Cooperative Game-theoretic Approach for Supplier Selection, Pricing and Inventory Decisions in a Multi-level Supply Chain

Yun Huang, George Q. Huang, Xianan Liu

***Abstract*—To implement supply chain management, the coordination and integration of the activities within organization and across the supply chain is necessary. Effectively selecting and evaluating suppliers and managing their involvement in critical supply chain activities play vital roles in building competitive supply chain. This paper proposes an integrated approach for optimal supplier selection, pricing and inventory decisions in a multi-level supply chain. A cooperative game approach is used to evaluate the marginal contribution of the supply chain members, especially the suppliers. A numerical study and sensitive analysis are conducted to examine the integrated supply chain model and cooperative game model. The results show that: the rise of one retail market scale increases the retail price and demand for the product in this market, while without influencing on the other retail market; furthermore, an increased market scale rises up the importance of this market and the suppliers who only provide components for the product in this market; the change of setup cost has relatively little impact on the pricing decisions and marginal contributions of the supply chain members.**

***Index Terms*—Cooperative game, Shapley value, Supplier selection, Pricing, Inventory.**

I. INTRODUCTION

Supply chain management (SCM) is an area received great attention in business community. To implement SCM, the coordination and integration of the activities within organization and across the supply chain is necessary. Many firms identify and qualify adequate suppliers to provide the materials and service needed by them [1]. Effectively selecting and evaluating these qualified suppliers and managing their involvement in critical supply chain activities enable manufacturers to achieve the four dimensions of customer satisfaction: competitive pricing, product quality, product variety and delivery service [2,3]. This paper coordinates supplier selection, pricing and inventory decisions and proposes a cooperative game theory approach to evaluate the suppliers for an integrated multi-level supply chain.

There is huge literature in industrial field on the vertical integrated supply chain. The literature shows that to maximize overall system profit and integrate operations among various entities through coordination are of best interest. For example, Alchian and Demsetz [4] and Jensen and Meckling [5] point that vertical integration would exploit synergies between different divisions appeared as economies of scope. Williamson [6] looks at the long-term relationship between a seller and buyer and finds the advantage of integration, for example, saving transaction cost. The integration of supply chain mainly focuses on the pricing model, distribution inventory model. Boyaci and Gallego [7] analyze the problem of integrating pricing and inventory replenishment policies in a supply chain consisting of a wholesaler, one or more geographically dispersed retailers. They show that optimally coordinated policy could be implemented cooperatively by an inventory-consignment agreement. Moutaz [8] develops inventory coordination mechanism for the supply chain composed of a single supplier, three manufacturers and two retailers per manufacturer. Jabber and Goyal [9] consider optimal order quantity model in a multiple suppliers, a single vendor and multiple buyers supply chain. Some researchers also consider supplier selection decisions in the vertical integration model. Huang et al. [10] study supplier selection, pricing, and inventory coordination problems using a dynamic game model.

Papers employing cooperative game theory to study supply chain management are becoming more popular. Gerchak and Gupta [11] model their inventory problem as a cooperative game and analyze the joint cost allocation problem. Granot and Sosic [12] study a multi-stage model of decentralized distribution system with inventory sharing consisting of n retailers. In the cooperative stage, they show that Shapley value encourages the retailers to share all of their residuals. Edward [13] constructs a cooperative supply chain game for calculating transfer prices for intermediate goods in vertically integrated supply chain.

This paper considers a three-level supply chain composing of multiple suppliers, one manufacturer and multiple retailers. The manufacturer obtains components from the potential qualified suppliers and produces final products for retailers in different markets. In this paper, we formulate a mixed-integer programming model to integrate the optimal supplier selection, pricing and inventory decisions. We put forward a cooperative game theoretic approach and use the Shapley value to evaluate the marginal contributions of the supply chain members, especially the suppliers, for the above supply chain in integrated process. Their use is tested through a numerical example. The impacts of the market scale parameter, setup cost and component cost on the optimal decisions and marginal contributions of all the chain members are also investigated.

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The reminder of this paper is organized as follows. Section 2 gives the problem description and some notations. We formulate the mathematical models and solution procedure in Section 3. Finally, this paper concludes in Section 4 with some limitations and suggestions for further work.

II. PROBLEM DESCRIPTION AND SOME NOTATIONS

The product platform consists of a series of different functionality elements. Once the architecture for the product platform is finalized, components are designed and selected to offer certain functionality. The components offering different levels of the same functionality are grouped together in the substitutable component set (SCS), indexed by $i = 1, 2, ..., I$. Suppose that the components within the same SCS can be ranked in order of decreasing functionality and higher functionality components can substitute ones with lower functionality completely, but not vice versa. Let N_i be the number of components in SCS i . L_{ij} is used to denoted the component which is the j^{th} element in the i^{th} SCS, where $i = 1, 2, ..., I$ and $j = 1, 2, ..., N_i$. In Fig.1, the two platform products share the same architecture, with SCS, processor, LCD display, memory, hard drive, miscellaneous components and metal housing, in sequence. Among them, processor and LCD display have several component options, ranked in order of decreasing functionality. For instance, in processor SCS, higher functionality Intel Core 2Duo can be used to replace lower functionality Intel Pentium Dual-core. The other SCSs involve one component only, thus we do not distinguish SCS or component for them. For example, the memory SCS and memory component we use the same sign to denote, as Fig.1 shows. This application case is concerned with a three-echelon supply chain involving multiple suppliers, one single manufacturer and multiple retailers. The manufacturer, indicated by m , designs and customizes a set of products for retailers (r_l , $l = 1, 2, ..., L$) in different independent market segments. Each retailer is served by one type of products. In Fig. 1, the manufacturer focuses on two computer platform products, involving Notebook A and Notebook B, and sells them to the retailers in two market regions respectively, namely Europe (EU) and North America (NA).

The architecture for the product is finalized which consists of a series of different functionality elements. The components offering different levels of the same functionality are grouped together in the substitutable component set (SCS), indexed by $i = 1, 2, ..., I$. Suppose that the components within the same SCS can be ranked in order of decreasing functionality and higher functionality components can substitute ones with lower functionality completely, but not vice versa. The lowest functionality components in all SCSs satisfying the products requirement have also been predefined.

Let N_i be the number of components in SCS i. L_{ij} is used to denoted the component which is the j^{th} element in the i^{th} SCS, where $i = 1, 2, ..., I$ and $j = 1, 2, ..., N_i$. In Fig.1, the two products share the same architecture, with SCSs, processor, LCD display, memory, hard drive, miscellaneous components and metal housing, in sequence. Among them, processor and LCD display have several component options, ranked in order of decreasing functionality. For instance, in processor SCS, Intel Pentium Dual-core has been fixed for Notebook B, but the manufacturer could select higher functionality Intel Core 2Duo to replace it. For those SCSs, which involve one component only, we do not distinguish SCS or component for them. For example, for the memory SCS and memory component, we use the same sign to denote, as Fig.1 shows.

All the components are provided by a fixed number of qualified potential suppliers (s_v , $v = 1, 2, ..., V$). We assume that each supplier's capacity is enough to satisfy the needs of the manufacturer. For the components in Fig.1, there are 6 alternative suppliers. Fig.1 also shows the relationship between the suppliers and the components they provided. For example, supplier 1 provides Intel Core 2Duo processor and SXGA+ display.

The suppliers, the manufacturer and the retailers would like to work in an integrated manner to maximize the overall supply chain profit. From the supply chain wide, the questions that arise when building integrated supply chain model are as follows: firstly, how to determine the optimal suppliers, retail price, inventory decisions to transfer the components to the final products for the customers to maximize the total profit of the integrated supply chain; secondly, for the optional suppliers, which one is more important to the supply chain system.

Prior to develop the mathematic model for solving the above problems, we make the following underlying assumptions and simplifications:

The demand at retailer l is almost invariably a downward sloping and convex function with respect to the retail price in real world.

Vendor managed inventory (VMI) system [14, 15] is employed between the suppliers and the manufacturer and between the manufacturer and the retailers to replenish the components and the products. This inventory system has been adopted by some industries for years (e.g. Wal-Mart, Procter&Gamble (P&G), Dell, etc.). Under this assumption, the components' inventories for the manufacturer and the suppliers are at the side of their upstream suppliers and their corresponding inventory holding costs are also borne by their upstream suppliers [16]. The inventories of the final products are on the manufacturer's side and the retailers take zero inventory.

Single sourcing strategy [17] is adopted between supplies and manufacturer. Thus, the manufacturer purchases one type of component from only one supplier.

Either all or none the demand of a component is replaced by the lower order component in the same SCS.

Shortage are not permitted, hence the annual production capacity is greater than or equal to the total annual market demand [18].

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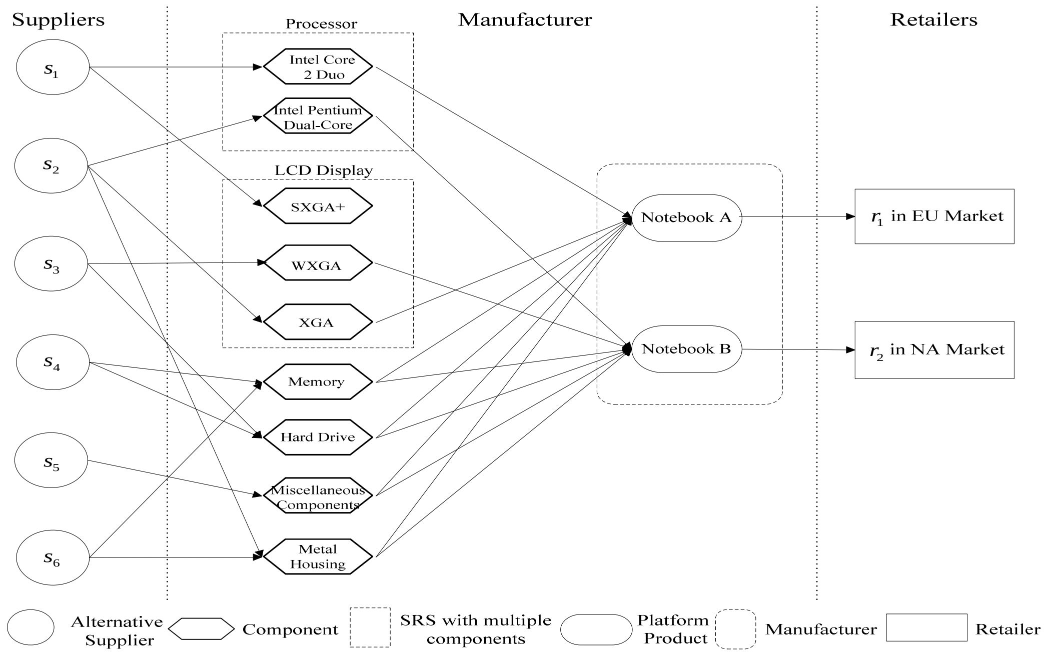

Figure 1. Coordination of suppliers and components selection, pricing and inventory decisions

III. The Mathematical Model

The relevant parameters and variables of the retailer *l* are as follows: D_{r_l} : Retailer *l*'s annual demand; A_{r_l} : A constant in the demand function of retailer *l*, which represents his market scale; e_{r_l} : Coefficient of the product's demand elasticity for retailer *l*; S_m : Setup cost per production; Ω_{s_v} : Number of different types of components supplier *v* is capable of supplying; R_{r_l} : Retailer *l*'s annual fixed costs for the facilities and organization to carry this product; R_m : Annual fixed costs for the facilities and organization for the production of the products ; R_{s_v} : Supplier *v*'s annual fixed costs for the facilities and organization to carry the components p_{r_l} : Retail price charged to the customer by retailer *l*. T : Decision variable, manufacturer's setup time interval; τ_{ijk} : Binary decision variable to indicate whether component L_{ij} has been used to replace L_{ik} ; σ_{s_v} : Binary decision variable to indicate whether supplier *v* is used; α_{r_l} : Binary decision variable to indicate whether retailer *l* is used; $t_{s_v L_{ij}}$: Binary decision variable to indicate whether component L_{ij} is supplied by supplier *v;* $z_{L_{ij}}$: Binary decision variable to indicate whether component L_{ij} is used.

Here, the objective function of the integrated supply chain model is concerned with the maximization of the overall profit of the supply chain. The total cost of the supply chain is composed of the production costs, fixed costs to contract with the suppliers and using components, holding costs for the products, setup and ordering costs, component costs and annual fixed costs for all the chain members. According to the given VMI policy, only the manufacturer has to pay for inventory for final products. The annual inventory for product *l*'s is given by $\frac{h_{mp_l}\left(P_l - D_{r_l}\right)TD_{r_l}}{2P_l}$ (suggested by [19]). The setup cost S_m occurs at the beginning of each production. Thus, the integrated supply chain model is formulated as the following constrained mixed-integer programming problem:

$$\max Z = \sum_{l=1}^{L} p_{r_l} D_{r_l} \alpha_{r_l} - \sum_{l=1}^{L} c_{m_l} D_{r_l} \alpha_{r_l} - \sum_{v=1}^{V} w_{s_v} \sigma_{s_v} - \sum_{i=1}^{I} \sum_{j=1}^{N_i} F_{L_{ij}} z_{L_{ij}} - \sum_{l=1}^{L} \frac{h_{mp_l}\left(P_l - D_{r_l}\right)TD_{r_l}}{2P_l} - \frac{S_m}{T}$$
$$- \sum_{v=1}^{V} \sum_{l=1}^{L} \sum_{i=1}^{I} \sum_{j=1}^{N_i} c_{L_{ij}} z_{L_{ij}} \left(u_{L_{ij}l} + \sum_{k=j+1}^{N_i} u_{L_{ik}l} \tau_{ijk} \right) D_{r_l} t_{s_v L_{ij}} - \sum_{l=1}^{L} R_{r_l} - R_m - \sum_{v=1}^{V} R_{s_v} \sigma_{s_v} \tag{1}$$

Subject to:

$$D_{r_l} = A_{r_l} - e_{r_l} p_{r_l} \tag{2}$$

$$0 \le D_{r_l} \le P_l \tag{3}$$

$$\sum_{j=1}^{k-1} \tau_{ijk} + z_{L_{ik}} = 1, \ \forall u_{L_{ik}l} \ne 0,$$
$$\forall i = 1,2,...,I; \ j = 1,2,...,N_i - 1; \ \ k = j+1,...,N_i; \tag{4}$$

$$\tau_{ijk} \le z_{L_{ij}},$$
$$\forall i = 1,2,...,I; \ j = 1,2,...,N_i - 1; \ k = j+1,...,N_i \tag{5}$$

$$t_{s_v L_{ij}} = 0, \ \forall L_{ij} \notin Q_{s_v}, \ \forall v = 1,2,...,V \tag{6}$$

$$\sum_{v=1}^{V} t_{s_v L_{ij}} = z_{L_{ij}}, \ \forall i = 1,2,...,I; \ j = 1,2,...,N_i \tag{7}$$

$$\sum_{L_{ij} \in Q_{s_v}} t_{s_v L_{ij}} \le \Omega_{s_v} \sigma_{s_v}, \ \forall v = 1,2,...,V \tag{8}$$

$$z_{L_{ij}}, t_{s_v L_{ij}}, \sigma_{s_v}, \tau_{ijk}, \alpha_{r_l} = \{0,1\},$$
$$\forall i = 1,2,...,I; \ j = 1,2,...,N_i - 1; \ k = j+1,...,N_i \tag{9}$$

$$p_{r_l} \ge 0 \quad T > 0. \ \forall l = 1,2,...,L \tag{10}$$

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Constraint (2) describes the demand function of the retail price. Constraint (3) gives the bounds of the annual demand, which cannot exceed the annual production capacity p_l of the product. As indicated in the fourth point of the assumption in Section 2, constraint (4) ensures that for the component predefined for the products, it is either used or replaced by higher functionality one, but not both. Constraint (5) makes sure that only procured components can be used to replace other components. (4) and (5) together ensure that the demands for all components are satisfied. Also, they met the one-way substitutability constraint which ensures that a higher functionality component can replace a lower functionality component but not vice versa. Constraint (6) sets the value of $t_{s_v L_{ij}} = 0$ for all components $L_{ij} \notin Q_{s_v}$ for all the suppliers. Constraint (7) indicates that a component is procured from exactly one supplier. Constraint (8) sets the value of σ_{s_v} to 1, if supplier *v* supplies a component, and ensures that the number of different types of components supplied by supplier *v* is no greater than Ω_{s_v}. The value ranges of all the variables are set by constraints (9) and (10).

IV. Model analysis and solution algorithm

In this section, we use a cooperative game to evaluate the suppliers involved in the above supply chain. To formulate a cooperative game, we must first identify the set of all players, *N*, and a value function v, that associate with every nonempty subset G (a coalition) of all the players. A real number $v(G)$ represents the worth of G that describes the total expected gain from the coalition G. And v satisfies the following two conditions: (1) $v(\varnothing)=0$, and (2) If $R,T \subseteq N$ and $R \cap T = \varnothing$, then $v(R \cup T) \ge v(R) + v(T)$.

Based on the definition, we define that the set of the game players is composed of the suppliers, the manufacturer and the retailers, i.e., $V+L+1$ supply chain members. The supply chain is an integrated process, wherein the components are manufactured to final products, then delivered to customers. Thus, to formulate cooperative game for such supply chain in an integrated process, the value function, here, we regard it to be,

$$\pi(G) = \begin{cases} Z(G), & \text{if coalition } G \text{ could transfer components to final products} \\ 0, & \text{otherwise} \end{cases}, \tag{11}$$

where $Z(G)$ is the integrated model (A) with the constraints that the selection variables for those supply chain members out of coalition G to be zero. For example, if supplier 1 is not within coalition G, $Z(G)$ is the model (A) adding constraint $\sigma_{s_1} = 0$. We can see that a coalition G is valid if and only if G could transfer components to one product at least. Obviously, the value function defined above satisfies conditions (1). For condition (2), $\forall R,T \subseteq V+L+1$ and $R \cap T = \varnothing$, if the manufacturer $m \notin R,T$, we have $\pi(R \cup T) = \pi(R) + \pi(T) = 0$, because the manufacturer is the indispensable supply chain member to transfer components to final products; otherwise, without loss of generality, we assume $m \in R$, thus, $\pi(T)=0$, Hence. $\pi(R \cup T) \ge \pi(R) + \pi(T)$. Thus, ($V+L+1, \pi$) is a cooperative supply chain game.

The Shapley value is a solution concept for cooperative game, which is defined as follows:

$$\phi_i(N,v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(n-|S|-1)!}{n!} \left(v(S \cup \{i\}) - v(S) \right), \tag{12}$$

where $\phi_i(N,v)$ is the Shapley value of player i, $|S|$ is the players' number in the coalition S, n is all players' numbers, and $v(S)$ is the value function of the coalition S. The marginal contribution of adding player i to coalition S is $\left(v(S \cup \{i\}) - v(S)\right)$. According to the definition, the Shapley value is obtained by averaging the marginal contributions for all the coalitions of the game players [20]. In this paper, we use the Shapley value to evaluate the supply chain members, especially the suppliers. Their importance to the integrated supply chain is classified according to their marginal contributions.

The integrated supply chain model has binary variables and $L+1$ non-integer variables. Some researchers solve such problems through genetic algorithms and conduct the comparison with the results from Lingo software. In this paper, we simply employ Lingo for the solving the integrated models. To find out the Shapley values for each supply chain member, we use the following procedure:

Step 1. Denote $R = \{r_1, r_2, ..., r_L\}$ to be the set of all the retailers; identify all the subset of R. For each X, $X \subseteq R$, find out all the suppliers combination S_X satisfying constraints (4)-(9) in Model (A) and all the valid coalitions $G_X = \left(S_{X_i}, m, X\right)$, $\forall S_{X_i} \in S_X$.

Step 2. Calculate the value function $Z\left(G_{X_t}\right)$, $\forall G_{X_t} \in G_X$, $\forall X \subseteq R$, using Lingo.

Step 3. Use (12) to calculate the Shapley values for all the supply chain members.

V. Conclusion

This paper proposes an integrated supply chain model for optimal supplier selection, pricing and inventory decisions in a multi-level supply chain. A cooperative game approach is used to evaluate the supply chain members. However, this paper has several limitations which can be extended in the further research. The competition among multiple products and among multiple retailers is not covered in this paper. Under this competition, the demand of one product / retailer is not only the function of his own price, but also the other products' / retailers' prices. Secondly, vendor managed inventory (VMI) system is the inventory policy mainly employed in the integrated model. Future research could consider some other inventory system, such as integer multipliers mechanism, with each supply chain member holding their own inventory. Also, we assume that the

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production rate is greater than or equal to the demand rate to avoid shortage cost. Without this assumption, the extra cost should be incorporated into the future work. Finally, the Shapley value of the proposed cooperative game cannot be regarded as a fair allocation rule of the total supply chain profit between the chain members, because it might not be in the core. In the future work, we may focus on working out fair allocation rule for the gains of the integrated supply chain.

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