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Alliance Formation Among Perfectly Complementary Suppliers in a Price-Sensitive Assembly System

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Independent parties that produce perfectly complementary components may form alliances (or coalitions or groups) to better coordinate their pricing decisions when they sell their products to downstream buyers. This paper studies how market demand conditions (i.e., the form of the demand function, demand uncertainty, and price-sensitive demand) drive coalition formation among complementary suppliers. In a deterministic demand model, we show that for an exponential or isoelastic demand function, suppliers always prefer selling in groups; for a linear-power demand function, suppliers may all choose to sell independently in equilibrium. These results are interpreted through the pass-through rate associated with the demand function. In an uncertain demand model, we show that, in general, the introduction of a multiplicative stochastic element in demand has an insignificant impact on stable coalitions and that an endogenous retail price (i.e., demand is price sensitive) increases suppliers' incentives to form alliances relative to the case with a fixed retail price. We also consider the impact of various other factors on stable outcomes in equilibrium, e.g., sequential decision making by coalitions of different sizes, the cost effect due to alliance formation (either cost savings or additional costs), and a system without an assembler.

Key words: alliance formation; demand curvature; pass-through rate; assembly system
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1. Introduction

Alliances of independent entities that produce complementary products often arise for different reasons. For example, they can be formed to access complementary resources, increase market power, attain a network effect, provide a one-stop shopping experience for downstream buyers, or save operational costs. The main objective of this paper is to study another possible motivation behind alliance formation among complementary players price coordination.

Alliances among complementary parties for price coordination can be found in several industries. For example, in the consumer electronic products market, when the DVD content and players were first introduced to the market, negotiation to commit to price cutting was conducted between complementary content providers and player suppliers, because the low prices of both the content and players were critical to ensure the adoption of the entire system (Varian 2001). In that regard, Lichtman (2000) argues that price coordination should be facilitated in a broad range of markets, where one set of firms sell some platform technology and another set sells peripherals compatible with that platform.

Price coordination is quite common among members of an international airline alliance on complementary legs of a flight. Indeed, as noted by Brueckner and Whalen (2000), the "...advantage of an alliance lies in the realm of pricing. Since the major alliances enjoy antitrust immunity, the alliance partners can engage in cooperative pricing of interline trips." Several recent papers provide some empirical evidence on the effect of airline cooperation on the level of the interline fares paid by international passengers. Brueckner (2003) empirically shows, based on fares generated by the International Air Transportation Association, that the presence of antitrust immunity (i.e., the ability to coordinate prices) reduces the fare by 13%–21%. Goh and Yong (2006) show that this reduction in interline fares is almost exclusively due to the airlines' ability to coordinate their pricing decisions. Similar cooperation and cooperative pricing is observed among complementary suppliers of other modes of transportation, e.g., railroad companies in Europe.

Joint pricing is also used by managers of different brands, possibly complementary products, within a firm. Traditionally, the product-focused approach leads to different managers being assigned to product lines and each product line being an independent profit and cost center (e.g., Proctor and Gamble (P&G) in the 1930s). A criticism of this approach is that it may lose the potential synergies within a firm. Thus, the recently developed consumer-focused philosophy requires the coordination of managers' activities in, e.g., pricing of their bundled products/packages (Dong et al. 2009). For example, according to Barham (2007), P&G sells bundles of its toothpaste and toothbrush to lower the cost of its goods to customers.

The rationale behind joint pricing of complementary products comes from Cournot (1929). He shows that the joint pricing of two complementary components leads to a selling price lower than the prices set independently, which thus generates higher sales. This would reduce the horizontal externalities from supplier decentralization and potentially increase their and other members' profits and social welfare. However, whether suppliers of these products can eventually benefit from such price coordination depends on the trade-off between the decrease in prices and the extent it increases demand (or sales). This motivates us to understand how market demand conditions (i.e., the form of the demand function, demand uncertainty, and price-sensitive demand) could shape the complementary suppliers' incentives to coordinate prices and to what extent they coordinate.

To facilitate our study, we propose a general price coordination phenomenon in an assembly system setting.[1] More specifically, we consider a single-period decentralized assembly system with a final product consisting of n different complementary components. Each component is provided by an independent supplier and sold to a downstream retailer/assembler at a wholesale price the supplier sets. The assembler then assembles components into the final product (or simply bundles them into a kit if no assembly is necessary) and sells it to the end customers at a retail price that it sets. Before selling to the assembler, suppliers can freely form alliances with one another to coordinate their wholesale prices. Suppliers in an alliance will offer a joint wholesale price for the bundle of components in this coalition, and different coalitions set prices independently. In the alliance-formation process, we assume that suppliers adopt the Nash stability concept, under which only unilateral deviations by individual suppliers are allowed. This concept applies to situations where unilateral moves are probably more feasible than defections from a coalition under a given coalition structure set up because of, e.g., long distances between suppliers of different coalitions that might create difficulty for effective communications and joint moves. The effect of group deviations on stable outcomes is discussed in §6.1. For tractability of a model with a general number of players, we also assume that there is only one supply source for each component and thus component suppliers are perfectly complementary to each other. This framework enables us to gain a complete understanding of the effect of market demand on suppliers' incentives to form alliances. This assumption fits well with the airline alliance on complementary legs of an international flight, e.g., where each leg is often operated by a monopolistic national airline company.

Our analysis of the assembly system with deterministic demand and perfectly complementary suppliers indicates that whether alliances are formed among suppliers crucially depends on the form of the demand curve and the pass-through rate associated with it. In marketing the pass-through rate is generally defined as the ratio of retail price reduction due to a decrease in the wholesale price. For example, if an assembler is willing to reduce its retail price by x amount because of a decrease of y amount in the wholesale price, then the ratio, x/y, is called the pass-through rate. We show that when the demand function is either exponential or isoelastic in the retail price, which results with the assembler passing through 100% or more of the wholesale price reduction to customers by reducing its retail price, suppliers always form groups when selling their components. In contrast, when demand is a linear power

[1] We use the term "assembly system" to represent a general framework in which there are multiple complementary components, each provided by an independent supplier and needed when customers use the final product. The downstream retailer/assembler may need to do some simple assembly before the final product is sold to customers, or it can sell all the components in a kit without any extra assembly activities.

function of the retail price, leading to a less than 100% pass-through rate, alliances may never be formed among suppliers.

The intuition is as follows. If the pass-through rate is relatively high, a decrease in the total wholesale price via alliances would lead to a relatively large decrease in the retail price and thus a significant increase in demand/sales. This implies a considerable benefit for suppliers and is thus a strong incentive for them to form coalitions. In contrast, if the pass-through rate is relatively low, the same amount of wholesale price reduction due to alliances has a relatively low impact on reduction of the retail price and on the increase in demand. This would lead to a relatively low or even no incentive for coalition formation. Thus, price coordination among complementary suppliers via alliances can be considered as a means to reduce wholesale prices, which further induces the downstream assembler to reduce its retail price to increase sales from the end customers. The overall benefit from such coordination depends on the extent of the decrease in the retail price, due to the wholesale price reduction, and how it changes the end-customer demand.

We extend our stability analysis to incorporate a number of other factors that may affect suppliers' incentives to form alliances, e.g., demand uncertainty, an endogenous retail price, cost effect from coalition formation, and different decision-making powers by coalitions of different sizes. Our analysis indicates that the introduction of a multiplicative random component to demand with a power distribution has an insignificant impact on alliance formation; in general, the assembler's capability to change demand by setting different values of the retail price increases suppliers' incentives to form coalitions. Two types of cost effect from alliance formation are considered—cost savings and extra costs. We show that they have opposite effects—cost savings motivate suppliers to sell in groups, but extra costs discourage such actions. Our analysis of a system with a small number of suppliers demonstrates that sequential decision making by coalitions of different sizes may significantly change suppliers' alliance formation behavior.

Overall, this paper contributes to the literature by (1) understanding how market demand shapes alliance formation among complementary players, (2) building a connection between the pass-through rate associated with a demand function and the stable coalitions formed in equilibrium, and (3) considering various factors that may affect suppliers' incentives for group selling. The remainder of the paper is organized as follows. Section 2 reviews some related papers. Section 3 introduces the basic model with deterministic demand, and §4 analyzes the model. Section 5 considers the impact of demand uncertainty, and §6 extends the basic model to study other factors that may affect alliance formation. Finally, we conclude and present some possible future research in §7.

2. Literature Review

Two streams of research are related to this paper: one studies the decentralized assembly models and the other considers coalition formation among multiple players. For papers studying the decentralized assembly systems with stochastic demand at a fixed retail price, their focus is mainly on equilibrium decisions, e.g., pricing and production (Bernstein and DeCroix 2004), inventory (Netessine and Zhang 2005, Bernstein and DeCroix 2006), lead time (Hsu et al. 2006, Fang et al. 2008), capacity (Wang and Gerchak 2003, Bernstein and DeCroix 2004), and information sharing (Feng and Zhang 2005). See Gerchak and Wang (2004) and Bernstein and DeCroix (2004, 2006) for extensive reviews. A few other papers extend assembly models to incorporate price-sensitive demand; see, e.g., Wang (2006) and Jiang and Wang (2009a, b). These papers are related to our paper in terms of the assembly setup. However, they do not allow suppliers to form alliances.

There are a very few papers considering the possibility of coalition formation among component suppliers in decentralized assembly systems. One of them is Nagarajan and Bassok (2008). They consider a decentralized assembly system wherein suppliers first form alliances among themselves, and then coalitions of suppliers sequentially negotiate with the assembler for profit allocation through a Nash bargaining process.

Our paper differs from their paper in several main dimensions. First, Nagarajan and Bassok (2008) assume that the retail price of the final product is fixed. Thus, demand is price independent and its distribution is exogenously given. Hence, the main issues we consider in our paper on how suppliers are motivated to coordinate prices to increase demand from the end customers and how and why market demand conditions affect their coordination become irrelevant in their model setup. Second, to predict stable coalition structures in equilibrium, they adopt a stability concept that allows suppliers to take into account other suppliers' future behaviors brought about by their own actions (i.e., suppliers are farsighted). In our paper, we assume that suppliers follow the Nash equilibrium to form alliances. Third, they use a bargaining framework to allocate the channel profit between coalitions of suppliers and the assembler, whereas we adopt a wholesale price-only contract because of its simplicity and popularity. Nagarajan and Bassok (2008) predict that stable outcomes are sensitive to the relative power of the assembler. Specifically, when the assembler's negotiation power is low, suppliers form a grand coalition; otherwise, suppliers act independently. In this paper, we show that alliance formation depends crucially on how end-customer demand is affected by a price reduction due to coalition formation.

Granot and Yin (2008) study two different assembly systems, push and pull, with stochastic demand. Note that, like Nagarajan and Bassok (2008), their paper also assumes a fixed retail price. Thus, demand is price insensitive and the research questions we address in this paper are not relevant in their paper. Granot and Yin (2008) analyze both Nash and farsighted stability concepts, and their analysis indicates that the grand coalition is stable in equilibrium if suppliers are farsighted. The differences on stable outcomes by using the Nash stability concept in their paper and ours will be discussed in detail in §5.

The paper most relevant to ours is Nagarajan and Sošić (2009). They also consider coalition formation in a decentralized assembly system with deterministic and retail price-sensitive demand. There are several main differences between their paper and ours. First, given suppliers as leaders, our goal is to understand how and why market demand conditions affect suppliers' coalition formation. However, their paper, similar to Nagarajan and Bassok (2008), tries to capture the effect of channel power (through competition and leader-follower roles) on coalition stability. Thus, the intent of both Nagarajan and Bassok (2008) and Nagarajan and Sošić (2009) is very different from ours. Second, Nagarajan and Sošić (2009) assume deterministic demand. In our paper, we analyze models with both deterministic and stochastic demand and explore the impact of demand uncertainty on stable coalitions. Finally, similar to Nagarajan and Bassok (2008) and Granot and Yin (2008), Nagarajan and Sošić (2009) assume that suppliers are farsighted and estimate that the grand coalition of all suppliers is always farsightedly stable when suppliers lead the game. However, under Nash stability, our paper shows that the grand coalition is never stable when the number of suppliers in the assembly system is relatively large (i.e., $n \geq 4$). Often, they form small coalitions or even act independently in equilibrium.

Note that unlike all three papers discussed above, in this paper, we are only interested in the Nash stability concept and will discuss the strong Nash equilibrium concept in the extension section (§6.1). The reason is because the Nash equilibrium is the dominant equilibrium used in the economics and operations literature, and it has been adopted by researchers and practitioners to formulate various gaming issues. Moreover, this concept allows us to characterize stable outcomes more easily than farsighted concepts and enables us to isolate the effects of demand shape, demand uncertainty, price-sensitive demand, and specifics of competition on coalition stability much more clearly than Nagarajan and Bassok (2008) and Nagarajan and Sošić (2009).

Finally, there are some papers analyzing coalition formation among competing players in the operations literature. They include Granot and Sošić (2005), Jin and Wu (2006), Oshkai and Wu (2005), Sošić (2006), and Nagarajan and Sošić (2007). Note that in our assembly framework, suppliers are perfectly complementary to each other.

3. The Model

Consider a decentralized assembly system with a single assembler and n suppliers each supplying a complementary component at their own costs. All players are risk neutral. The assembler buys components from the suppliers, assembles them into a final product, and sells it to the end customers over a single-period selling season. Without loss of generality, we assume that a unit of the final product requires a unit from each component. Demand for the final product is deterministic and sensitive to the retail price set by the assembler. Before selling to the assembler, the suppliers are allowed to freely form coalitions among themselves. Thus, we analyze two levels of problems: Level I is concerned with coalition formation among suppliers prior to their interaction with the assembler. Level II models the interaction between the assembler and the coalitions formed in Level I.

In Level I, suppliers are assumed to follow the Nash equilibrium to form coalitions. We identify coalition structures that prevent suppliers from deviation in equilibrium, which are defined as *stable outcomes* or *stable coalition structures*. Level II is formulated as a two-stage Stackelberg game. In Level II, we assume that suppliers conduct trade with the assembler through a wholesale price-only contract, because of its popularity and simplicity in practice (see, e.g., Lariviere and Porteus 2001). Thus, by forming alliances, suppliers of the same coalition would offer a single joint wholesale price for the bundle of the components produced by this coalition (hereafter, the coalitional wholesale price). Therefore, in Level II, each coalition of suppliers chooses its coalitional wholesale price in Stage 1, and then in Stage 2, provided with the vector of the wholesale prices, the assembler sets the retail price, p, for the final product. That results with an order quantity, or demand, $D(p)$, where $D(p)$ is downward sloping and twice-differentiable in p. Note that studying the stability issue of coalition structures in Level I necessitates the equilibrium analysis of Level II. Thus, we use backward induction to solve these two levels of problems.

For convenience, we summarize some of the notation used in the paper as follows.

N: Set of suppliers, $N = \{1, \ldots, n\}$.

w_i: Wholesale price of supplier i, for $i \in N$.

c_i: Marginal manufacturing cost of supplier i.

$\mathcal{B}$: Coalition structure, $\mathcal{B} = \{B_1, \ldots, B_m\}$, where $\bigcup_{j=1}^m B_j = N$, $B_h \cap B_k = \emptyset$ for $h \neq k$.

m: Number of coalitions in a coalition structure $\mathcal{B}$.

W_{B_j}: Coalitional wholesale price of coalition $B_j \in \mathcal{B}$; i.e., $W_{B_j} = \Sigma(w_i\colon i \in B_j)$.

W: Total wholesale price of all suppliers or coalitions; i.e., $W = \Sigma_{i=1}^n (w_i) = \Sigma_{j=1}^m (W_{B_j})$.

C_{B_j}: Coalitional manufacturing cost of coalition $B_j \in \mathcal{B}$; i.e., $C_{B_j} = \Sigma(c_i\colon i \in B_j)$.

C: Total cost of all suppliers or coalitions; i.e., $C = \Sigma_{i=1}^n (c_i) = \Sigma_{j=1}^m (C_{B_j})$.

Note that the equality $C_{B_j} = \Sigma(c_i\colon i \in B_j)$ implies that there are no economies of scope (or cost savings) when suppliers form coalitions. The possibility of cost savings from alliance formation will be further studied in §6.3. For a given $\mathcal{B} = \{B_1, \ldots, B_m\}$ and a given wholesale price vector $\{W_{B_1}, \ldots, W_{B_m}\}$, we observe that, because of complementarities of all the components, the assembler would always order the same quantity for each component,[2] i.e., $Q = D(p) = Q_{B_1} = \cdots = Q_{B_m}$, where Q_{B_j} is the production quantity of each component of coalition $B_j \in \mathcal{B}$. Thus, the assembler's profit function, Π_A, and the profit function of coalition B_j, Π_{B_j}, for any $B_j \in \mathcal{B}$ can be expressed as

$$\Pi_A(p) = (p - \Sigma_{j=1}^m (W_{B_j}))Q = (p - W)D(p) \quad \text{and} \tag{1}$$

$$\Pi_{B_j}(W_{B_j}) = (W_{B_j} - C_{B_j})Q = (W_{B_j} - C_{B_j})D(p), \quad \text{for any } B_j \in \mathcal{B}. \tag{2}$$

This paper assumes that the assembler's assembly cost, c_A, is zero. If $c_A > 0$, it is not difficult to verify that the only change is to replace the total system cost C with $C' = C + c_A$ in all equilibrium profits and decisions. It will not affect any of the stability results derived in the sequel. The following proposition characterizes the profit of each coalition (i.e., the coalitional profit) in equilibrium. All proofs are presented in the online appendix.

Proposition 1. *In the decentralized assembly system with perfectly complementary suppliers, for a given coalition structure, all coalitions realize equal profits in equilibrium.*

Equal profits for all coalitions, regardless of their possibly different manufacturing costs, are due to the fact that all components are perfectly complementary in the assembly system considered here.

[2] The reason is as follows. If one of the components is ordered more than Q, then by reducing the quantity of this component to Q the assembler would maintain the same revenue but lower the purchasing cost. In contrast, if one of the components is ordered less than Q, say, $Q' < Q$, then by reducing the quantities of all other components to Q', the assembler would keep the revenue and lower the purchasing cost.

4. Model Analysis

We consider a simple deterministic assembly system with the demand function $D(p)$ satisfying the following assumption, which has also been used by, e.g., Song et al. (2008).

Assumption 1. *Denote the price elasticity of the demand function, $D(p)$, to be $\eta(p) = -pD'(p)/D(p)$, where $D'(p) = dD(p)/dp$. Assume that $\eta(p) = p/(\alpha + \beta p)$, where α and β are constant, $\alpha \geq 0$, and $\beta \leq 1$.*

The expression of $\eta(p) = p/(\alpha + \beta p)$ requires that[3] $\alpha + \beta p > 0$, and it implies that the *curvature* of the demand function, denoted by $\psi(p) = D(p)D''(p)/(D'(p))^2$, is a constant; i.e., $\psi(p) = 1 + \beta$, where $D''(p) = d^2D(p)/dp^2$. The curvature of a demand function captures its log-concavity property. Specifically, when $\psi(p) \leq 1$ or $\beta \leq 0$, $D(p)$ is log-concave in p, and when $\psi(p) \geq 1$ or $\beta \geq 0$, $D(p)$ is log-convex in p; see, e.g., Bresnahan and Reiss (1985). According to Tyagi (1999), to guarantee the existence of an equilibrium solution for the assembler's retail price, the curvature of the demand function has to be restricted by $\psi(p) \leq 2$ (Equation (5) in his paper). This leads to $\beta \leq 1$. A large family of demand functions satisfies Assumption 1. Examples include the linear-power function $D(p) = (a - bp)^\gamma$ for $a, b, \gamma > 0$; the exponential function $D(p) = ae^{-bp}$ for $a, b > 0$; and the isoelastic function $D(p) = ap^{-b}$ for $a > 0$ and $b > 1$. These demand functions are commonly used in the economics and operations literature.

Proposition 2. *In an assembly system with perfectly complementary suppliers, when demand function $D(p)$ satisfies Assumption 1, for any given $\mathscr{B} = \{B_1, \ldots, B_m\}$, we have the following equilibrium decisions and profits.*

(1) $W^*_{B_j} - C_{B_j} = (1/m)(W^* - C) = (\alpha + \beta C)/(1 - \beta m)$, *for any $j \in \{1, \ldots, m\}$, and $\partial W^*/\partial m \geq 0$.*

(2) $p^* = (\alpha(1-\beta)m + \alpha + C)/((1-\beta)(1-\beta m))$, *and $\partial p^*/\partial m \geq 0$ and $\partial Q^*/\partial m \leq 0$, where $Q^* = D(p^*)$.*

(3) $\Pi^*_{B_j} = \Pi(m) = ((\alpha + \beta C)/(1 - \beta m))D(p^*)$, *for any $j \in \{1, \ldots, m\}$, and $\partial \Pi(m)/\partial m \leq 0$ and $\partial m\Pi(m)/\partial m \leq 0$.*

(4) $\Pi^*_A = ((\alpha + \beta C)/((1-\beta)(1-\beta m)))D(p^*)$ *and $\partial \Pi^*_A/\partial m \leq 0$.*

An implicit assumption made here is that $1 - \beta m > 0$ for all m. In most example functions listed above, indeed, $\beta < 0$; e.g., $D(p) = (a - bp)^\gamma$ for $a, b, \gamma > 0$, and $D(p) = ae^{-bp}$ for $a, b > 0$. If this condition does not hold, the analysis in the proof of Proposition 2 indicates that there will be no transactions at all between suppliers and the assembler, and all the players end up with a zero profit, which is not an interesting scenario to consider. Thus, in what follows, we assume that $1 - \beta m > 0$ and we will discuss the effect of this condition when we go to specific demand functions.

Proposition 2 provides several important implications.

(1) *Channel inefficiency*. Items (1) and (2) in Proposition 2 suggest that there exist two sources of inefficiency in assembly systems: the traditional vertical double marginalization between the assembler and suppliers (Spengler 1950), because $W^* > C$, and the horizontal decentralization of suppliers, because W^* and p^* increase in m. The second source of inefficiency implies the existence of the horizontal externalities in wholesale pricing. It also indicates that decentralized suppliers charge a higher total wholesale price, resulting in a higher retail price and a lower stocking quantity, compared with the case of centralized suppliers.[4] This is consistent with the result in Cournot (1929).

(2) *Total supplier profit*. Item (3) implies that both the profit of each coalition and the total profit for all suppliers decrease in m. Thus, they are maximized (minimized) when all suppliers form a grand coalition (the independent structure). However, whether the grand coalition will emerge to be stable in equilibrium depends on individual suppliers' incentives.

(3) *Assembler's profit*. Item (4) in the proposition indicates that the assembler always benefits from coalitions formed among his suppliers. There is a debate on whether alliances among suppliers should be formed from the assembler's viewpoint, which has been investigated by some empirical studies in the operations literature, see, e.g., Choi et al. (2002). Some

[3] For $\beta \geq 0$, this condition is always satisfied. For $\beta < 0$, it is never optimal for the assembler to charge a retail price high enough so that $\alpha + \beta p < 0$, because this would lead to a negative $D(p)$ (due to $-pD'(p)/D(p) = (p/(\alpha + \beta p)) \leq 0$ and $D'(p) \leq 0$) and thus a negative profit for the assembler. Note that this condition implies that $\alpha + \beta C \geq 0$, since $p \geq C$.

[4] The inefficiency due to decentralization of complementary suppliers has recently received some attention in the operations literature; see, e.g., Netessine and Zhang (2005) and Wang (2006).

studies argue that alliances of suppliers may hurt the assembler because alliances may increase suppliers' negotiation power relative to the assembler. The result derived in this paper for the assembly system with suppliers being the game leaders and having the full bargaining power suggests that the assembler should encourage his suppliers to form coalitions and better coordinate their wholesale pricing decisions, if the business conditions fit into the model setting studied here.

(4) *Consumers' surplus*. Finally, from Items (1) and (2), we can conclude that when coalitions are formed to coordinate suppliers' wholesale prices, consumers' surplus is higher than when all suppliers act independently, because of a reduced retail price and an increased availability of the final product to the end customers. Thus, this result undermines one of the arguments in favor of blocking alliance formation among complementary suppliers by antitrust laws, which aim to forbid only those alliances or mergers that are "likely to hurt consumers." This conclusion is consistent with the relatively recent commentary regarding suggestions to break up Microsoft into two price-setting independent firms—the operating system and the applications groups (see, e.g., Liebowitz 2000a, b).

Proposition 2 (3) indicates that each coalition gains an equal profit (consistent with Proposition 1) and the coalitional profit does not depend on the actual composition of coalitions, but only on the number of coalitions in a coalition structure, the total cost of all suppliers, and the form of the demand function. We denote by $\Pi(m)$ the equilibrium coalitional profit under a coalition structure with m coalitions. To facilitate the study of the suppliers' coalition formation problem in Level I, we first need to figure out how members of the same coalition would split the coalitional profit among themselves. A classical way to allocate the gains from cooperation among players is the Shapley value (Shapley 1953). The Shapley value generates a unique allocation to each member of the coalition, and it has many desirable properties (i.e., symmetry, null player, efficiency, and additivity). Due to these properties, it is often considered one of the fairest allocations of collective gains by cooperative players. The following proposition reveals that members of the same coalition should share the coalitional profit equally.

Proposition 3. *In a given coalition structure, the Shapley value generates an equal allocation of the coalitional profit to each member of the same coalition.*

Given the equal profit allocation among members of the same coalition, suppliers form alliances in Level I. Under the Nash stability concept, an individual supplier can make a unilateral defection from her current coalition in a given coalition structure if she is strictly better off from such a deviation. We assume that a *feasible deviation* by a supplier in any given coalition structure is either from her coalition to become independent, or to join another coalition, provided that the receiving coalition becomes strictly more profitable from having the deviating supplier join it.

Definition 1. The Nash stable set of coalition structures consists of all coalition structures in which no supplier has a strictly profitable and feasible deviation.

Following Definition 1, we next characterize the necessary and sufficient conditions under which a given coalition structure is Nash stable. Denote by $|B_j|$ the number of suppliers in coalition B_j (i.e., the size of the coalition) and define $U(m) = \Pi(m)/\Pi(m+1)$. For a given coalition) structure $\mathcal{B} = \{B_1, \ldots, B_m\}$, let us assume, without loss of generality, that $|B_1| \leq \cdots \leq |B_m|$, and one can also classify its members into two possible categories—independent and nonindependent suppliers.

Proposition 4. *A given coalition structure $\mathcal{B} = \{B_1, \ldots, B_m\}$ is Nash stable if and only if*

(1) *$U(m-1) \leq |B_2| + 1$, provided that there are any independent suppliers and*

(2) *$U(m) \geq |B_m|$, provided that there are any nonindependent suppliers.*

Condition (1) of the above proposition prevents an independent supplier, say supplier i, from deviating to join any other coalitions. The reason is as follows. If supplier i decides to deviate, then joining the smallest coalition except her own, i.e., B_2, will give her the highest profit, relative to joining any other coalitions. Because Condition (1) makes supplier i worse off by forming a group with B_2, supplier i would stay independent. Condition (2) deals with nonindependent suppliers' incentive to deviate to be independent. The nonindependent suppliers who have the strongest incentive to be independent are the ones in the largest coalition, i.e., B_m. Condition (2) ensures that even suppliers in the largest coalition have no incentive to defect to be independent, and thus no nonindependent suppliers will deviate. Note that both conditions are required for a coalition structure to be stable if it contains both independent and nonindependent suppliers.

By its definition, the value of $U(m)$ represents the ratio of the coalitional profits before and after some player moves from one coalition structure to another. This measures a supplier's incentive to join a coalition or to deviate from an alliance to act independently. More specifically, from the proof of Proposition 4 in the appendix, for a given coalition structure with m coalitions, $U(m-1)$ measures independent suppliers' incentives to stay independent, and $U(m)$ measures nonindependent suppliers' incentives not to deviate to be independent. Thus, the value of $U(m)$ plays an important role in determining the stability of a coalition structure. We will refer to $U(m)$ as the *stability factor* in the rest of the paper. Intuitively, following the conditions in Proposition 4, one can predict that a smaller value of $U(m)$ makes an independent supplier more likely to remain independent and a nonindependent supplier more likely to defect to be independent. Thus, it is more likely for coalition structures with relatively small coalitions (e.g., the independent structure in the extreme case) to be stable. Finally, note that the conditions in Proposition 4 for the system with deterministic and price-sensitive demand are consistent with those derived in Granot and Yin (2008) for a system with stochastic and price-independent demand.

To test whether a coalition structure is Nash stable, it is important to understand the behavior of the stability factor, $U(m)$. Based on Proposition 2, we next derive some properties of $U(m)$.

Proposition 5. *In an assembly system with a demand function, $D(p)$, satisfying Assumption 1, the stability factor satisfies $U(m)=\Pi(m)/\Pi(m+1)=((1-\beta(m+1))/(1-\beta m))((D(p_m^*))/(D(p_{m+1}^*)))$, and accordingly*:

$$\frac{\partial U(m)}{\partial m}=\frac{(1-\beta)\beta}{(1-\beta m)^2}\cdot\frac{D(p_m^*)}{D(p_{m+1}^*)}, \tag{3}$$

where $p_k^*=(\alpha(1-\beta)k+\alpha+C)/((1-\beta)(1-\beta k))$ is the equilibrium retail price in a coalition structure with k coalitions.

Recall that the stability factor, $U(m)$, measures an independent supplier's incentive to form a coalition with others, and higher values of $U(m)$ give suppliers stronger incentives to form groups. From necessary and sufficient conditions for a coalition structure to be Nash stable in Proposition 4, $U(m)$ determines whether a coalition structure with m coalitions is stable. According to Equation (3), whether $U(m)$ increases or decreases in m depends solely on the sign of β, or equivalently, it depends only on the curvature of the demand function, $\psi(p)=1+\beta$. When $\beta>0$, i.e., $\psi(p)>1$, $U(m)$ increases in m, which implies that it is very likely to observe suppliers forming alliances with one another in equilibrium. However, when $\beta<0$, i.e., $\psi(p)<1$, $U(m)$ decreases in m, which suggests that suppliers may prefer to be independent. Tyagi (1999) shows a nice relationship between the demand curvature and the pass-through rate. The latter will be used to interpret the impact of the demand curve on stable coalition structures. Recall from the introduction section that the pass-through rate is the ratio of retail price reduction to a decrease in the wholesale price. In mathematical notation, it is $(dp)/(dW)$, which can be written as a function of the demand curvature: $(dp)/(dW)=1/(2-\psi(p))$. Thus, the pass-through rate is less than 100% if $\psi(p)<1$, equal to 100% if $\psi(p)=1$, and greater than 100% if $\psi(p)>1$ (Theorem 1 in Tyagi 1999).

To further characterize the stable coalition structures, we next consider three different classes of demand functions. These three functions are commonly used in the operations literature; more importantly, they capture three different signs that β could take:

- $\beta<0$: Linear-power demand function, $D(p)=(a-bp)^\gamma$, for $a, b, \gamma>0$.
- $\beta=0$: Exponential demand function, $D(p)=ae^{-bp}$ for $a, b>0$.
- $\beta>0$: Isoelastic demand function, $D(p)=ap^{-b}$ for $a>0$, and[5] $b>n$.

For each of these demand functions one can derive the values of α, β, the curvature of the demand function, $\psi(p)$, the pass-through rate, and the stability factor, $U(m)$, in Table 1.

[5] The condition, $b>n$, is derived from the assumption that $1-\beta m>0$ (see discussion following Proposition 2).

Table 1 Values of α, β, $\psi(p)$, Pass-Through Rate, and $U(m)$ Under Three Demand Functions

Demand function	α	β	$\psi(p)$	Pass-through rate (%)	$U(m)$
$D(p)=(a-bp)^{\gamma}$ for $a, b, \gamma > 0$	$\frac{a}{b\gamma}$	$-\frac{1}{\gamma}$	$1-\frac{1}{\gamma}<1$	<100	$\left(\frac{\gamma+m+1}{\gamma+m}\right)^{\gamma+1}$
$D(p)=ae^{-bp}$ for $a, b > 0$	$\frac{1}{b}$	0	$1=1$	100	$e \approx 2.72$
$D(p)=ap^{-b}$ for $a > 0, b > n$	0	$\frac{1}{b}$	$1+\frac{1}{b}>1$	>100	$\left(\frac{b-m}{b-m-1}\right)^{b-1}$

Following $U(m)$ in Table 1 and the conditions in Proposition 4, we derive the stable outcomes in the system under each of the three demand functions. To emphasize the qualitative insights of these results, we summarize them in Proposition 6 and provide more details of the exact stable outcomes and their derivation in the proof of this proposition in the online appendix. For convenience, we denote by $\overline{\mathcal{B}}$ the independent structure, i.e., $\overline{\mathcal{B}} = \{\{1\}, \{2\}, \dots, \{n\}\}$, $\mathcal{B}^*$ the grand coalition, i.e., $\mathcal{B}^* = \{N\}$, and $\mathcal{B}_{(j)(n-j)} = \{B_1, B_2\}$ with $|B_1| = j$ and $|B_2| = n - j$, where $j \le n - j$. For an odd n, define $\mathcal{B}_{12} = \{B_1, \dots, B_m\}$ with $|B_1| = 1$ and $|B_2| = \dots = |B_m| = 2$, and define $\mathcal{B}_{23} = \{B_1, \dots, B_m\}$ with $|B_1| = \dots = |B_{m-1}| = 2$ and $|B_m| = 3$. When $n = 3$, $\mathcal{B}_{23}$ coincides with the grand coalition. For an even n, define $\mathcal{B}_{22} = \{B_1, \dots, B_m\}$ with $|B_1| = \dots = |B_m| = 2$.

Proposition 6. *In an assembly system with perfectly complementary suppliers, for $n = 2$, both suppliers prefer forming a coalition in equilibrium for all three demand functions. For $n \ge 3$, stable coalition structures are different under different demand functions. More specifically, we have:*

- *For an exponential demand function, whenever possible, coalitions of two suppliers will be formed. That is, $\mathcal{B}_{12}$ ($\mathcal{B}_{22}$) is uniquely stable for an odd (even) n.*
- *For a linear-power demand function, $\overline{\mathcal{B}}$ is uniquely stable if the power of the demand function is small, otherwise, $\mathcal{B}_{12}$ for an odd n ($\mathcal{B}_{22}$ for an even n) is uniquely stable for a small n, both $\mathcal{B}_{12}$ ($\mathcal{B}_{22}$) and $\overline{\mathcal{B}}$ are stable for a moderate n and $\overline{\mathcal{B}}$ is uniquely stable for a large n.*
- *For an isoelastic demand function, $\overline{\mathcal{B}}$ is never stable. For $n = 3$, $\mathcal{B}^*$ is uniquely stable if the price elasticity of demand is small; otherwise, $\mathcal{B}_{12}$ is uniquely stable. For $n \ge 4$, we have (1) $\mathcal{B}^*$ is never stable; (2) for an even n, $\mathcal{B}_{22}$ is stable, and for an odd n, $\mathcal{B}_{23}$ ($\mathcal{B}_{12}$) is stable if the price elasticity is small (large); and (3) $\mathcal{B}_{(1)(n-1)}$ is stable only if the price elasticity is small.*

From Proposition 6, when $n \ge 3$, different demand functions lead to different stability results in equilibrium. We next explain these differences using the pass-through rate determined by the curvature of the demand function. We first consider the exponential demand function, $D(p) = ae^{-bp}$, under which we have the demand curvature, $\psi(p) = 1$, and a 100% pass-through rate. We can easily verify that a demand function with $\psi(p) = 1$ will always have an exponential form. Thus, the stability factor, $U(m)$, is a constant, and $U(m) \approx 2.72 \in (2, 3)$ (Proposition 5). In a given coalition structure with m coalitions, suppose that there are two independent suppliers. If these two independent suppliers form a coalition, the new coalitional profit, $\Pi(m-1)$, shared by these two members is more than the sum of their original profits when they are independent, i.e., $2 \cdot \Pi(m)$, because $U(m-1) = \Pi(m-1)/\Pi(m) > 2$. Thus, it is not possible for two independent suppliers to coexist in a stable coalition structure. If there is a coalition with l members, where $l \ge 3$, then any member in the coalition would have an incentive to deviate to be independent, because $\Pi(m)/l \le \Pi(m)/3 < \Pi(m+1)$ due to the fact that $U(m) < 3$. Therefore, a coalition structure will never be stable if it has a coalition with three or more members. Hence, we conclude that either $\mathcal{B}_{12}$, for an odd n, or $\mathcal{B}_{22}$, for an even n, would emerge in equilibrium as the unique stable outcome.

Next, we examine the linear-power demand function, $D(p) = (a - bp)^{\gamma}$. From Table 1, $\psi(p) = 1 - 1/\gamma < 1$, which leads to a pass-through rate of less than 100%; i.e., $(dp)/(dW) < 1$ or $dp < dW$. This implies that a dollar decrease in the wholesale price would lead to a less-than-a-dollar decrease in the retail price. Thus, the increase in demand or order quantity is relatively insensitive to the wholesale price reduction stemming from alliances formed among suppliers. Therefore, suppliers' incentives to form alliances are dampened or even eliminated. Note that both $\psi(p)$ and the pass-through rate increase in γ, the exponent of the demand function. When γ is relatively small, i.e., $\gamma < 2.35$ in this case, the pass-through is too low to create any incentives for suppliers to form alliances. This implies that for the commonly used linear demand function (i.e., when $\gamma = 1$), in a system with more than two suppliers, all suppliers would stay independent. Even for a high value of γ, Proposition 6 indicates that suppliers would still act independently when there is a relatively large number of suppliers in the system. A possible reason is that in this case, the amount of wholesale price reduction via an alliance, relative to the large value of the total wholesale price from a large number of suppliers, is insignificant, and thus the increase in demand and order quantity is not sufficient to motivate coalition formation.

In contrast to the linear-power demand function, for the isoelastic demand function, $D(p) = ap^{-b}$, from Table 1, $\psi(p) = 1 + 1/b > 1$ and the pass-through rate is greater than 100%; i.e., $(dp)/(dW) > 1$ or $dp > dW$. Thus, demand or order quantity is quite sensitive to the wholesale price reduction from alliance formation among suppliers. Therefore, suppliers have a strong incentive to form coalitions to reduce the wholesale price and increase demand. As a result, we observe that coalitions of suppliers would always be formed in equilibrium.

Finally, it is worth pointing out that even though the grand coalition maximizes the total suppliers' profit and consumers' surplus (see Proposition 2 and the discussion thereafter), it is never stable when the number of suppliers in the assembly system is relatively large; i.e., $n \geq 4$.

5. Model Under Stochastic Demand

We incorporate uncertainty into demand in a multiplicative fashion, i.e., demand $X = D(p)\xi$, where $D(p)$ is the expected demand function, which is downward sloping, twice differentiable, and satisfies Assumption 1, and $\xi \in [L, U]$ measures the randomness in demand. The multiplicative demand model is appropriate for the setting when the variance of uncertain demand increases but the coefficient of variation is unaffected when the retail price decreases. The implications of an additive demand model will be discussed at the end of this section. Denote by ϵ any realization of ξ, and let $F(\epsilon)$ and $f(\epsilon)$ be the distribution and density functions of ξ, respectively. Working backward, we first analyze the assembler's optimal decisions under a given coalition structure, $\mathscr{B} = \{B_1, \ldots, B_m\}$, and a given wholesale price vector offered by coalitions, $\{W_{B_1}, \ldots, W_{B_m}\}$. Because of demand uncertainty, the assembler now needs to choose both the retail price, p, and the ordering quantity, Q, and bears the risk of unsold inventory to maximize

$$\begin{aligned} E\Pi_A &= pE_X \min(Q, X) - wQ \\ &= pD(p)[z - \Lambda(z)] - WD(p)z, \end{aligned} \tag{4}$$

where $z \equiv Q/D(p)$ is the *stocking factor*,[6] $\Lambda(z) = \int_L^z (z-\epsilon) f(\epsilon)\, d\epsilon = \int_L^z F(\epsilon)\, d\epsilon$ is the expected unsold inventory, and $W = \Sigma_{j=1}^m W_{B_j}$. It is equivalent for the assembler to choose (p, Q) or (p, z) (see, e.g., Petruzzi and Dada 1999). Song et al. (2008) show that the assembler's profit function is well behaved in (p, z), when ξ has an increasing generalized failure rate (IGFR) property (i.e., $\epsilon f(\epsilon)/(1 - F(\epsilon))$ increases in ϵ). Thus, for any given W, the first-order conditions of $E\Pi_A$ uniquely determine the assembler's optimal (p^*, z^*) as follows:

$$\begin{gathered} p[1 - F(z)] - W = 0 \quad \text{and} \\ \left[z - \int_L^z F(\epsilon)\, d\epsilon\right](\alpha + \beta p - p) + zW = 0. \end{gathered} \tag{5}$$

Observe that (p^*, z^*) depends on the wholesale prices only through the total wholesale price. Knowing the assembler's (p^*, z^*), coalitions determine their optimal wholesale prices to maximize

$$E\Pi_{B_j} = (W_{B_j} - C_{B_j}) D(p^*) z^*, \quad \text{for any } B_j \in \{B_1, \ldots, B_m\}. \tag{6}$$

It is not difficult to extend Proposition 1 for a deterministic demand case into a system with stochastic demand. Thus, coalitions will realize equal profits in equilibrium under any given coalition structure, regardless of stochastic or deterministic demand.

Note from equations in (5) that for $\alpha = 0$, i.e., when $D(p)$ is isoelastic, the assembler's optimal stocking factor is independent of both W and p. This property will greatly simplify the analysis of equilibrium profits and decisions for a given coalition structure. Indeed, we have the following stability proposition in the case with an isoelastic demand function.

[6] The interpretation for z is that if z is larger than the realized value of ξ, there is inventory leftover, and if z is smaller than the realized value of ξ, there is shortage in meeting demand.

Proposition 7. *In an assembly system with perfectly complementary suppliers, when demand is stochastic, $X = D(p)\xi$, $D(p) = ap^{-b}$, and ξ has the IGFR property, the Nash stable set coincides with that in a system with deterministic demand $D(p) = ap^{-b}$. Thus, for an isoelastic expected demand function, demand uncertainty has no impact on suppliers' coalition formation.*

This result is due to the property of the iso-elastic demand function. The interpretation is directly stemming from the fact that the assembler's optimal stocking factor, the main element through which randomness in demand affects the profits and decisions, is independent of the coalitional wholesale prices and thus independent of the coalition structure.

However, when $\alpha > 0$, it is difficult to derive explicit expressions for equilibrium decisions and profits (see, e.g., Song et al. 2008) and the stability factor, $U(m)$. Thus, we resort to numerical studies for the exponential or linear-power demand function case. For tractability, we assume in the rest of this subsection that the randomness ξ follows a class of power distributions[7] with $f(\epsilon) = \lambda(\epsilon)^q$ and $F(\epsilon) = \lambda(\epsilon)^{q+1}/(q+1)$, where $\xi \in [0, ((q+1)/\lambda)^{1/(q+1)}]$, for any $\lambda > 0$ and $q \geq 0$. To further simplify, we assume that $\lambda = 1$. Note that the family of power distributions satisfies the IGFR property. Because of space considerations, we only present our observations on stable outcomes from the numerical studies. The detailed analysis of both cases is provided in the appendix.

Observation 1. *In an assembly system with perfectly complementary suppliers, when demand is stochastic, $X = D(p)\xi$, where $D(p) = ae^{-bp}$, and ξ has the IGFR property:*
- *The independent structure is never stable.*
- *The grand coalition is uniquely stable for $n = 2$, and it is not stable for $n \geq 3$.*
- *For $n \geq 3$, coalitions formed in equilibrium have no more than three members, and $\mathscr{B}_{12}$ ($\mathscr{B}_{22}$) is uniquely stable for an odd (even) n if the total production cost or q is relatively large.*

Compared with the stable outcomes for a deterministic system with an exponential demand function in Proposition 6, we can conclude that the stability results under $D(p) = ae^{-bp}$ are generally consistent in cases both with and without demand uncertainty. Table A.1 in the appendix indicates that when C or q increases, $U(m)$ approaches its corresponding value in the deterministic system. From our numerical study, we also observe that when $C \to \infty$ or $q \to \infty$, $U(m)$ reduces to coincide with its corresponding value in the deterministic system. This is because when C increases, the retail price would increase accordingly, which in turn reduces the expected demand and thus the impact of the random demand component on equilibrium decisions and profits. When $q \to \infty$, the variance of stochastic demand approaches 0, which reduces the system to a deterministic one.

Observation 2. *In an assembly system with perfectly complementary suppliers, when demand is stochastic, $X = D(p)\xi$, where*[8] *$D(p) = (a-p)^{\gamma}$, and ξ has the IGFR property:*
- *The independent structure is uniquely stable when n is relatively large.*
- *The grand coalition is uniquely stable for $n = 2$, and it is not stable for $n \geq 3$.*
- *A stable coalition structure will not contain a coalition with more than two suppliers.*
- *A decrease in γ decreases $U(m)$ and thus increases suppliers' incentives to be independent.*

Comparing Observation 2 with the results in the case with deterministic demand in Proposition 6, we conclude that for a linear-power expected demand function, stable outcomes are qualitatively consistent in cases with and without demand uncertainty. Finally, we note from Table A.2 in the appendix that an increase in the value of C/a decreases $U(m)$ and

[7] The expected value of ξ, $E(\xi) = (\lambda/(q+2))((q+1)/\lambda)^{(q+2)/(q+1)}$, may not be equal to 1. Strictly speaking, $D(p)$ is a scaled expected demand function of X, and the scale is $E(\xi)$. Due to the multiplicative form of $X = D(p)\xi$, $E(\xi)$ becomes a multiplier factor in the coalitional profit functions in (6), which does not affect the stability factor and thus does not affect the stability results derived. For convenience, we still refer to $D(p)$ as the expected demand function.

[8] For a general function, $D(p) = (a - bp)^{\gamma}$, b can be normalized to 1. $D(p) = (a - bp)^{\gamma}$ can be rewritten as $D(p) = b^{\gamma}(a/b - p)^{\gamma}$. Due to the multiplicative demand model, $X = D(p)\xi$, the expression b^{γ} becomes a multiplier in the coalitional profit functions. Thus, the stability factor, $U(m)$, which is a ratio of coalitional profits, depends on a and b only through their ratio, a/b. Therefore, the stability results depend on parameters a and b only through their ratio. This implies that we can normalize $b = 1$ when we derive $U(m)$ and the stable outcomes.

moves it toward its corresponding value in the deterministic system given in Table 1. This is because when C/a increases, the value of $D(p)$ decreases, because the retail price, p, approaches its upper bound a. The smaller the value of $D(p)$, the less impact the stochastic component of demand has on the system and its profits and decisions in equilibrium, due to a multiplicative demand model. Thus, when C/a approaches 1, $U(m)$ in the stochastic demand case approaches its value in the deterministic demand case. We also note that an increase in q decreases $U(m)$, and when q increases, $U(m)$ is less sensitive to the value of C/a. Note that when $q \to \infty$, the variance of the random factor in demand, ξ, reduces to 0, which leads to a system with deterministic demand. Indeed, from Table 1, $U(m)$ in the deterministic model with $D(p) = (a-p)^\gamma$ is independent of values of a and C.

For all three expected demand functions considered in this paper, in general, demand uncertainty has an insignificant impact on stable coalition structures in equilibrium. This insignificant effect can be explained from the following two aspects. First, recall that in the model with stochastic demand, suppliers do not bear any inventory risk from demand uncertainty. Thus, their profit functions in the stochastic demand case, presented in Equation (6), are essentially deterministic. Second, the demand uncertainty, ξ, is introduced into the system in a multiplicative form, i.e., random demand $X = D(p) \cdot \xi$. Randomness in demand leads to an additional decision variable, stocking factor z, compared to the case with deterministic demand. The stocking factor plays a scale role to expected demand $D(p)$ based on demand uncertainty. It is also a multiplier in the profit functions of coalitions. Because the stability factor, $U(m)$, is defined as a ratio of coalitional profits, it is intuitive to conclude that the effect of the demand uncertainty on the stability results is dampened because of the multiplicative form of the demand model.

For a linear-power or exponential demand function, the numerical results in Tables A.1 and A.2 indicate that, although demand uncertainty does not change stable outcomes qualitatively, it does appear to have some impact on them. By comparing the values of $U(m)$ in the deterministic and stochastic systems (presented in Tables 1, A.1, and A.2, respectively), one can easily verify that demand uncertainty increases $U(m)$ by a very small amount (approximately by $0-0.5$), which makes it possible for suppliers to form slightly larger groups in the stochastic system relative to the deterministic model. For example, in the case with an exponential demand function, when values of both C and q are extremely small (close to zero), with demand uncertainty, coalitions with three members are possible to emerge. However, with deterministic demand, no more than two members can stay in the same coalition in any stable coalition structure. One possible interpretation for the small increase in $U(m)$ due to demand uncertainty is as follows. In the stochastic model, a wholesale price reduction caused by alliance formation has two effects—a decrease in the retail price (and thus an increase in expected demand) and an increase in the stocking factor (see Equation A.1 in the online appendix). However, in the deterministic system, a wholesale price reduction can only reduce the retail price, leading to an increase in expected demand. Thus, demand uncertainty is likely to yield a higher benefit for suppliers (and a higher value of $U(m)$) when they sell in groups to lower their wholesale prices.

This discussion on stable coalitions is based on the multiplicative demand model. It is natural to ask whether an additive demand model, $X = D(p) + \xi$, would have a more significant impact on stable outcomes than the multiplicative case. The additive demand model is appropriate if the variance of demand is independent of the expected demand level. Our analysis suggests that an additive demand model may predict qualitatively different stability results than a multiplicative demand model. For example, with a uniform demand distribution, for an exponential or isoelastic expected demand function, the independent structure can be a stable outcome under an additive model, whereas it is never stable in a multiplicative case.

A related issue is whether the assembler's ability to influence demand would affect suppliers' incentives to form alliances. To answer this question, we compare the stable outcomes in the retail price-setting and the fixed-retail price systems. In both systems, demand is stochastic. For the system with an endogenous retail price, from the analytical and numerical results derived above, we observe that coalitions, in particular the small coalitions, are always formed when the pass-through rate of an expected demand function is sufficiently large, i.e., when the expected demand function is isoelastic or exponential. When the pass-through is relatively low, e.g., for a linear-power expected demand function with a relatively low γ, suppliers all act independently when there are more than two. The system with a fixed retail price has been studied by Granot and Yin (2008), and they show that all suppliers that adopt the Nash stability concept would act independently in a system with more than two suppliers.

The difference on the stable outcomes between the cases with fixed and endogenous retail prices suggests the following. When the pass-through rate is large enough, suppliers tend to be more willing to form alliances and coordinate their wholesale prices if the assembler has the capability of manipulating demand by adjusting its retail price. We next provide an explanation. It is known that alliances among independent suppliers would remove the horizontal externalities and reduce the total wholesale price offered to the assembler. In the fixed-price (and thus fixed-demand) case, when the wholesale price decreases because of alliances, the assembler tends to increase its order quantity. In the price-setting case, when the wholesale price decreases, the assembler is likely to increase its order quantity *and* lower its retail price, leading to higher demand and presumably an even higher order quantity, relative to the fixed-price case. Thus, as long as the decrease in the total wholesale price due to alliances in the price-setting case is not too much larger than in the fixed-price case, suppliers would have more incentives to form groups in the price-setting case. For further illustration, see an example presented in Example 1 in the appendix.

6. Model Extensions and Discussions

In this section, we extend our analysis to consider some other factors that may affect suppliers' coalition formation, assuming that demand is deterministic. In §6.1, we adopt the strong Nash stability concept, which allows for unilateral *and* coalitional deviations, to study stable outcomes. In §6.2, we consider the possibility of sequential decision making among different coalitions of suppliers, and in §6.3, we incorporate a cost effect from alliance formation in the model studied in §§3 and 4. Finally, in §6.4, we examine the robustness of our results if the assembler is removed from the previously studied assembly system.

6.1. Strong Nash Equilibrium

Recall that the stability solution concept based on the Nash equilibrium allows for only unilateral deviations by individual suppliers. It is natural to also consider multilateral deviations by groups of suppliers. One such concept is the *strong Nash equilibrium* (Aumann 1959). This concept refines the Nash equilibrium by allowing for both individual and coalitional deviations. Similar to Definition 1, the strong Nash stable set is defined to consist of coalition structures in which no individual or groups of suppliers have a strictly profitable and feasible deviation.[9] Because the strong Nash equilibrium is a refinement of the Nash equilibrium, we need to verify whether elements in the Nash stable set identified in Proposition 6 would survive coalitional deviations. Note that for $n = 2$, there is no difference between Nash and strong Nash approaches. Hence, both suppliers form a coalition in equilibrium. We next discuss the stable outcomes under each demand function when $n \geq 3$. A detailed derivation of these outcomes is given in the appendix.

For the exponential demand function, recall from Table 1 that the stability factor $U(m) = e$ and from Proposition 6 that $\mathcal{B}_{12}$ for an odd n ($\mathcal{B}_{22}$ for an even n) is uniquely Nash stable, and suppliers form coalitions of two members (or two-member coalitions), if possible, in equilibrium. Under strong Nash stability, group deviations are allowed. Thus, two two-member coalitions would have an incentive to merge together as a coalition of four, because $\Pi(m-1)/4 \geq \Pi(m)/2$. This deviation makes $\mathcal{B}_{12}$ for an odd n ($\mathcal{B}_{22}$ for an even n) unstable under the strong Nash solution concept if $n \geq 4$. Thus, we conclude that the strong Nash stable set uniquely contains coalition structure $\mathcal{B}_{12}$ for $n = 3$, and it is empty for $n \geq 4$.

For the linear-power demand function, under Nash stability, only the independent structure and $\mathcal{B}_{12}$ for an odd n ($\mathcal{B}_{22}$ for an even n) can possibly be stable. Our analysis indicates that the independent structure

[9] Note that the stability concept based on the strong Nash equilibrium applied to the coalition formation game is also called the coalition structure core (Aumann and Dreze 1975).

will not survive the coalitional deviations. Similar to the case with an exponential demand function, two two-member coalitions will always have an incentive to merge and have a four-member coalition. Thus, $\mathscr{B}_{12}$ for an odd n ($\mathscr{B}_{22}$ for an even n) is not strong Nash stable. Therefore, for a linear-power demand function, the strong Nash stable set is empty except when $n=3$, and the power of the demand function is relatively large, under which it uniquely contains $\mathscr{B}_{12}$.

For the isoelastic demand function, consistent with the case with an exponential or linear-power demand function, any structure with two or more equal-sized coalitions (including the independent structure) is not strong Nash stable. For $n \geq 4$, the grand coalition is not strong Nash stable either. For $n=3$, either $\mathscr{B}^*$ or $\mathscr{B}_{12}$ is uniquely strong Nash stable; for $n \geq 4$, $\mathscr{B}_{1,n-1}$ is strong Nash stable only if the price elasticity of the demand function is small.

6.2. Sequential Decision Making by Coalitions of Different Sizes

In this subsection, we consider the possibility that alliance formation may change the order of suppliers' decision making. More specifically, a larger coalition may be more powerful than a smaller one in the sense that it can set the coalitional wholesale price before the smaller one can. To be able to fully explore the impact of such a power shift due to coalition formation, we consider a simple case with three suppliers.[10] Hence, there are three possible coalition structures—independent structure, $\bar{\mathscr{B}}$; a structure with one independent supplier and a coalition of two suppliers, $\mathscr{B}_{12}$; and the grand coalition of all three suppliers, $\mathscr{B}^*$. We first analyze the equilibrium decisions and profits for each structure, and then we check their stability.

In an assembly system with three suppliers, the analysis of the independent structure, $\bar{\mathscr{B}}$, and the grand coalition, $\mathscr{B}^*$, under sequential decision making coincides with that under simultaneous decision making. For coalition structure $\mathscr{B}_{12}$ under sequential decision making, the game becomes three stages, where the coalition of two members sets its coalitional wholesale price first, and then the independent supplier determines its wholesale price, and finally, the assembler chooses the retail price. Without loss of generality, we name members in the coalition of two as suppliers 1 and 2. The equilibrium analysis under a given coalition structure is straightforward. We summarize the equilibrium decisions and profits in Table 2 and omit the detailed analysis. Note from this table that in a coalition structure with coalitions of different sizes, coalitions may make different profits in equilibrium, depending on the form of the demand function. Surprisingly, a supplier of a larger coalition that sets its wholesale price first may make a lower profit than a supplier of a smaller coalition, which sets its price afterward.

Proposition 8. *In an assembly system with three perfectly complementary suppliers, when coalitions of different sizes make decisions sequentially, for an exponential or isoelastic demand, $\mathscr{B}_{12}$ is uniquely stable, and for a linear-power demand, $\mathscr{B}^*$ is uniquely stable if the power of demand is sufficiently large; otherwise, both $\mathscr{B}^*$ and $\mathscr{B}_{12}$ are stable.*

Comparing this result with the stable outcomes when coalitions of suppliers make decisions simultaneously in Proposition 6, we conclude that sequential decision making due to alliance formation significantly changes the stable outcomes for a linear-power demand function, whereas it predicts the same stable outcomes for an exponential or isoelastic demand function. For example, for a linear demand function under sequential decision making, the grand coalition is always stable; with simultaneously decision making, it is never stable. Hence, our analysis suggests that for a system with three suppliers, sequential decision making improves suppliers' incentives for alliance formation, relative to simultaneous decision making. Proposition 8 also indicates that stable outcomes under sequential decision making are, again, sensitive to the form of the demand function. However, the pass-through rate concept may not be applicable to interpreting the differences. We use coalition structure $\mathscr{B}_{12}$ as an example to explain why. Under sequential decision making, the coalition with two members will set the wholesale price first, and then the independent supplier will. Hence, wholesale price change due to alliance formation of the two members will have a direct effect on the wholesale price

[10] When there are two suppliers, the issue of sequential decision making due to coalition formation is irrelevant. When the system has a large number of suppliers, a general analysis of the stable outcomes is quite complex.

Table 2 Equilibrium Decisions and Profits in a System with Three Suppliers Under Sequential Decision Making

Coalition structure	$\overline{\mathcal{B}}$	$\mathcal{B}_{12}$	$\mathcal{B}^*$
Wholesale prices	$w_i - c_i = \frac{\alpha+\beta C}{1-3\beta}$ for $i \in \{1,2,3\}$	$w_1 - c_1 = w_2 - c_2 = \frac{\alpha+\beta C}{2(1-\beta)}$, $w_3 - c_3 = \frac{\alpha+\beta C}{(1-\beta)^2}$	$w_1 - c_1 = w_2 - c_2 = w_3 - c_3 = \frac{\alpha+\beta C}{3(1-\beta)}$
Retail price	$\frac{C+4\alpha-3\alpha\beta}{(1-\beta)(1-3\beta)}$	$\frac{3\alpha-3\alpha\beta+\alpha\beta^2+C}{(1-\beta)^3}$	$\frac{2\alpha-\alpha\beta+C}{(1-\beta)^2}$
Suppliers' profits	$\Pi_i = \frac{\alpha+\beta C}{1-3\beta}D(p)$ for $i \in \{1,2,3\}$	$\Pi_1 = \Pi_2 = \frac{\alpha+\beta C}{2(1-\beta)}D(p)$, $\Pi_3 = \frac{\alpha+\beta C}{(1-\beta)^2}D(p)$	$\Pi_1 = \Pi_2 = \Pi_3 = \frac{\alpha+\beta C}{3(1-\beta)}D(p)$

change of the independent supplier, but not on the retail price change of the assembler or on the demand function. Thus, the stability factor and its property given in Proposition 5 cannot be directly applied to the sequential decision-making case.

6.3. Cost Effect Due to Alliance Formation

Alliance formation may lead to extra costs for suppliers (e.g., additional administrative costs) or it may reduce their operational costs. In this subsection, we consider the effect of these costs. Denote by $\triangle C(k)$ the total cost change due to a group formed by k suppliers. We assume that the total cost change increases in k and it is 0 when $k=1$. Assuming that members of the same coalition share $\triangle C(k)$ equally, the ending profit function of an individual supplier in a coalition with k members becomes:

$$\Pi_k^{\triangle C}(m) = \frac{\Pi(m)}{k} + \frac{\triangle C(k)}{k}. \tag{7}$$

Note that a positive $\triangle C(k)$ implies a cost-saving effect due to alliance formation, and a negative $\triangle C(k)$ means additional costs. For a general form of $\triangle C(k)$, we can characterize the necessary and sufficient conditions under which the independent suppliers would stay independent and the non-independent suppliers would not defect to be independent (see Lemma 1 and its proof in the online appendix). To make the cost effect more realistic and guarantee a positive ending final profit for each supplier, we assume that $|\triangle C(k)| \le \Pi(m)$. That is, the absolute change (either increase or decrease) in the total cost due to alliance formation will not be more than the coalitional profit. Comparing conditions in Lemma 1 with those without cost effect in Proposition 4, we conclude the following.

Proposition 9. *The introduction of a cost-saving effect (additional costs) due to alliance formation increases (reduces) suppliers' incentives to form alliances. More specifically, under cost savings (additional costs), it is less (more) likely that independent suppliers will stay independent, and it is also less (more) likely for non-independent suppliers to deviate to be independent, relative to the case without cost effect.*

This result is quite intuitive, because cost savings (additional costs) give suppliers extra (fewer) benefits in addition to reduction of horizontal externalities when they form groups.

6.4. Assembly Systems without an Assembler

In our previous analysis, we assumed that there is an independent assembler who sets the retail price and sells the final product to the end customers. It is interesting to investigate whether the existence of an assembler plays an important role in suppliers' coalition formation. To address this question, we first analyze the assembly system without an assembler and then compare it with the system with an assembler. In the system without an assembler, it is reasonable to assume that the retail price of the final product is simply the sum of the wholesale prices charged by all suppliers or all coalitions of suppliers. The effect of removing the assembler from the system is presented below.

Proposition 10. *In the assembly system without an assembler, when $D(p)$ satisfies Assumption 1:*

- *For a given $\mathcal{B} = \{B_1, \ldots, B_m\}$, for any $j \in \{1, \ldots, m\}$, $W_{B_j}^* - C_{B_j} = (1/m)(W^* - C) = (\alpha + \beta C)/(1 - \beta m)$, and the coalitional profit is $\Pi_{B_j} = \Pi(m) = ((\alpha + \beta C)/(1 - \beta m))D(W^*)$.*
- *The stability factor, $U(m)$, coincides with that given in Table 1 for the system with an assembler; thus, assembly systems with and without an assembler predict the same stable outcomes.*

This proposition indicates that double marginalization (or vertical inefficiency) due to vertical decentralization of suppliers and the assembler has no impact on suppliers' alliance formation to reduce or eliminate horizontal inefficiency. It is interesting to note that the total wholesale price does not depend on whether there is an assembler in the system, but the realized demand will be higher if there is no assembler, due to elimination of vertical inefficiency, relative to the case with an assembler.

In addition to the assembly system with an assembler acting as a follower (§3 and §4), and the system without an assembler, there might be a situation where the assembler becomes the game leader and determines his profit margin, followed by suppliers choosing their own wholesale prices. The retail price of the final product is the sum of all individual wholesale prices and the assembler's margin. In such an assembly system, our analysis (online appendix) shows that the value of the stability factor for all three demand functions analyzed in this paper also coincides with that in a system where suppliers are the game leader in Table 1. Hence, stable outcomes are not affected by the power structure of the model.

7. Conclusions and Future Research

We have examined the complementary suppliers' incentives to coordinate prices via alliance formation when selling their products to a downstream buyer who faces price-sensitive demand. Our analysis demonstrates that whether suppliers would sell in groups depends significantly on the form of the demand function. When demand is deterministic with an exponential or isoelastic demand function, suppliers are always willing to form coalitions due to a high pass-through rate. In contrast, for a linear-power demand function with a low pass-through rate, it is very likely that suppliers will conduct their businesses independently. Indeed, with a linear demand function, the independent structure is uniquely stable. In the model with stochastic demand, where the random part is multiplicative to the deterministic part, we have shown that the stable outcomes are qualitatively consistent with those in the deterministic system. Further, by comparing the stochastic systems with endogenous and fixed retail prices, we have also shown that price dependency increases suppliers' incentives to form alliances, because of multiple positive effects of the wholesale price reduction on the order quantity increase. We have also extended our analysis to incorporate several other important factors that may affect suppliers' motivation to form alliances, e.g., possibility of coalitional deviations, sequential decision making, and cost effect due to coalition formation.

Given the significant impact of the demand function form on whether alliances will be formed, it is important to discuss which demand function is suitable for what kind of product. It is known that the isoelastic demand function is appropriate for products with a constant price elasticity. In marketing, this function is used extensively to fit into data for many categories of products in retail stores, such as laundry detergent, toothpaste, fabric softener, and paper towels (see Tyagi 1999 for a review of empirical papers on this issue). Indeed, we often observe bundles/packages of complementary products in these categories. One example would be various bundled products from P&G. The exponential demand function can be generated when customers' reservation price (or valuation) of a product is exponentially distributed. The marketing and economics literature shows that reservation prices are often formulated to follow an exponential distribution. For example, in their paper studying the advance selling phenomenon in, e.g., the airline industry, Shugan and Xie (2005) adopt an exponential distribution for customers' valuation of the product. This is consistent with the observation of price coordination in the airline industry. Our analysis also suggests that in a product market with customers' valuation being approximated by a uniform distribution (which leads to a linear demand function), component suppliers of this product should not sell in groups.

In this paper, we have only considered three possible motivations for complementary suppliers to form coalitions—price coordination, operational cost reduction, and sequential decision making. As mentioned in the introduction section, there are various other reasons for such behaviors. For instance, suppliers may form coalitions to provide the downstream buyers with a one-stop shopping solution. The one-stop shopping experiences may potentially reduce the assembler's cost. Together with the cost reduction to the assembler from the decrease in the wholesale price due to alliances, these experiences would make the assembler willing to further lower its retail price, leading to higher demand, and pass more benefits to consumers. This suggests that the one-stop shopping solution would probably increase suppliers' incentives to form alliances. Similar to the cost-saving benefit, the extent to which suppliers would form alliances to create such one-stop shopping solutions would depend on how much convenience or cost reduction the coalitions would bring to the assembler. Another motivation behind coalition formation could be to increase suppliers' decision-making power. This paper has assumed that coalitions of suppliers (either independent or non-independent) have an equal power in setting their coalitional wholesale prices (i.e., these decisions are made simultaneously). In a setting where larger coalitions have the ability to set their coalitional wholesale prices before the smaller ones, i.e., wholesale prices are made sequentially based on the power of each coalition, then stable outcomes may change significantly. We have reached such a conclusion based on the analysis of a system with three components only in §6.2. A further exploration in this direction with a general number of components would be interesting.

Finally, there are other limitations in the model studied in this paper. For example, we have assumed that there is only one supply source for each component. In practice, potential suppliers of the same component may compete with each other for a supply contract. Thus, it would be worthwhile to conduct a thorough analysis of a system with imperfectly complementary suppliers in future research.

Electronic Companion

An electronic companion to this paper is available on the *Manufacturing & Service Operations Management* website (http://msom.pubs.informs.org/ecompanion.html).

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References

Aumann, R. J. 1959. Acceptable points in general n-person games. A. W. Tucker, R. D. Luce, eds. *Contributions to the Theory of Games IV*, Annals of Mathematics Study 40. Princeton University Press, Princeton, NJ, 287–324.

Aumann, R. J., J. Dreze. 1975. Cooperative games with coalition structures. *Internat. J. Game Theory* **4** 217–237.

Barham, R. 2007. Building balance: The secret by-product of bundling. Retrieved November 28, 2009, http://www.wib.org/publications_resources/article_library/2007-08/Feb07_prod_design.html.

Bernstein, F., G. DeCroix. 2004. Decentralized pricing and capacity decisions in a multitier system with modular assembly. *Management Sci.* **50**(9) 1293–1309.

Bernstein, F., G. DeCroix. 2006. Inventory policies for decentralized assembly systems. *Oper. Res.* **54**(2) 324–336.

Bresnahan, T. F., P. C. Reiss. 1985. Dealer and manufacturer margins. *RAND J. Econom.* **16**(2) 253–268.

Brueckner, J. K. 2003. International airfares in the age of alliances: The effects of codesharing and antitrust immunity. *Rev. Econom. Statist.* **85**(1) 105–118.

Brueckner, J. K., W. T. Whalen. 2000. The price effects of international airline alliances. *J. Law Econom.* **43**(2) 503–545.

Choi, T. Y., Z. Wu, L. Ellram, B. R. Koka. 2002. Supplier-supplier relationships and their implications for buyer-supplier relationship. *IEEE Trans. Engrg. Management* **49**(2) 119–130.

Cournot, A. 1929. *Researches into the Mathematical Principles of the Theory of Wealth*. Translated by Nathaniel Bacon. Macmillan, New York.

Dong, L., C. Narasimhan, K. Zhu. 2009. Product line pricing in a supply chain. *Management Sci.* **55**(10) 1704–1717.

Fang, X., K. C. So, Y. Wang. 2008. Component procurement strategies in decentralized assemble-to-order systems with leadtime-dependent product pricing. *Management Sci.* **54**(12) 1997–2011.

Feng, T., F. Zhang. 2005. The impact of modular assembly on supply chain efficiency. Working paper, University of California, Irvine.

Gerchak, Y., Y. Wang. 2004. Revenue-sharing vs. wholesale-price contracts in assembly systems with random demand. *Production Oper. Management* **13**(1) 23–33.

Goh, M., J. Yong. 2006. Impacts of code-share alliances on airline cost structure: A truncated third-order translog estimation. *Internat. J. Indust. Organ.* **24**(4) 835–866.

Granot, D., G. Sošić. 2005. Formation of alliances in Internet-based supply exchanges. *Management Sci.* **51**(1) 92–105.

Granot, D., S. Yin. 2008. Competition and cooperation in decentralized push and pull assembly systems. *Management Sci.* **54**(4) 733–747.

Hsu, V. N., C. Y. Lee, K. C. So. 2006. Optimal components stocking policy for assembly-to-order systems with leadtime-dependent component and product pricing. *Management Sci.* **52**(3) 337–351.

Jiang, L., Y. Wang. 2009a. Supplier competition in decentralized assembly systems with price-sensitive and uncertain demand. *Manufacturing Service Oper. Management* ePub ahead of print June 12, http://or.journal.informs.org/cgi/content/abstract/msom.1090.0259.v1.

Jiang, L., Y. Wang. 2009b. The effect of decision sequence on supplier competition in decentralized assembly systems. Working paper, Hong Kong Polytechnic University.

Jin, M., D. Wu. 2006. Supplier coalitions in on-line reserve auctions: Validity requirements and profit distribution scheme. *Internat. J. Production Econom.* **100** 183–194.

Lariviere, M. A., E. Porteus. 2001. Selling to the newsvendor: An analysis of price-only contracts. *Manufacturing Service Oper. Management* **3**(4) 293–305.

Lichtman, D. 2000. Property rights in emerging platform technologies. *J. Legal Stud.* **29**(2) 615–648.

Liebowitz, S. 2000a. Economist predicts Microsoft breakup would harm consumers and software developers. *Tech Law J.* (February 27).

Liebowitz, S. 2000b. Economist estimates that court ordered Microsoft breakup would cost U.S. consumers $50 billion. *Tech Law J.* (September 25).

Nagarajan, M., Y. Bassok. 2008. A bargaining framework in supply chains. *Management Sci.* **54**(8) 1482–1496.

Nagarajan, M., G. Sošić. 2007. Stable farsighted coalitions in competitive markets. *Management Sci.* **53**(1) 29–45.

Nagarajan, M., G. Sošić. 2009. Coalition stability in assembly models. *Oper. Res.* **57**(1) 131–145.

Netessine, S., F. Zhang. 2005. Positive vs. negative externalities in inventory management: Implications for supply chain design. *Manufacturing Service Oper. Management* 7(1) 58–73.

Oshkai, S., D. Wu. 2005. Supplier coalition formation in buyer-oriented market. Working paper, Lehigh University, Bethlehem, PA.

Petruzzi, N., M. Dada. 1999. Pricing and the newsvendor problem: A review with extensions. *Oper. Res.* **47**(2) 183–194.

Shapley, L. S. 1953. A value for *n*-person games. H. Kuhn, A. W. Tucker, eds. *Contributions to the Theory of Games*, Vol. 2. Princeton University Press, Princeton, NJ, 307–317.

Shugan, S. M., J. Xie. 2005. Advance-selling as a competitive marketing tool. *Internat. J. Res. Marketing* **22** 351–373.

Song, Y., S. Ray, S. Li. 2008. Structural properties of buyback contracts for price-setting newsvendors. *Manufacturing Service Oper. Management* **10**(1) 1–18.

Sošić, G. 2006. Transshipment of inventories among retailers: Myopic vs. farsighted stability. *Management Sci.* **52**(10) 1493–1508.

Spengler, J. 1950. Vertical integration and antitrust policy. *Political Econom.* **58** 347–352.

Tyagi, R. K. 1999. A characterization of retailer response to manufacturer trade deals. *J. Marketing Res.* **36**(4) 510–516.

Varian, H. R. 2001. High-technology industries and market structure. *Proc. Federal Reserve Bank of Kansas City*, 65–101.

Wang, Y. 2006. Joint pricing-production decisions in supply chains of complementary products with uncertain demand. *Oper. Res.* **54**(6) 1110–1127.

Wang, Y., Y. Gerchak. 2003. Capacity games in assembly systems under uncertain demand. *Manufacturing Service Oper. Management* **5**(3) 252–267.

Zhang, F. 2006. Competition, cooperation, and information sharing in a two-echelon assembly system. *Manufacturing Service Oper. Management* **8**(3) 273–291.