Two-stage game-theoretic approach to supplier evaluation, selection and order assignment

Jonas C.P. Yu[a], Hui-Ming Wee[b,*], Schnell Jeng[b], Yosef Daryanto[b,c]

[a]Logistics Management Department, Takming University of Science and Technology, Taipei 114, Taiwan, ROC

[b]Department of Industrial and System Engineering, Chung Yuan Christian University, Chungli 32023, Taiwan, ROC

[c]Department of Industrial Engineering, Universitas Atma Jaya Yogyakarta, Yogyakarta 55281, Indonesia

Abstract: This study proposes a framework for supplier evaluation, selection, and assignment that incorporates a two-stage game-theoretic approach method. The objective is to provide insights to manufacturers in choosing suitable suppliers for different manufacturing processes. The framework applies to the decision logic of multiple manufacturing processes. In the first stage, a non-cooperative game model is utilized for supplier evaluation and selection. The interactive behaviors between a manufacturer and some supplier candidates are modeled and analyzed so that the supplier evaluation value (SEV) can be obtained using the Nash equilibrium. In the second stage, the supplier evaluation values become the input for the Shepley values calculation of each supplier under a cooperative game model. The Shapley values are utilized to create a set of limited supplier allocation. This paper provides managerial insights to verify the proposed approach on supplier selection and allocation. Thus, enables supply chain management (SCM) manager to optimize supplier evaluation, selection, and order assignment.

Keywords: Supplier selection; Nash equilibrium; Supplier evaluation value; Shapley value

* Correspondence to Hui-Ming Wee, Department of Industrial and System Engineering, Chung Yuan Christian University, Chungli, Taiwan 32023, ROC.
Tel.: +886-3-2654409; Fax: +886-3-2654499;
E-mail address: jonasyu@takming.edu.tw (J. Yu), weehm@cycu.edu.tw (H. M. Wee), schnell.jeng@chrobinson.com (S. Jeng), yosef.daryanto@uajy.ac.id (Y. Daryanto)

1. Introduction

Due to globalization, supply chain management (SCM) managers in organizations must seek to reduce costs and increase their competitive advantage through global sourcing. The uncertain supply and demand makes global sourcing more challenging [1]. Supplier selection is a vital aspect of supply chain sourcing, particularly in a competitive environment. However, most enterprises have different criteria for selecting their suppliers [2]. Since each manufacturer faces multiple suppliers that possess different capabilities, SCM managers need to develop an effective mechanism to perform supplier evaluation, selection, and order allocation among the qualified suppliers. Different approaches, such as multiple-criteria decision analysis, metaheuristic optimization, and game theory, have been studied to optimize those decisions [3].

Game theory has been used in many business decisions, including supply chain management. This paper explores how a manufacturer evaluates and selects qualified suppliers using game theory. This study proposes a two-stage model that connects the non-cooperative game model during supplier selection with the cooperative game model. The chosen suppliers are in a “cooperative game” relationship with the manufacturer in order to accomplish the expected supply quality.

The remainder of this paper is arranged as follows: Section 2 discusses previous research related to supplier selection, allocation problem and game theory. Section 3 presents the proposed two-stage game theory model. Then, an experimental simulation is performed in Section 4 to study the proposed framework. Finally, Section 5 concludes the findings and suggests for future research.

2. Literature review

This section discusses previous research related to supplier selection and allocation problem as well as game theory in inventory and supply chain management.

2.1. Supplier selection and allocation problem

The supplier selection problem has attracted much attention over the years. Dickson [4] applied questionnaires to identify 23 influencing factors of supplier selection criteria and showed that product quality, delivery, and past performance are critical factors. Choi and Hartley [2] generalized 26 supplier evaluation criteria according to the research of Dickson [4] and Weber et al. [5]. Weber et al. [6] showed that supplier facilities, capacity, and technological capabilities are related to supplier evaluation. Maurizio and Alberto [7] adopted financial ability, cost, technical competence, organizational culture, after-sales technical support, flexibility, quality management, and just-in-time procurement as criteria for evaluating suppliers. Chan and Kumar [8] indicated that product cost was the primary consideration in selecting suppliers.

In recent years, new approaches have been developed for supplier selection and allocation problems. Freeman and Chen [9] used an Analytic Hierarchy Process (AHP)-Entropy-Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) framework for supplier selection combining the traditional and environmental selection criteria. The aim is to integrate an environmentally friendly supplier into the supply chain. Neyestani et al. [10] studied supplier order allocation considering uncertain information on buyer demand and supplier delivery rate. Particle Swarm Optimization and Genetic Algorithm are used to solve the multi-objective model. Hosseini and Barker [11] combined the primary evaluating criteria (e.g., cost, quality, and delivery time) with some green and resilience criteria in supplier evaluation and selection. They proposed a Bayesian network to model the causal relationship among the variables. Tezenji et al. [12] developed an integrated supplier location-selection and order allocation model to minimize the establishment, transportation, and inventory-related costs. A systematic literature review on supplier selection research streams and future scope was presented in Wetzstein et al. [13]. Recently, Zaheri et al. [14] considered an all-unit quantity discount policy in supplier selection problem. Adeinat and Ventura [15] developed an integrated pricing and supplier selection model when the demand is price sensitive. Suppliers' limited capacity and quality were taken into consideration. Rabieh et al. [16] integrated robust optimization and fuzzy programming for supplier selection under multiple uncertainties. A real case from automobile industry has been provided.

Recently, some researchers started to use game theory approach in supplier selection problem. Mohammaditabar et al. [17] studied supplier selection considering supply chain inventory costs under cooperative and non-cooperative relationships. Liu et al. [18] considered game theory for supplier selection, combined with the Analytic Network Process (ANP) method, entropy weight, and DEMATEL. Previous research investigated the supplier selection process based on manufacturers' interests but disregarded the concerns of suppliers. The purpose of this study is to allow manufacturers to settle supplier evaluation criteria according to the concerns of manufacturers as well as suppliers.

2.2. Game theory

Game theory is derived from the "Theory of games and economic behavior" (von Neumann and Morgenstern [19]). The book was a significant achievement in economic science during the 20th century. Mathematical formulas represent interpersonal strategic thinking in a game. Through a series of deductions, game theory searches for maximum returns for participants. The well-known Nash equilibrium was an important milestone in game theory. Nash [20] proposed bargaining theory and non-cooperative game theory to explain traditional game theory further. Most economists have adopted the Nash equilibrium. Essentially, game participants wish to produce the most favorable results for themselves. Under certain assumptions, the game theory uses a mathematical model to predict participant behavior and help participants choose optimal strategies involving conflicts of interest. General games are often expressed using standard formulas. In most studies, dynamic games have been expressed using a game tree [21]. Two types of game theory protocols are found in cooperative and non-cooperative games. The difference between these games lies in whether a binding force exists between participants: if so, the game is cooperative, and if not, the game is non-cooperative. Shapley [22] investigated various pairing methods under the assumption that two parties cooperate. Based on game theory, Roth [23] conducted an empirical study with two types of protocol behaviors that described the crucial difference between cooperative and non-cooperative games.

Game theory works empirically in many circumstances and has become influential in a variety of disciplines beyond economics [24]. For example, Nash equilibrium becomes a powerful tool for understanding human interactions in many practical situations [25]. Game theory provides an analytical technique to study the interaction, including competition among some multiple agents of a system [26]. Game theory is a type of strategic thinking that provides a mathematical analysis method to configure a system and identify an optimal strategy for solving problems with conflicts of interest. It can be applied to fields such as politics, management, transportation, biology, and military strategy. Game theory can maximize the benefits of all players in a competitive environment and can be used to analyze interactions between multiple decision-makers. Generally, a game involves a player who makes decisions, chooses a method during the game, selects a strategy for determining the action, and determines payoffs (i.e., outcome assessments). Finally, potential payoffs are quantified to determine whether a strategy is feasible accurately. At a specific time, participants have various information sources and variables. It assumes that each participant is rational and possesses a set of assessment criteria to select a solution and maximize benefits. When each participant considers their set of strategies to be optimal, and they will settle for it, this set of strategies is called the equilibrium solution.

Game theory has been widely applied in recent years. Huang and Li [27] constructed a game model for advertising manufacturers (leaders) and retailers (followers) to explore the cooperative relationships between them. Leng and Parlar [28] applied game theory in supply chains and divided application areas into five categories. Under the assumption of fixed unit purchase cost, supply chain members competed and cooperated in inventory control. Numerous researchers had extended game theory application and used it to supply chain systems to establish cooperative relationships between suppliers and manufacturers. In civil engineering, Peldschus and Zavadskas [29] applied game theory and fuzzy theory for water supply decision making with multiple criteria. In another study on cooperative games and supply chains, Hennet and Arda [30] proposed a decision-making assessment model that integrated queuing theory and game theory. This model was used to assess supply chain efficiency among conflicting partners. Besides, Bompard et al. [31] constructed a power market simulator by game theory. To test the simulator, the researchers compared real and simulated markets.

Long and Yu [32] used game theory to analyze the government's and enterprises' optimal strategies for energy saving and carbon reduction. They found the Nash equilibrium solution and provided suggestions for sustainable energy policy. Chen et al. [33] utilized game theory to evaluate terrorist threats and appropriate responses. Runyan et al. [34] used multidimensional game theory to analyze difficulties in airplane design. Madani [35] conducted a literature review on how to solve conflicts in a non-cooperative water resource game. In electrical engineering, game theory has been applied in wireless networks [36]. Sharma and Gopal [37] introduced a new research direction, integrated reinforcement learning, and game theory, and designed a reliable, intelligent controller. Dayi and Jianwei [38] proposed a simple optimal model to describe restrictions on carbon emissions and how regulations inhibited production. Based on game theory, they analyzed factors that influenced the government and enterprises. Also, numerous researchers have applied game theory to computer science. Liu et al. [39] proposed a multi-objective game theory using the Markov process and Shapley value to assess the satisfaction of participants.

2.3. Game theory application in supply chain management

Purchasing and inventory management are two important activities in supply chain management. Purchasing plays a vital role because a qualified material supply differentiates the manufacturer's final goods, including the cost and quality, while inventory management determines the efficiency of the operations [40], [41], [42], [43], [44], [45]. Recently, people also recognize the importance of such decisions in terms of sustainability [46], [47] [48].

Some researchers have indicated that cooperative game theory could be applied to centralized inventory management systems to reduce costs and enhance customer service [49]. Zhao et al. [50] used game theory to analyze how vendors reduced lifecycles and environmental risks of materials and chose a strategy for reducing carbon emissions to developing a green supply chain. Besides, Zhao et al. [50] speculated that manufacturers would be influenced by punishment and reward systems developed by the government. Zhao et al. [51] evaluated various strategies designed by the government and manufacturers using game theory. They promoted green products through various games to simulate different circumstances and suggested a strategic decision framework for government agencies and vendors. As local concerns have become global, a carbon reduction project can, therefore, be developed through global cooperation. Wu et al. [52] also applied games to reduce costs and carbon dioxide emissions. Sadigh et al. [53] used the Nash equilibrium for supply chain decisions of pricing and inventory management. The model studied a multi-echelon supply chain consists of multiple suppliers, single manufacturer, and multiple retailers with equal power. Recently, Nazari et al. [54] implemented Nash and Stackelberg game theory to solve the pricing and inventory problem in a closed-loop supply chain.

To mitigate supply risk, manufacturers tend to have several suppliers. This study aims to explore how manufacturers evaluate and select qualified suppliers by game theory. The evaluation rating develops a corresponding quantity of orders. In this situation, manufacturers and suppliers who strive for orders intend to achieve the optimal expected benefit. They are in a "non-cooperative game" competitive relationship. Therefore, they must convince each other via competitiveness. In non-cooperative games, players do self-enforcing coordination. Each player optimizes the decision to minimize the cost of utilizing each resource and maximize the rewards it earns [55]. Nash equilibrium is widely used in non-cooperative games to help predict the outcome of the game that will make every player feel satisfied with what each other deserves. However, once they become qualified suppliers, they are in a "cooperative game" relationship to accomplish the expected supply quality. In a cooperative game, the Shapley value is applied for order allocation to suppliers in the network. Thus, this study proposes a two-stage model that connects the non-cooperative game model and the cooperative game model. The two-stage model will analyze all the players' best responses and obtain their decisions. An experimental simulation is presented to study the proposed framework. It clarifies that the supplier evaluation value (SEV) for each supplier and the Shapley values help the decision-making to select qualified suppliers and allocate orders to the suppliers. This framework can be used to enhance a plant manager’s decision-making ability to control his or her supply chain and efficiently allocate suppliers in it.

3. Modeling

This study proposes a two-stage game-theoretic model that connects the non-cooperative game model and the cooperative game model. The framework is shown in Figure 1. In the first stage, supplier evaluation and selection are performed. The interactions between a manufacturer and its supplier candidates are modeled as a non-cooperative game. When a manufacturer wants to construct a supply chain to produce its product, the behavior interactions between the manufacturer and supplier candidates will create a competitive situation. Nash equilibrium is employed to provide a steady-state of moves concerning computing the objective functions for players. Every player interacts with other players to create optimal decisions. A game reaches equilibrium, in a game-theoretic sense, when each player’s strategy is strategically stable and self-enforcing. A strategic stable or self-enforcing policy implies that no player can benefit by deviating from the equilibrium strategy. A finite non-cooperative game must have a Nash equilibrium. The Nash equilibrium is used to derive the SEV. The payoff functions will depend on the competence measurement in the manufacturing flow.

In the second stage, the interaction of all suppliers is modeled as a cooperative game. Shapley values measure the marginal contribution of each supplier in all manufacturing processes. The objective is to assign a limited vendor order to qualified suppliers efficiently. Multiple suppliers are organized into coalition groups about figuring the threshold majority to arrange appropriate and optimal supplier distribution in a manufacturing flow. Later, the Shapley value vector is used to allocate the order to all suppliers.

3.1. Supplier evaluation game

The two-player non-cooperative game for supplier evaluation is defined as follows.

(a) Player i: The model only has two players. $i = \{1, 2\} = \{\text{Manufacturer, Supplier}\}$. The player not only plays a role as a person but also as a group, where the manufacturer is the supply chain driver that produces the final product.

(b) Strategy space Θ_i: A set of all possible strategies of two players in a game. When player i has n pure strategies, $\Theta_i = \{ s_i^1, \ldots, s_i^n \}$

(c) Payoff Ψ_i: The utility or the expected utility of a player as a function of the strategy chosen by the manufacturer and suppliers.

Let $\Phi = \{ i, \Theta_i, \Psi_i \}$ be such a normal form game. This game cannot determine the pure strategy of the Nash equilibrium, because this game probably is not a Nash equilibrium. However, every finite normal form game has a mixed strategy Nash equilibrium. Thus, this study derives another strategic game from Φ, called the mixed extension of Φ, in which the actions of each player i are the set of all mixed strategies in Φ. The concept is adopted from Cheheltani & Ebadzadeh [56] and Wu [57].

The Nash equilibrium mix strategy is identical to the stochastic state. It can predict the outcome of a game by capturing the stochastic regularity. In this case, manufacturer and supplier candidates possess all the past information about their payoff and other players' behavior. This situation helps each player predicts the upcoming choices of other players, to decide a strategy.

Let J and K denote the number of pure strategies in Θ_1 and Θ_2 for the manufacture and supplier respectively. They are written in $\Theta_1 = \{M_1, M_2, ..., M_J\}$ and $\Theta_2 = \{S_1, S_2, ..., S_K\}$. Suppose ω_i^n is the probability that player i will play s_i^n strategy. Therefore, the mixed strategy for player i is (ω_i^1, …, ω_i^n). For $N = 1, \ldots, n$, the condition for ω_i^n is $0 \leq \omega_i^n \leq 1$ and $\sum_{N=1}^{n} \omega_i^N = 1$. This study uses ω_i to denote an arbitrarily mixed strategy from the set of probability distributions over Θ_i, just as this study uses s_i to denote an arbitrary pure strategy from Θ_i.

Table 1 shows the payoff matrix (J x K) for the supplier evaluation created based on the manufacturer and supplier strategies and interactions.

The manufacturer's expected payoff from playing the pure strategy M_j, when the manufacturer believes that the supplier will play the strategies $\Theta_2 = \{S_1, S_2, ..., S_k\}$ with the probability $\omega_2 = \{\omega_2(S_1), \omega_2(S_2), \ldots, \omega_2(S_k)\}$ can be expressed as:

$$\sum_{k=1}^{K}\omega_2(S_k)\cdot\psi_1(M_j,S_k) \qquad (1)$$

We can also calculate the manufacturer's expected payoff from performing the other pure strategies $\Theta_1 = \{M_1, M_2, ..., M_J\}$. This calculation will lead to the manufacturer's expected payoff from performing the mixed strategy $\omega_1 = \{\omega_1(M_1), \omega_1(M_2), \ldots, \omega_1(M_J)\}$ as follow:

$$E_1(\omega_1,\omega_2)=\sum_{j=1}^{J}\omega_1(M_j)\left[\sum_{k=1}^{K}\omega_2(S_k)\cdot\psi_1(M_j,S_k)\right]=\sum_{j=1}^{J}\sum_{k=1}^{K}\omega_1(M_j)\cdot\omega_2(S_k)\cdot\psi_1(M_j,S_k) \qquad (2)$$

where $\omega_1(M_j)$, $\omega_2(S_k)$ is the probability that the manufacturer plays M_j, and supplier plays S_k. $0 \le \omega_1(M_j), \omega_2(S_k) \le 1$ for $k = 1,\ldots, K$ and $j = 1,\ldots, J$; $\sum_{j=1}^{J}\omega_1(M_j)=1$ and $\sum_{k=1}^{K}\omega_2(S_k)=1$.

Equation (2) is actually the weighted sum of the expected payoff for each of the pure strategies of the manufacturer $\Theta_1 = \{M_1, M_2, ..., M_J\}$. Thus, for the mixed strategy $\omega_1(M_1)$, $\omega_1(M_2)$, …, $\omega_1(M_J)$ to be the best response for the manufacturer to supplier's mixed strategy $\omega_2(S_k)$, it must be that $\omega_1(M_j) > 0$ only if:

$$\sum_{k=1}^{K}\omega_2(S_k)\cdot\psi_1(M_j,S_k)\ge\sum_{k=1}^{K}\omega_2(S_k)\cdot\psi_1(M_{\hat{j}},S_k),\ \forall M_{\hat{j}}\in\Theta_1 \qquad (3)$$

for every M_j in S_1. That is, for a mixed strategy to be the best response to ω_2, it should place a positive probability on a purely given strategy only if the pure strategy itself is the best response to ω_2 [58]. Contrarily, if the manufacturer has several pure strategies that are best responses to ω_2, then any mixed strategy that puts all of its probability on some or all of these pure-strategy best responses (and zero probability on all other pure strategies) is also the best response for the supplier to ω_2. This study computes supplier's expected payoff when the manufacturer and supplier perform the mixed strategies ω_1 and ω_2, respectively. If supplier predicts the manufacturer performs the strategy set Θ_1 with the probabilities $\{\omega_1(M_1), \omega_1(M_2), \ldots, \omega_1(M_J)\}$, then the supplier's expected payoff from performing the strategy set Θ_2 with the probabilities $\{\omega_2(S_1), \omega_2(S_2), \ldots, \omega_2(S_k)\}$ is:

$$E_2(\omega_1,\omega_2)=\sum_{k=1}^{K}\omega_2(S_k)\left[\sum_{j=1}^{J}\omega_1(M_j)\cdot\psi_2(M_j,S_k)\right]=\sum_{j=1}^{J}\sum_{k=1}^{K}\omega_2(S_k)\cdot\omega_1(M_j)\cdot\psi_2(M_j,S_k) \qquad (4)$$

$E_1(\omega_1, \omega_2)$ and $E_2(\omega_1, \omega_2)$ rehash Nash's equilibrium requirement that any player's mixed strategy should be the best reaction to a mixed strategy of other players. And ω_1^* and ω_2^* represent the optimal mixed strategy for the manufacturer and supplier candidate, respectively. For a pair of mixed strategies (ω_1^*, ω_2^*) to become Nash equilibrium ω_1^* should meet:

$$E_1(\omega_1^*, \omega_2^*) \geq E_1(\omega_1, \omega_2^*) \tag{5}$$

$$E_2(\omega_1^*, \omega_2^*) \geq E_2(\omega_1, \omega_2^*) \tag{6}$$

where every probability distribution ω_1 is over Θ_1, and for ω_2^* every probability distribution ω_2 is over Θ_2. The ω_1^* and ω_2^* represent the optimal mixed strategy for manufacturer and supplier in the game, respectively.

The probability vector of the optimal strategy (ω_1^*, ω_2^*) is $\omega_1^* = \{\omega_1^*(M_1), \omega_1^*(M_2), \ldots, \omega_1^*(M_J)\}$ with actions $\{M_1, M_2, ..., M_J\}$ for the manufacturer and the vector $\omega_2^* = \{\omega_2^*(S_1), \omega_2^*(S_2), \ldots, \omega_2^*(S_K)\}$ with actions $\{S_1, S_2, ..., S_K\}$ for the supplier candidate. Player 1 (i.e., the manufacturer) pays a minus cost (–) because the manufacturer gains a profit from supplier's responses. Player 2 (i.e., the supplier) pays a plus cost (+), which means the supplier pays according to the manufacturer's evaluation. Let v_i be the i^{th} evaluation absolute value for the supplier candidates, and one has:

$$\begin{aligned} v_{i,2}(\omega_1^*, \omega_2^*) &= v_i \\ &= \left| \sum_{j=1}^{J} \sum_{k=1}^{K} \omega_1^*(M_j) \cdot \omega_2^*(S_k) \cdot \psi_2(M_j, S_k) \right|, \quad \omega_1^*(M_j), \omega_2^*(S_k) \in N.E. \end{aligned} \tag{7}$$

Therefore, v_i represents the evaluation value of the supplier candidates and is derived from two optimal strategy probabilities. The evaluation value will be used in the second stage of the model to calculate the Shapley value of each supplier.

3.2. Order allocation game

In this second stage, the interactions of all suppliers in the manufacturing process are equated with a cooperative game. The objective is to decide the priority of order assignment to the supply chain, particularly when available suppliers are limited in a manufacturing process.

In a cooperative game, we can use the Shapley value to divide the total gains among the players equitably. Shapley value uniquely determines the outcomes of the game.

The Shapley value considers multiple decision-makers who generate marginal contributions in a cooperative game. We can compute the average contribution of each player with this formula. Before the formula calculates the Shapley value, it assumes that all players' optimal results are utilized in the computation. Each player adds to a situation or coalition, which can generate the average contribution in a coalition. In the various coalitions, when one player participates in a coalition, the formula can compute its marginal contributions within a cooperative game. The proposed model utilizes a majority coalition concept to analyze supplier allocation. The concept is based on party voting game. Here, the voters build a majority coalition to win. Each voter has a power that depends on how important they are to form a winning coalition. When the sum of SEVs of some suppliers reach the majority level threshold, the power index (i.e., Shapley value) of each supplier can be computed as we can construct the winning coalition.

All selected suppliers play an N-person game with $P = \{1, 2, \ldots, N\}$. Each subset $V \subset P$ and where $v_j \neq 0$, $\forall \lambda \in V$ is called a coalition. The function f: $V \rightarrow R^+$ gained by assigning a positive real number to each element of V (i.e., SEV) and $f(0) = 0$, $V = \{v_1, v_2, .., v_i, .., v_n\}$, $i \in N$. Let $f(Z) = \sum_{i \in Z} v_i$, $v_i \in V$, $Z \subset P$ be the value of coalition Z with a cardinality of z. The vendor rating level, $L = \{L_1, L_2, \ldots, L_{\lambda}, \ldots L_n\}$, $\lambda \in N$, is derived from a majority of all SEVs of a manufacturing process. The corresponding threshold value, $H = \{h_1, h_2, .., h_{\lambda}, \ldots h_n\}$, $\lambda \in N$, where $0 < h_1 < h_2 < \ldots < h_n$.

Then,

$$L = \begin{cases} L_1 & \text{if } \sum_{i=1}^{n} v_i \geq h_1 \\ L_2 & \text{if } \sum_{i=1}^{n} v_i \geq h_2 \\ L_{\lambda} & \text{if } \sum_{i=1}^{n} v_i \geq h_{\lambda} \\ & \vdots \\ L_n & \text{if } \sum_{i=1}^{n} v_i \geq h_n \end{cases} \tag{8}$$

Different levels of evaluation are then set for supplier grouping, based on the average value of the threshold interval. Each threshold is assumed as $h_{\lambda} = (v_{max} - v_{min})/2$ using the Alpcan method [59]. According to the output vector of all SEVs of the manufacturing process, the majority of competence levels are L_λ if Σ SEVs ≥ h_λ. Thus, all SEVs of suppliers formed a grouped of majority level L_λ.

We can define the Shapley value of the i^{th} as follow:

$$SV(i) = \sum_{\substack{Z\subset X\\ i\in Z}} \frac{(z-1)!(n-z)!}{n!} \cdot \left(f(Z) - f(Z - \{i\}) \right) \\ = \sum_{\substack{Z_w\subset X\\ i\in Z_w}} \frac{(z-1)!(n-z)!}{n!} \tag{9}$$

The term $f(Z)$-$f(Z$-$\{i\})$ will always have a value of 0 or 1. When Z_w is a winning coalition, the value is 1. In the opposite condition, the terms Z-$\{i\}$ and $f(Z)$ are 0. The Shapley value ($SV(i)$) requires a winning coalition with $\sum_{i\in Z} v_i \geq L_\lambda$. The Shapley value of the i^{th} supplier expresses the relative competence value of different thresholds. In our model, the competence level of all suppliers is represented by these Shapley values. We can compute the order allocation for each qualified supplier in each process based on the supplier's Shapley values. The order allocation assigned to the i^{th} supplier is defined by:

$$O(i) = SV(i) \times R_j, \quad i, j \in N \tag{10}$$

where R_j is the total orders of the manufacturer in the j^{th} manufacturing process. The order allocation of the i^{th} supplier is derived by multiplying $SV(i)$ and R_j. Finally, the manufacturer can allocate orders to all qualified suppliers in each process.

3.3. Solution procedure

This procedure aims to find an acceptable order allocation to qualified suppliers based on the expected marginal contribution creating a minimum set of order deployment costs. The solution procedure is as follows:

(1) Assume a set of suppliers, for k = 1 to K.

(2) Considering a non-cooperative game performs the supplier evaluation: compute the manufacturer and supplier mixed strategy Nash equilibrium and find the SEV value.

(3) Set the evaluation levels: find the threshold value h_λ on the evaluation level L_λ.

(4) Considering a cooperative game, performs the supply chain allocation: compute the Shapley value of the supplier based on the threshold value h_λ.

(5) If coalition $\sum_{i\in Z} v_i \geq h_\lambda$, then finds an adjustable scale (step 6); otherwise, go to step (4).

(6) Find an adjustable scale: adjust the preference of scale by increasing or decreasing the value within the total Shapley value. Allocate the available orders to the suppliers.

4. The application of the two-stage game-theoretic approach

The framework is mainly applied when manufacturers construct the decision logic of multiple manufacturing processes and supplier candidates. The framework uses a two-stage game-theoretic approach to select qualified suppliers and classify them according to competence indicators. Based on ratings, manufacturers propose the corresponding quantity of orders. In the supplier evaluation game, the manufacturer is player 1, and the decision-maker who chooses qualified suppliers for the manufacturing process. Suppose that M denotes the strategy space of the manufacturer: $M = \{M_1, M_2, M_3, M_4\}$ = {quality of products, cost of manufacture, delivery performance, and technique of supplier} adopted from Chan and Kumar [8]. The supplier is player 2. Both players predict the behavior/strategy of their opponents and decide on their response. Table 2 shows the 4×4 payoff matrix from the manufacturer and supplier interactions.

The variable $F_{j,k}$ denotes the manufacturer's request from each supplier at each strategy, where the value is assumed to be classified from 1 to 10, as shown in Table 3. W_j denotes the strategy-weighted value, where it is assumed to be classified from 1 to 4, indicating the significances of the specific strategies.

S denotes the strategy space of the supplier: $S_k = \{S_1, S_2, S_3, S_4\}$ = {quality of products, cost of manufacture, delivery performance, and technique of supplier} also adopted from Chan and Kumar (2007). C_k denotes the set of the supplier's reputation: $C_k = \{C_1, C_2, C_3, C_4\}$, where the reputation value or score is assumed to be classified from 1 to 10. Table 4 shows the score for the strategy space of the supplier.

The formula for the suppliers' strategies is as follows:

Quality of product evaluation: this study defines S_1 as the quality capability of the i^{th} supplier, which is the product yield rate. The formula is expressed as:

$$\frac{\text{Good units}}{\text{Production units}}\%$$

Cost of manufacture evaluation: this study defines S_2 as the cost capability of the i^{th} supplier. The formula is expressed as:

$$\frac{\text{Bargain price of Manufacturer}(P_M)}{\text{Bargain price of Supplier}(P_S)} \times 10$$

Delivery performance evaluation: this study defines S_3 as the delivery capability of the i^{th} supplier, given by:

$$\frac{\text{Number of on} - \text{time deliveries}}{\text{Total number of deliveries}}\%$$

where $C_{max,i}$ is the greatest delivery performance, and $C_{min,i}$ is the smallest.

The technique of supplier evaluation: this study defines S_4 as the process capability of the i^{th} supplier, given by:

$$C_{pk} = \min\left\{\frac{USL - u}{3\sigma}, \frac{u - LSL}{3\sigma}\right\}$$

In this interaction, the manufacturer's payoff for selecting a specific strategy when the supplier has taken a choice results in the manufacturer's gain, and a loss to the supplier. The sum of loses from the supplier is illustrated, and it is assumed that the manufacturer tries to maximize her gain. The minus cost (–) indicates the manufacturer gains a payoff from the supplier's response. The plus cost (+) means the supplier pays as a result of the manufacturer's response. From Equation (2), the payoff formula for the k^{th} strategy of the supplier and the j^{th} strategy of the manufacturer is given by:

$$E_1 = \sum_{j=1}^{4}\sum_{k=1}^{4} \omega_1^*(M_j)\cdot\omega_2^*(S_k)\cdot\left(S_k - F_{j,k}\right)W_k C \tag{11}$$

In this non-cooperative interaction, we assume a zero-sum game. Hence, from Equation (4), the payoff formula of the manufacturer can be formulated as:

$$E_2 = -\sum_{j=1}^{4}\sum_{k=1}^{4} \omega_1^*(M_j)\cdot\omega_2^*(S_k)\cdot(S_k - F_{j,k})W_k C \tag{12}$$

Strategy space Θ_i is a set of all possible strategies of two players in a game. Each of the pure strategies $\Theta_1 = \{M_1, M_2, M_J\}$, is given in Equation (1), where the weights are the probabilities $\omega_1 = \{\omega_1(M_1), \omega_1(M_2), \ldots, \omega_1(M_J)\}$ and the strategy set Θ_1 and Θ_2 is a uniform distribution.

The above numerical example simulates the proposed two-stage game theory framework. First, the model studies the behavioural interactions between the manufacturer and supply candidates. The model created Nash equilibrium points to compute the SEV. Table 5 shows the numerical example for calculating the SEVs. Given the vector output for all the values, this study uses Equation (8) to compute the majority of threshold values (i.e., m_h). Then, all the SEVs are utilized to calculate the supplier's Shapley value based on Alpcan and Başar's [59] formula. Table 6 presents the Shapley values and allocation. The result shows how Shapley values of each supplier determine different order allocation. From the example, we illustrate the ability of the proposed game theory framework and solution procedure to evaluate and select suppliers, as well as allocate the required supplies.

5. Conclusions and future works

This paper presents a two-stage game theory framework for supplier evaluation, selection, and allocation in a competing supply chain. The framework applies to the decision logic of multiple manufacturing processes. In the first stage, a non-cooperative game model is utilized to analyze the interactive behavior between a manufacturer and some suppliers. All the parties possess the past information about their payoffs and the other players' behaviors. The model uses a mixed strategy Nash equilibrium to obtain the SEV. In the second stage, the interactions of all suppliers in the manufacturing process are equated with a cooperative game. When the sum of SEVs of some suppliers reach the majority level threshold, the power index (i.e., Shapley value) of each supplier can be computed by finding the winning coalition. The Shapley values become the basis for creating an evaluation mechanism for allocating suppliers in each manufacturing process. The numerical example verifies the ability of the proposed approach regarding the selection and the allocation of suppliers. Therefore, the two-stage game theory approach helps the SCM managers in their supplier evaluation, selection and order assignment.

Future work can be done with actual data to verify the proposed framework. Moreover, this research can be extended to examine supplier selection problem considering environmental Zhao et al. [50], [51], Kumar et al. [60] and Big Data (Lamba et al. [61]).

Acknowledgments

The author would like to thank the Editor, the anonymous referees for their helpful suggestions, and the Ministry of Science and Technology, Taiwan, R.O.C. for financing this research project MOST 108-2410-H-147-003 -.

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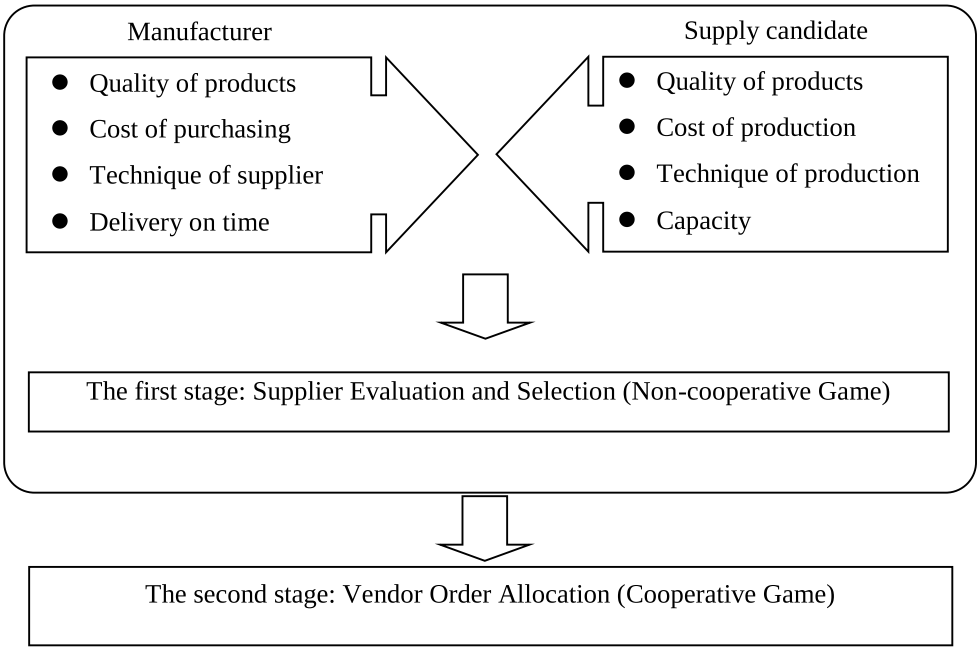

Figure 1. The proposed framework of the two-stage game-theoretic approach for supplier evaluation, selection and order assignment

Table 1. A *J*-by-*K* payoff matrix for the supplier evaluation game (ψ_i, i = 1, 2)

Supplier / Manufacturer	S_1	S_2	...	S_K	The probability of manufacturer mixed strategy
M_1	$\psi_i(M_1, S_1)$	$\psi_i(M_1, S_2)$	...	$\psi_i(M_1, S_K)$	$\omega_1(M_1)$
M_2	$\psi_i(M_2, S_1)$	$\psi_i(M_2, S_2)$	...	$\psi_i(M_2, S_K)$	$\omega_1(M_2)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
M_J	$\psi_i(M_J, S_1)$	$\psi_i(M_J, S_2)$	...	$\psi_i(M_J, S_K)$	$\omega_1(M_J)$
The probability of supplier mixed strategy	$\omega_2(S_1)$	$\omega_2(S_2)$	...	$\omega_2(S_K)$	

Table 2. A payoff matrix for the supplier evaluation game

M_j \ S_k	Quality of products	Cost of manufacture	Delivery performance	Technique of supplier
Quality of products	$(S_1 - F_{1,1})W_1C_1$	$(S_2 - F_{1,1})W_2C_2$	$(S_3 - F_{1,1})W_3C_3$	$(S_4 - F_{1,1})W_4C_4$
Cost of manufacture	$(S_1 - F_{2,1})W_1C_1$	$(S_2 - F_{2,1})W_2C_2$	$(S_3 - F_{2,1})W_3C_3$	$(S_4 - F_{2,1})W_4C_4$
Delivery performance	$(S_1 - F_{3,1})W_1C_1$	$(S_2 - F_{3,1})W_2C_2$	$(S_3 - F_{3,1})W_3C_3$	$(S_4 - F_{3,1})W_4C_4$
Technique of supplier	$(S_1 - F_{4,1})W_1C_1$	$(S_2 - F_{4,1})W_2C_2$	$(S_3 - F_{4,1})W_3C_3$	$(S_4 - F_{4,1})W_4C_4$

Table 3. The manufacturer's request ($F_{j,k}$)

Player 1 \ Player 2	S_1	S_2	S_3	S_4	W_j
M_1	5.5	4.5	3.5	4.5	2.5
M_2	4.5	5.5	3.5	4.5	2.0
M_3	4.5	4.5	5.5	3.5	1.0
M_4	4.5	4.5	3.5	5.5	1.5

Table 4. The reputation value for the strategy space of player 2

Score	S_1	S_2	S_3	S_4
10	100%		100%	$2 \leqq C_{pk}$
9	98%		98%	$1.83 \leqq C_{pk} < 2$
8	96%		96%	$1.67 \leqq C_{pk} < 1.83$
7	94%		94%	$1.5 \leqq C_{pk} < 1.67$
6	92%	$\left[\frac{P_M}{P_S} \text{x}10 \right]$	92%	$1.33 \leqq C_{pk} < 1.5$
5	90%		90%	$1.17 \leqq C_{pk} < 1.33$
4	88%		88%	$1 \leqq C_{pk} < 1.17$
3	86%		86%	$0.83 \leqq C_{pk} < 1$
2	84%		84%	$0.67 \leqq C_{pk} < 0.83$
1	82%		82%	$C_{pk} < 0.67$

Table 5. Numerical examples for the generation of SEVs

Process	Supplier	S_1	S_2	S_3	S_4	Player#1 Strategy	Player# 2 Strategy	SEV
I	A	9	8	7	10	1	3	30.3
	B	8	9	6	8	1	3	20.0
	C	6	6	7	9	1, 4	3	23.8
	D	7	7	6	7	1, 2, 4	3	17.1
II	E	8	6	7	7	1	2	21.2
	F	6	8	9	8	2	1	27.9
	G	7	6	8	9	1	2	21.9
	H	6	8	9	7	2	1	27.1
III	I	8	6	9	10	1	2	24.0
	J	6	7	10	6	3	4	34.0
	K	9	7	7	7	1	3	27.0
	L	7	8	7	8	1	3	26.0

Table 6. Results for computing the Shapley values and the allocation of suppliers

Manufacturing processes	Suppliers	Threshold value h	Shapley values $SV(i)$	The allocation of suppliers $O(i)$
I	A	23.7	0.417	1250
	B		0.083	250
	C		0.417	1250
	D		0.083	250
II	E	24.55	0.083	167
	F		0.417	833
	G		0.083	167
	H		0.417	833
III	I	29	0.167	833
	J		0.500	2500
	K		0.167	833
	L		0.167	833

Biographies

Jonas C.P. Yu received his PhD in Industrial Management at National Central University (Taiwan) in 2006 and his MSc degree from Chung Yuan Christian University (Taiwan) in 1995. After a long career in several international firms, he is now an Associate Professor of Logistics Management at Takming University of Science and Technology, and adjunct professor at Chung Yuan Christian University. His research interests are in production & material control, inventory and supply chain management, optimization problems, and yield management.

Hui-Ming Wee is a Distinguished Professor of Industrial & Systems Engineering at the Chung Yuan Christian University (Taiwan). He received his BSc (Hons) in Electrical and Electronic Engineering from the Strathclyde University (UK), MEng in Industrial Engineering and Management from the Asian Institute of Technology (AIT) and PhD in Industrial Engineering from the Cleveland State University, Ohio (USA). His research interests are in the field of production/ inventory control, optimization and supply chain management.

Schnell Jeng is is a Ph D candidate in Industrial & Systems Engineering at the Chung Yuan Christian University (Taiwan).

Yosef Daryanto is with the Department of Industrial Engineering, Universitas Atma Jaya

Yogyakarta in Indonesia**.** He received his bachelor’s degree in Industrial Engineering from Universitas Atma Jaya Yogyakarta (Indonesia), MSc in International Technology Transfer Management from the Technische Fachhochschule Berlin (Germany), and PhD in Industrial and Systems Engineering from the Chung Yuan Christian University (Taiwan). His current research interests include inventory control, supply chain management, and sustainability.