D1	0.22	0.08	0.13	0.11	−0.19
Suppliers D2	0.1	0.37	0.18	0.22	0.05
Suppliers D3	0.16	−0.09	−0.13	−0.12	−0.29
Green production suppliers (PCB)					
Suppliers B1	0.2	0.04	0.26	0.11	0.15
Suppliers B2	0.13	0.16	0.19	0.14	0.28
Suppliers B3	0.21	−0.21	−0.16	−0.22	0.14
Recycling/disposal suppliers					
Suppliers R1	0.24	−0.02	0.10	0.31	0.1
Suppliers R2	0.27	0.3	0.19	0.10	−0.13
Suppliers R3	0.17	−0.12	−0.16	−0.12	−0.23
Logistics suppliers					
Suppliers L1	0.11	0.06	0.10	0.15	−0.09
Suppliers L2	0.21	0.08	0.17	0.26	0.15
Suppliers L3	0.02	−0.1	−0.04	−0.18	−0.12
Distribution channels					
Channel S1	0.28	−0.02	0.24	0.21	0.05
Channel S2	0.12	0.03	0.10	−0.21	−0.19
Channel S3	0.03	0.09	0.05	0.37	0.17

[a] The sum of the cost and performance variance rates.

[b] The weighted sum of the cost and performance variance rates. The weight is 1 for cost and 1.5 for performance.

two tables only list the supplier-related evaluation, and a fixed flow quantity is used as a basis for comparison. LCD component is used as an example in Table 1. For parsimony and practicability, this model does not consider the interaction effects between the cost drivers, performance measures, activity layers, and suppliers. For data reliability, the three-year average values of the cost and performance data are adopted. In practice, the data of the ABC and performance measures can be collected by a project team based on the profession and relevant literature (e.g. Pré Consultants 2000, SCC 2001, Bullinger *et al.* 2002, Hilton 2005, Hansen and Mowen 2006). ISO 9000 series and ISO 14000 series also provides useful measures and standards for TQM, TRM, and TEM. Due to space limitation, Table 1 does not show the detailed cost drivers and performance measures.

As discussed above, primary suppliers not only use primary resources but also secondary and LTS resources, and NVA expenses, so the evaluation of GSC suppliers should consider all these layers. For comparison, the costs and performance goals are symmetric. As for the NVA activities, the performance goals of such activities are to eliminate such expenses, so only the NVA cost evaluations are needed in Table 1. For better comparison, the green production cost also includes the direct material/labour and the purchasing freight of material. The primary costs listed in Table 1 do not include the costs of the other layers, and so do the performances. The unit logistics related cost in Table 1 is limited to the freight to the downstream plants by the same freight standard. The business sustaining activities are the general management activities of the initiating company, because it is the final payer and controller of the GSC costs, while the other activities are not limited to the initiating company. If performances are difficult to be identified on a unit basis, then period performances are defined to be unit performances for these cases.

Company GT has established the standard measures and values by benchmarking. In Table 1, the calculation steps of the cost variance rates are as follows: step 1 is multiplying the unit cost drivers by the pool rates (or cost per driver) to obtain the ABC costs, and step 2 is using the formula [(Standard cost − ABC cost)/Standard cost] to calculate the cost variance rates for the activity layers. For example, primary cost variance rate is 0.13 [$(14.5-12.6)/14.5=0.13$] for D1 suppliers. Lower cost is favourable, so it has a positive variance rate. Besides, in order to facilitate comparison, the green production cost also contains the direct material/labour and the purchasing freight of material.

In Table 1, the supplier performance value is also compared with the standard value in each performance measure to obtain the performance variance rate. The numbers in the performance columns are performance variance rates. Positive variance rates mean favourable cases such as lower defect rate, less excess expenses, and so on. As a vertical treatment, activity variance rate is calculated by averaging the performance variance rates in each activity layer. From the perspective of AHP, this means that the measures in the same activity layer are equally weighted (Fletcher and Smith 2004). For example, performance variance rate of D1 in primary activity is 0.09 [$(0.12+0.06)/2=0.09$]. By AHP, the decision-maker can still use unequal weights according to real situation. A critical requirement here is that the production quantities must be the same (or one unit) for the three suppliers to make the performances comparable. The performance variance rate may not really be set on a unit basis, but the decision-maker can still define and use period variance rate as unit performance as long as it is comparable between the suppliers and can identify the allocation of higher performance (Kumar *et al.* 2004, Wang *et al.* 2004).

As for the horizontal treatment, summing up the unit variance rates of cost and performance in Table 1 obtains the unit CPIs of the various suppliers in Table 2. For example, the unit CPI of supplier D1 in primary activities is 0.22 ($=0.13+0.09$). It is worth noting that the decision-maker can give cost and performance different weights. For example, the decision-maker may consider that performance is more important than cost in LTS1 activities, so the weighted index for supplier D1 in LTS1 activities is 0.13 [$=0.01+1.5\times 0.08$]. Again, as long as the indices are weighted in the same way for all suppliers in the same activities, the comparison basis will not be destructed. In this case study, weighted index is used in LTS1 activities and TEM activities. The integration of cost and performance can also resort to AHP, while for simplicity, weighted summation is used as a substitution.

Table 3 shows the supplier ranking with no constraint under different objectives. As there is no constraint, the ranking is determined by the CPIs in Table 2. The long-term effectiveness CPIs are the weighted averages of LTS1 (0.67) and TEM (0.33) CPIs. 'Weighted sum' here is the equally weighted sum of all layer CPIs, while unequally weighted sum is allowed, if necessary. Rank 1 suppliers are the suppliers that have the highest composite performance according to the specified objectives, and rank 3 suppliers have the lowest composite performance. For example, if the objective is 'environment first', then the decision-maker should give the top priority to suppliers D2,

Table 3. GSC supplier ranking based on Table 2 under different objectives.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Objectives	Environment first	Efficiency first	Long-term effectiveness[a] first	Primary effectiveness first	Weighted sum[b]
Descriptions	TEM goal must be first satisfied and maximised	NVA goal must be first satisfied and maximised	LTS goal must be first satisfied and maximised	Primary goal must be first satisfied and maximised	No goal must be first satisfied, but different goals can have different weights
Rank					
1	D2,B2,R1,L2,S3	D2,B2,R1,L2,S3	D2,B1,R1,L2,S1	D1,B3,R2,L2,S1	D2,B2,R2,L2,S1
2	D1,B1,R2,L1,S1	D1,B1,R2,L1,S1	D1,B2,R2,L1,S3	D3,B1,R1,L1,S2	D1,B1,R1,L1,S3
3	D3,B3,R3,L3,S2	D3,B3,R3,L3,S2	D3,B3,R3,L3,S2	D2,B2,R3,L3,S3	D3,B3,R3,L3,S2

[a] The weight is 0.67 for LTS1 and 0.33 for TEM to obtain the long-term combination.

[b] Equal weights except for the long-term combination.

B2, R1, L2, and S3. If these suppliers do not have sufficient capacities, then the decision-maker could resort to the rank 2 suppliers D1, B1, R2, L1, and S1.

The formation of the CPIs involves some weighting and averaging processes, so the decision-maker should test once again whether these weights reflect real situation. If not, modification of the weights to obtain the precise and suitable CPIs will be necessary.

4.2 *The FGP supplier selection and flow allocation model*

Table 4 lists the supplier data of the illustrated mobile phone GSC. The data requirements for solving the model are rather complex, because the model comprises four types of suppliers (production, recycling/disposal, logistics, and distribution channel), and the production suppliers have two kinds of components (LCD and PCB). In addition to traditional managerial data, GSC-related data such as ecological capacity, late delivery rate, flexibility rate, transport time, maximum demand, and account receivable days are also needed for such a comprehensive GSC model. In practice, the decision-maker should collect these data first. In this case, the economic capacities are larger than the ecological capacities, so the ecological capacities are the final limitations. The thresholds are listed on the right side of Table 4. The data for logistics suppliers are rather complicated. One logistics supplier can serve more than one component supplier, but each component supplier can only be served by one logistics supplier. Since the unit freights and transport time can vary with different mixes of component and logistics suppliers, the decision problem turns to the selection of these mixes to lower the freight and logistics time. In Table 4, the numbers in the parentheses are the unit freights and transport times under different mixes of component and logistics suppliers. Table 5 shows the fuzzy goals of the GSC. The fuzzy intervals are set by the decision-maker according to the company's situation. Again, the intervals can be corrected to reflect real situations and reasonable decision results.

The data in Tables 2, 4 and 5 are substituted in the model stated in Section 3 to solve the optimal flow allocation. Table 6 shows the numerical FGP models. There are five objective structures, seven activity goals (membership functions), and other constraints which include logistics time, purchasing cost/freight, revenue, defect rate, late delivery rate, flexibility rate, account receivable days, flow quantity, selection variable, and capacity, For simplicity, the denotations used in Table 6 are a little different from the model in Section 3. Variables $x_1 \sim x_3$ correspond to the flow quantities of LCD suppliers (X_{m1}), $x_4 \sim x_6$ correspond to PCB suppliers (X_{m2}), $x_7 \sim x_9$ correspond to recycling/disposal suppliers (E_r), $x_{10} \sim x_{12}$ correspond to logistics suppliers (Y_h), and $x_{13} \sim x_{15}$ correspond to distribution channels (D_s). Variables $x_{1101} \sim x_{6122}$ correspond to λ_{mhi}, which are the binary variables for selecting logistics mix (m, h, i) and determining the flow allocation for the logistics suppliers. For example, x_{6122} refers to the situation that supplier 12 (logistics supplier L3) carries component 2 (PCB) for supplier 6 (PCB suppliers B3). If $x_{6122} = 1$, then the transport time 2.5 hours and the unit freight $0.289 will have effect, otherwise these data will have no effect. The optimisation operation determines the optimal λ_{mhi} to lower total freight and logistics time to the targeted intervals.

The objective structures (OS) have five types based on benchmarking. OS1 and OS2 pursue the maximisation of TEM performance and financial profit, respectively. These are the extreme cases. The maximum values are calculated first and used as goals, and then the deviations from these maximum values are minimised (Gerner *et al.* 2005).

Table 4. Supplier data of the illustrative mobile phone GSC.

		Supplier 1	Supplier 2	Supplier 3	Thresholds
Green production suppliers (LCD)					
Unit purchasing cost ($)	C_{m1}	13.5	15	12.4	
Economic capacity (units)	CAP_{m1}	7000	5000	6500	
Ecological capacity (units)	CAP^{e}_{m1}	5000	3500	4500	
Defect rate	σ_{m1}	0.04	0.03	0.04	0.04
Late delivery rate	ϕ_{m1}	0.05	0.03	0.04	0.045
Flexibility rate	ϕ_{m1}	0.03	0.05	0.02	0.025
Green production suppliers (PCB)					
Unit purchasing cost ($)	C_{m2}	3.6	3.27	3.33	
Economic capacity (units)	CAP_{m2}	4000	8000	5300	
Ecological capacity (units)	CAP^{e}_{m2}	3000	6000	3000	
Defect rate	σ_{m2}	0.01	0.02	0.02	0.02
Late delivery rate	ϕ_{m2}	0.02	0.05	0.04	0.04
Flexibility rate	ρ_{m2}	0.06	0.04	0.03	0.035
Recycling/disposal suppliers					
Unit recycling/disposal cost ($/kg)	C_r	3	2.78	2.86	
Economic capacity (kg)	CAP_r	9300	8500	9800	
Ecological capacity (kg)	CAP^{e}_{r}	8000	7000	9000	
Defect rate	σ_r	0.05	0.06	0.07	0.06
Late delivery rate	ϕ_r	0.05	0.04	0.06	0.05
Flexibility rate	ρ_r	0.07	0.05	0.05	0.05
Logistics suppliers					
[Unit freight ($), transport time (h)]					
(LCD_D1)	(η_{1h1}, T_{1h1})	(0.8, 5)	(0.96, 5.8)	(0.88, 5.3)	
(LCD_D2)	(η_{2h1}, T_{2h1})	(0.6, 4.2)	(0.72, 5)	(0.66, 4.8)	
(LCD_D3)	(η_{3h1}, T_{3h1})	(0.5, 3.5)	(0.60, 4.7)	(0.55, 4.2)	
[Unit freight ($), transport time (h)]					
(PCB_B1)	(η_{4h2}, T_{4h2})	(0.278, 2.4)	(0.222, 2.2)	(0.315, 2.6)	
(PCB_B2)	(η_{5h2}, T_{5h2})	(0.233, 1.9)	(0.186, 1.7)	(0.264, 2.3)	
(PCB_B3)	(η_{6h2}, T_{6h2})	(0.255, 2.1)	(0.204, 1.8)	(0.289, 2.5)	
Capacity (units)	CAP_h	18,000	12,000	15,000	
Late delivery rate	ϕ_h	0.01	0.02	0.04	0.03
Flexibility rate	ρ_h	0.04	0.05	0.02	0.035
Distribution channel					
Selling prices ($/unit)	P_s	50	48	46.5	
Maximum demand (units)	CAP_s	5500	7000	5000	
Account receivable days	θ_s	15	17	18	17
Flow quantities					
LCD (units)	Q_1		10,000		
PCB (units)	Q_2		10,000		
Recycling/disposal (kg)	Q_R		1050		
Logistics of LCD/PCB (units)	Q_H		20,000		
Mobile phone (units)	Q_V		10,000		

As for the moderate cases, OS3 is to control the objectives of higher priority first, and then maximise the TEM performance. OS4 is a compromise that maximises primary performance after the other goals are controlled. In order to obtain a more reasonable result, deviation d_1 is multiplied by a weight 10. OS5 keeps controlling the special goals,

Table 5. Fuzzy goals of the illustrative mobile phone GSC.

Goals	Aspiration levels (A_g)	Lower tolerance limits ($A_g - u_g$)	Upper tolerance limits ($A_g + u_g$)	Ranges (u_g)
1. Primary activities	7500	6750		750
2. Secondary activities	2000	1800		200
3. LTS1 activities	4500	4050		450
4. TEM activities	4000	3600		400
5. NVA activities	78	70		8
6. Special LTS1 activities	392	350		42
7. Special TEM activities	129	117		12
8. Logistics time(h)	22		25	3
9. Purchasing cost & freight($)	210,000		230,000	20,000
10. Revenue($)	485,000	450,000		35,000

but moves the secondary, LTS1, TEM, and NVA objectives to the maximisation group. The presentation of these five objective structures is mainly used for comparison and further selection. In practice, a company may design its own objective structures based on its real situations.

The objectives may conflict among themselves. For example, reducing cost may conflict with raising performance. Generally, such a problem can be solved by a compromise solution, priority solution, or mixed solution (Gerner *et al.* 2005). Final objective structure still should be determined by preference and strategic factors which are not completely technical (Hugo and Pistikopoulos 2005). Therefore, an AHP method is needed to determine the most suitable objective structure and corresponding results.

4.3 *Sensitivity analysis*

Table 7 shows the decision results of the five objective structures in Table 6. The numerical models all have global optima. The flow quantities for the various suppliers are determined. The flow allocation for logistics suppliers is more complicated, because they can take charge of more than one production suppliers. The production supplier codes are shown in the parentheses. For example, logistics supplier L1 carries 8000 units in OS1, which contain 5000 units LCD from D1 and 3000 units PCB from B1. As each component supplier can only be served by one logistics supplier, the transported quantities (5000 units LCD and 3000 units PCB) are just the production quantities of supplier D1 and B1.

The Euclidean distance (ED) is used to measure the precision degree of an objective structure (Biswas and Pal 2005).

$$\mathrm{ED} = \left\{ \sum_{g=1}^{10} [1 - \mu_g(\mathbf{x})]^2 \right\}^{1/2} \tag{34}$$

The membership values are used to obtain the ED value of each objective structure. If the ED value is higher, then this objective structure has a larger distance to the aspiration goals listed in Table 5. As seen in Table 7, the extreme structure OS2 has the highest ED value, and the moderate structures, OS3 and OS4, have the lowest ED values. If the decision-maker pursues financial performance only, OS2 can generate the highest revenue and the lowest pecuniary cost, while in the context of multi-objective GSC, this

Table 6. FGP model for GSC supplier selection and flow allocation.

Minimise	
$\mathrm{OS1}^a : d_4$	
$\mathrm{OS2} : d_{10} + d_9$	
$\mathrm{OS3} : \mathrm{P}_1(d_6^- + d_7^- + d_8^- + d_{10}^-) + \mathrm{P}_2(d_1^- + d_2^- + d_3^- + d_5^-) + \mathrm{P}_3(d_4)$	(Objective functions)
$\mathrm{OS4} : \mathrm{P}_1(d_4^- + d_6^- + d_7^-) + P_2(d_2^- + d_3^- + d_5^- + P_3(10d_1 + d_8 + d_9 + d_{10})$	
$\mathrm{OS5} : \mathrm{P}_1(d_6^- + d_7^-) + \mathrm{P}_2[10(d_1 + d_2 + d_3 + d_4 + d_5) + d_8 + d_9 + d_{10}]$	
subject to	
$(0.22x_1 + 0.1x_2 + 0.16x_3 + 0.2x_4 + 0.13x_5 + 0.21x_6 + 0.24x_7 + 0.27x_8 + 0.17x_9 + 0.11x_{10} + 0.21x_{11} + 0.02x_{12}$ $+ 0.28x_{13} + 0.12x_{14} + 0.03x_{15} - 6750)/750 + d_1^- - d_1^+ = 1;$	(Primary activities)
$(0.08x_1 + 0.37x_2 - 0.09x_3 + 0.04x_4 + 0.16x_5 - 0.21x_6 - 0.02x_7 + 0.3x_8 - 0.12x_9 + 0.06x_{10} + 0.08x_{11} - 0.1x_{12}$ $- 0.02x_{13} + 0.03x_{14} + 0.09x_{15} - 1800)/200 + d_2^- - d_2^+ = 1;$	(Secondary activities)
$(0.13x_1 + 0.18x_2 - 0.13x_3 + 0.26x_4 + 0.19x_5 - 0.16x_6 + 0.1x_7 + 0.19x_8 - 0.16x_9 + 0.1x_{10} + 0.17x_{11} - 0.04x_{12}$ $+ 0.24x_{13} + 0.1x_{14} + 0.05x_{15} - 4050)/450 + d_3^- - d_3^+ = 1;$	(LTS1 activities)
$(0.11x_1 + 0.22x_2 - 0.12x_3 + 0.11x_4 + 0.14x_5 - 0.22x_6 + 0.31x_7 + 0.1x_8 - 0.12x_9 + 0.15x_{10} + 0.26x_{11} - 0.18x_{12}$ $+ 0.21x_{13} - 0.21x_{14} + 0.37x_{15} - 3600)/400 + d_4^- - d_4^+ = 1;$	(TEM activities)
$(-0.19x_1 + 0.05x_2 - 0.29x_3 + 0.15x_4 + 0.28x_5 + 0.14x_6 + 0.1x_7 - 0.13x_8 - 0.23x_9 - 0.09x_{10} + 0.15x_{11} - 0.12x_{12}$ $+ 0.05x_{13} - 0.19x_{14} + 0.17x_{15} - 70)/8 + d_5^- - d_5^+ = 1;$	(NVA activities)
$(0.13x_1 + 0.18x_2 - 0.13x_3 - 350)/42 + d_6^- - d_6^+ = 1;$	(Special LTS1 activities)
$(0.31x_7 + 0.1x_8 - 0.12x_9 - 117)/12 + d_7^- - d_7^+ = 1;$	(Special TEM activities)
$\{25-[(5x_{1101} + 4.2x_{2101} + 3.5x_{3101}) + (5.8x_{1111} + 5x_{2111} + 4.7x_{3111}) + (5.3x_{1121} + 4.8x_{2121} + 4.2x_{3121}) + (2.4x_{4102}$ $+ 1.9x_{5102} + 2.1x_{6102}) + (2.2x_{4112} + 1.7x_{5112} + 1.8x_{6112}) + (2.6x_{4122} + 2.3x_{5122} + 2.5x_{6122})]\}/3 + d_8^- - d_8^+ = 1;$	(Logistics time)
$\{230{,}000-[(13.5x_1 + 15x_2 + 12.4x_3) + (3.6x_4 + 3.27x_5 + 3.33x_6) + (3x_7 + 2.78x_8 + 2.86x_9) + (0.8x_1x_{1101} +$ $0.6x_2x_{2101} + 0.5x_3x_{3101}) + (0.96x_1x_{1111} + 0.72x_2x_{2111} + 0.6x_3x_{3111}) + (0.88x_1x_{1121} + 0.66x_2x_{2121} + 0.55x_3x_{3121})$ $+ (0.278x_4x_{4102} + 0.233x_5x_{5102} + 0.255x_6x_{6102}) + (0.222x_4x_{4112} + 0.186x_5x_{5112} + 0.204x_6x_{6112}) + (0.315x_4x_{4122}$ $+ 0.264x_5x_{5122} + 0.289x_6x_{6122})]\}/20{,}000 + d_9^- - d_9^+ = 1;$	(Purchasing cost & freight)
$(50x_{13} + 48x_{14} + 46.5x_{15} - 450\ 000)/35\ 000 + d_{10}^- - d_{10}^+ = 1;$	(Revenue)
$0.04x_1 + 0.03x_2 + 0.04x_3 \leq 400;$ $0.01x_4 + 0.02x_5 + 0.02x_6 \leq 200;$	(Defect rates)

(continued)

Table 6. Continued.

$0.05x_7+0.06x_8+0.07x_9\leq 63;$	
$0.05x_1+0.03x_2+0.04x_3\leq 450;$	(Late delivery rates)
$0.02x_4+0.05x_5+0.04x_6\leq 400;$	
$0.05x_7+0.04x_8+0.06x_9\leq 52.5;$	
$0.01x_{10}+0.02x_{11}+0.04x_{12}\leq 600;$	
$0.03x_1+0.05x_2+0.02x_3\geq 250;$	(Flexibility rates)
$0.06x_4+0.04x_5+0.03x_6\geq 350;$	
$0.07x_7+0.05x_8+0.05x_9\geq 52.5;$	
$0.04x_{10}+0.05x_{11}+0.02x_{12}\geq 700;$	
$15\times 50x_{13}+17\times 48x_{14}+18\times 46.5x_{15}\leq 17\times(50x_{13}+48x_{14}+46.5x_{15});$	(Account receivable days)
$x_1+x_2+x_3=10{,}000;$	(Flow quantities)
$x_4+x_5+x_6=10{,}000;$	
$x_7+x_8+x_9=1050;$	
$x_{10}+x_{11}+x_{12}=20{,}000;$	
$x_{13}+x_{14}+x_{15}=10{,}000;$	
$x_1x_{1101}+x_2x_{2101}+x_3x_{3101}+x_4x_{4102}+x_5x_{5102}+x_6x_{6102}=x_{10};$	
$x_1x_{1111}+x_2x_{2111}+x_3x_{3111}+x_4x_{4112}+x_5x_{5112}+x_6x_{6112}=x_{11};$	
$x_1x_{1121}+x_2x_{2121}+x_3x_{3121}+x_4x_{4122}+x_5x_{5122}+x_6x_{6122}=x_{12};$	
$x_{1101}+x_{1111}+x_{1121}=1;$	(Selection variables)
$x_{2101}+x_{2111}+x_{2121}=1;$	
$x_{3101}+x_{3111}+x_{3121}=1;$	
$x_{4102}+x_{4112}+x_{4122}=1;$	
$x_{5102}+x_{5112}+x_{5122}=1;$	
$x_{6102}+x_{6112}+x_{6122}=1;$	
$x_1\leq 5000;\ x_2\leq 3500;\ x_3\leq 4500;$	(Capacity constraints)
$x_4\leq 3000;\ x_5\leq 6000;\ x_6\leq 3000;$	
$x_7\leq 8000;\ x_8\leq 7000;\ x_9\leq 9000;$	
$x_{10}\leq 18{,}000;\ x_{11}\leq 12{,}000;\ x_{12}\leq 15{,}000;$	
$x_{13}\leq 5500;\ x_{14}\leq 7000;\ x_{15}\leq 5000;$	
$x_i\geq 0;\ x_i\in \mathrm{Z}^{\mathrm{b}}$, for $i=1,\ldots,15;$	
$d_g,\ d_{\mathrm{g}}^{-},\ d_g^{+}\geq 0$, for $g=1,\ldots,10;$	
$x_{mhi}\in\{0;1\}$.for $m=1,2,\ldots,6.\ h=10,\ 11,\ 12.\ i=1,\ 2.$	

[a] d_g represents the deviation (absolute value) between the actual value and the maximum or minimum value of each goal for $g=1,\ldots,10$.
[b] Z refers to integers.

Table 7. GSC supplier selection and flow allocation results under FGP model.

Objective structures	OS1: TEM performance maximisation (min $= d_4$) OS2: Financial profit maximisation (min $= d_9 + d_{10}$) OS3: TEM performance maximisation (min $= d_4$) after controlling the other goals OS4: Primary activity/resource performance maximisation (min $= 10d_1 + d_8 + d_9 + d_{10}$) after controlling the other goals OS5: Overall performance maximisation [min $= 10(d_1 + d_2 + d_3 + d_4 + d_5) + d_8 + d_9 + d_{10}$] after controlling the special goals				
	OS1	OS2	OS3	OS4	OS5
LCD manufacturers (LCD units)					
D1	5000	5000	5000	5000	5000
D2	3500	500	3500	1265	3500
D3	1500	4500	1500	3735	1500
PCB manufacturers (PCB units)					
B1	3000	2334	3000	3000	3000
B2	6000	4668	6000	4000	6000
B3	1000	2998	1000	3000	1000
Recycle/disposal suppliers (kg)					
R1	1050	0	1050	115	115
R2	0	1050	0	935	935
R3	0	0	0	0	0
Logistics suppliers (component units)					
L1	8000 (D1,B1)	10,000 (D1,D2,D3)	8000 (D2,D3,B1)	8000 (D1,B3)	8000 (D1,B1)
L2	12,000 (D2,D3,B2,B3)	10,000 (B1,B2,B3)	12,000 (D1,B2,B3)	12,000 (D2,D3,B1,B2)	12,000 (D2,D3,B2,B3)
L3	0	0	0	0	0
Distribution channels (product units)					
S1	5000	5500	5500	5500	5500
S2	0	4500	500	4500	0
S3	5000	0	4000	0	4500
Euclidean distance	0.071	1.732	0	0	0.021
Total logistics time (h)	20.6	18.4	20	20.7	20.6
Total cost ($)	185,074	175,917.1	184,936	178,930.1	184,868.3
Total revenue ($)	482,500	491,000	482,100	491,000	484,250

solution may not be satisfactory. In practice, a decision-maker may want to find an optimal solution under the given resources. However, this optimisation is conditional, and depends on the preset objective structure. Since the selection of objective structures may be qualitative, and needs to consider multiple stakeholders and criteria, this paper suggests using an AHP approach to determine the final objective structure and solution.

Table 8 shows the preferable objective structures generated by AHP. AHP contains four major steps (Saaty 1980). Step 1: Problem statement: the selection problem is manifested through the brainstorming of decision-makers and experts. Step 2: Pairwise comparison: elements under each decision component are compared in pairs according to their relative importance. Step 3: Priority vectors: the eigenvectors of the pairwise comparison matrices are computed to obtain the normalised priority vectors. Step 4: Priorities of the alternatives: the final AHP weights of the alternatives are obtained by multiplying the priority matrix of the alternatives under the criteria by the priority vector of the criteria. The AHP weights can also be calculated by software such as Expert Choice. Generally, the consistency of each comparison matrix should be tested by consistency index and consistency ratio. A consistency ratio of 0.1 or less is acceptable. Due to space limitation, the detailed criteria and pairwise comparison process are not shown in this paper. All of the comparison matrices in Table 8 meet the standard of consistency.

Relevant experts, major shareholders, managers, and other stakeholders are invited to judge the relative importance of the criteria and objective structures. The objective structures are assessed by the criteria of mission, circumstance, product stage, and precision degree. The mission is a description of the existence reason of the organisation. The circumstance includes customers, suppliers, competitors, pressure groups, globalisation, government policy/legislation, social/culture, technology, and so on (Robbins and Coulter 2001). The stage refers to the life cycle of the product (Sarkis 2003). The precision criterion measures the feasibility of the objective structures by the ED values (Biswas and Pal 2005). These criteria generally have greater influence on the choice of objective structures.

Table 8. AHP weights of the objective structures.

	Mission	Circumstance	Stage	Precision	Final AHP weights
Criterion weights:					
	0.318	0.332	0.237	0.113	
Original weights[a]:					
OS1	0.143	0.122	0.135	0.236	
OS2	0.172	0.156	0.125	0.033	
OS3	0.237	0.240	0.237	0.245	
OS4	0.212	0.231	0.262	0.245	
OS5	0.236	0.251	0.241	0.242	
Synthesised weights[b]:					
OS1	0.045	0.041	0.032	0.027	0.144
OS2	0.055	0.052	0.030	0.004	0.140
OS3	0.075	0.080	0.056	0.028	0.239
OS4	0.067	0.077	0.062	0.028	0.234
OS5	0.075	0.083	0.057	0.027	0.243*

[a] Objective structure weight under each criterion.

[b] Results of multiplying the criterion weights by the original weights.

In Table 8, the circumstance and the mission criteria are given higher weights. After synthesising the criterion weights and the original weights under the criteria, OS5 has the highest AHP weight. As a result, OS5 and its flow allocation is chosen.

5. Conclusion

GSCs give more attention to environmental issues such as eco-design, pollution prevention, depletive resources, and EOL processes. Furthermore, GSC management is also concerned with wastage reduction and multi-objective performance. Many companies have been aware of the importance of GSC management, while prior researches did not provide an integrated ABC and performance evaluation system that can reduce wastage and raise performance for GSC optimisation. To fill the gaps, this paper aimed to provide an FGP approach for GSC supplier selection and flow allocation under integrated ABC and performance assessment in a value chain structure. GSC performance will be clearer when cost and benefit measures are integrated based on value-chain activities. ABC can provide a GSC with information of value-added and non-value-added cost in a systematic way. FGP can allow more flexible goals and multi-objective GSC decisions.

A more precise measurement based on activities and value chain structure is useful for GSC optimisation. The value-chain framework divides GSC activities into four layers: primary, secondary, LTS and NVA activities. Each unit allocated to the GSC suppliers will be evaluated by the CPIs derived from the cost and performance variance rates in the multiple layers of value chain.

An FGP framework with multiple objective structures is proposed. In the illustrative case, the OS have five types which contain compromise and priority. The extreme structures have higher ED values than the moderate ones. This result implies that appropriate design of objective structure can raise feasibility and satisfaction in a multi-objective GSC. Final objective structure and corresponding results can be determined by an AHP method that contains the criteria of mission, circumstance, product stage, and precision degree.

If a real-world company wants to implement the proposed evaluation system and decision model, the collection of the data of ABC, performance measures, and GSC-related measures is the first step. A feasible way is to require a project team to collect the data, and report them on the enterprise resource planning (ERP) system. After that, the FGP model built in the information system will quickly figure out the optimal solution. The proposed FGP model leaves several limitations that can be investigated in further researches. First, the determination process of suitable cost drivers and performance measures is not explored. Second, this system does not consider the interaction effects between the drivers, measures, layers, and suppliers. Third, in the real world, companies may have their specific goals and constraints.

For further researches, this paper provides a fundamental evaluation system and decision model for GSC decision-making problems. The evaluation structure proposed by this paper also provides GSC managers with a concise approach to monitor their GSC operations systematically and comprehensively. As this system is based on ABC and value chain structure, the usage of this system can generate a more precise, efficient and effective GSC performance with sustainable consciousness. The combination of composite performance indices and FGP model gives the decision-maker more flexibility to design and compare their objective structures. After the objective structures and corresponding results are listed, AHP can help the decision-maker to select suitable decisions in a qualitative but reasonable way.

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