Strategic Information Management under Leakage in a Supply Chain*

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Abstract

The importance of material flow management for a profit-maximizing firm has been well-articulated in the supply chain literature. We demonstrate in our analytical model that a firm must also actively manage *information flows* within the supply chain, which translates to controlling what it knows, *as well as* what its competitors and suppliers know. In our model of horizontal competition between an informed and an uninformed firm with a common upstream supplier, material and information flows intersect through *leakage* of demand (order) information to *unintended* recipients. As a result, the informed firm's drive to control information flows within the supply chain can trigger operational losses through material flow distortion. These losses can be so severe that the firm may prefer *not* to acquire information even when it is costless to do so. Our results underscore the importance of *Strategic Information Management– actively managing the supply chain's information flows, and making trade-offs with material flows where appropriate*, in order to maximize profits.

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1 Introduction

Contemporary supply chains operate in environments characterized by escalating levels of uncertainty, due to globalization, outsourcing, shorter product life-cycles and proliferation of products and categories. The resulting supply-demand mismatch leads to lost sales, product markdowns, inventory writeoffs and customer dissatisfaction. One remedy for this crisis frequently advocated in both the academic and the trade literatures is *information sharing*, particularly among firms *within* a supply chain. An extensive academic literature models and analyzes the many benefits of information sharing (Chen, 2003), and empirical studies of industry practices support these analytical findings (Hays, 2004; Salmon and Blasberg, 1997). However, once a firm shares its valuable proprietary information with other firms, its ability to control or limit access to this information is severely compromised. Thus, a dark side of information sharing is *'information leakage',* which refers to how shared information could reach *unintended* recipients– deliberately or unintentionally. The case of Newbury Comics in the music industry illustrates this issue (Singer, 1999).

> **Information leakage in the music industry: The case of Newbury Comics.** The music industry is notorious for the 'hit-and-miss' nature of its business: It is difficult, but critically important, to identify and separate potential hot-sellers from the duds. Music retailers range from the more specialized, trendy outlets like Newbury Comics, Waterloo Records and Music Millenium to large chains such as Wal-Mart, HMV, Best Buy and Tower Records. Upstream 'record labels' (such as Sony, EMI and Warner Music) tie up with artists to produce music, and push the product either directly to the music retailers or indirectly through large wholesale intermediaries such as Handleman Co., Anderson Merchandisers and Alliance Entertainment Corporation. Many of these intermediaries also act as rackjobbers: They manage the shelf-inventories of individual stores for the larger retailers such as Wal-Mart and K-Mart.
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> Record labels see pronounced benefits in obtaining retailer information, so that breakout artists and markets can be quickly identified and promoted. SoundScan is a private company that electronically tracks and tallies every single record sold by some 85% of music retailers in the country, crunches these numbers, and then sells the data to record labels, promoters and managers. Not surprisingly then, the music labels find common cause with SoundScan. In fact, the labels virtually lure retailers into sharing information with SoundScan, by offering attractive *quid pro quo* promotional support, including price-and-position dollars, artist appearances and cooperative advertising.
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> Newbury Comics is a trendy, 20-store chain in the North-East that sells music records. The chain is one of the places to which the industry turns to see what trends are being set, which artists are breaking out, and who might be the 'next big thing'. Every Sunday, Mike Dreese (the owner of Newbury Comics) would steadfastly report the sales numbers from his 20 stores – location by location, label by label, artist by artist– to SoundScan.
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> Given the 'hit-and-miss' nature of the music business, a key competitive edge for a trendsetting retailer like Newbury Comics is knowing what will sell, and then selling these products aggressively

and exclusively within a short window of time. As Dreese of Newbury Comics discovered, among the beneficiaries of the information provided by SoundScan are intermediaries like Handleman. Handleman credits SoundScan with getting them detailed information that it uses for inventory planning and replenishment at the stores of clients like Wal-Mart. Once Newbury Comics realized to what extent its mainstream competitors such as Wal-Mart were benefitting from the precise regional data that it shared with SoundScan– information which these competitors could never compile on their own– it 'pulled the plug' and stopped sharing information with SoundScan, even though this entailed the loss of promotional and co-advertising support from the major music labels.

SoundScan contends that "retailers know what their competitors are selling [anyway] because record-labels' salespeople talk. They talk to other retail customers, and they talk to the labels about who's ordering what. For instance, if Newbury Comics has taken a box of 25 copies of Goo Goo Dolls, the salesman for Sony Music or WEA Distribution calls back the distributor and says, *'Hey I need 25 more copies of the Goo Goo Dolls... I am doing really well with these'. Don't you think the distributor calls Strawberries and Harvard Coop* [Newbury Comics's competitors]*?*" The sales representatives of the music labels may also directly leak a retailer's information to its competitors in informal conversations when they visit the retail stores and learn about each store's current best-sellers.

Whether directly or through a handpicked third-party information aggregator (SoundScan), leakage by the music labels to other retailers cost Newbury Comics the control of its painstakingly acquired and valuable demand information. Looking back, Mike Dreese of Newbury Comics says, *"We lost control of our data...I am talking about a region and its specific tastes...and letting Best Buy and Wal-Mart and people like that come in and just scoop your customer."* (*cf* Singer (1999)).

While the case of Newbury Comics starkly illustrates the dark side of information sharing, it is by no means an isolated incidence. Information leakage is pervasive across a wide variety of industries. Wal-Mart announced that it would no longer share its sales data with outside companies like Information Resources Inc. and ACNielsen, which paid Wal-Mart for the information and then sold it to other retailers (Hays, 2004). In Ward's 2007 survey of 447 automotive suppliers, more than 28% of the respondents said that their company's intellectual property had been compromised (i.e., leaked) by at least one Detroit automaker within the past five years; 16% of these respondents also said that their intellectual property had been compromised by transplant automakers (foreign OEMs operating in the U.S.) (Murphy, 2007). Lee and Whang (2000) highlight the risk of information leakage to competitors, *specifically through the supplier*, as a key deterrent to sharing information in supply chains. In a recent survey conducted by supplychainaccess.com, an astounding 64% of supply chain managers pointed to leakage of valuable information by their suppliers to competitors as one of the most significant threats to their supply chain operations (Zhang and Li, 2006). Sometimes the mere potential for information leakage can create havoc in a supply chain. Liz Claiborne wanted retailers to share their POS data for newly introduced fashion products so that demand uncertainty could be resolved faster, reducing both lost sales and inventory write-offs (Salmon and Blasberg, 1997). However, stiff resistance from retailers, who feared (intentional) leakage of their valuable demand information to competitors, scuttled this initiative.

The previous examples of leakage have the following common structure: *One firm is privy to a second firm's private information as a result of a special (vertical) relationship, and then leaks this information to a horizontally competing firm.* In this spirit, our model of a supply chain consists of two horizontally competing manufacturers sourcing from the same supplier. One manufacturer, the 'incumbent', takes the lead in introducing a new product with uncertain demand in a market. The second manufacturer, the 'entrant', follows the incumbent in the market with the same or a perfectly substitutable product. The incumbent firm has superior demand information (compared to the entrant), such as information "about a region and its specific tastes" as in the Newbury Comics example discussed above. Consequently, the incumbent's order to the supplier is likely to reflect some of that information. The supplier in turn could leak the incumbent's order information to the entrant. Knowing this, the incumbent needs to order strategically. This structure in its barest form is akin to the Newbury Comics and Liz Claiborne examples detailed above; it captures *supplier-driven* leakage, highlighted as a leading supply chain risk in multiple surveys (*cf* Lee and Whang (2000), Zhang and Li (2006)).

We analytically study the impact of information leakage on both information and material flows in the supply chain. We explicitly model firms' *incentives* to acquire, share and disseminate demand information, and their impact on order quantities and sales. A number of important questions arise, that we address in our analysis: How does the threat of leakage affect the supply chain's information flows (acquisition and sharing) and material flows (order quantities and sales)? When does the supplier leak information? Can the incumbent conceal information to prevent leakage? Does the incumbent acquire information in equilibrium? How can the supplier influence information and material flows (and ultimately, his profits) through the wholesale price?

In the following Section, we develop a framework for *Strategic Information Management,* within which these and related questions fit naturally and can be addressed.

1.1 Operational and Informational Imperatives; Strategic Information Management

We define a firm's efforts to maximize its profits by *optimizing material flows* within the supply chain as its *Operational Imperative.* Examples of the operational imperative include centralized inventory control (*cf* Zipkin, 2000), cleverly chosen vertical contracts such as quantity discounts, buy-back contracts and options (Cachon, 2003), and Cournot or Stackelberg outcomes under horizontal competition (*cf* Tirole, 1988). With a few notable exceptions (surveyed in the literature review below), the supply chain literature has focused on the operational imperative, while assuming that the supply chain's *information endowment* ('who knows what') is fixed. This conflates the profit maximization objective with material flow optimization. While reasonable in many settings, this conflation can lead to sub-optimal outcomes for firms, particularly in information-rich contexts. In such settings (as we demonstrate), firms must take into account the effect of their decisions on both their own information endowments and their competition's. Jensen and Meckling (1992) point out that economists, going back to Hayek (1945)'s seminal work, have also often assumed that the information endowment of the economy or system under analysis is exogenously fixed. They argue that "Hayek (1945) takes the distribution of knowledge in the economy as given and *never mentions the cost of transferring or producing this knowledge...like Hayek, economists have taken the distribution of knowledge as a given...*they have extensively analyzed the effects of information asymmetry [taken as given] on contracting relations." (Emphasis added). In contrast, the *endogeneity of information endowments* for individual firms is central to our model of the supply chain.

When information endowments are endogenously determined, firms need to manage them strategically. This gives rise to the firm's *Informational Imperative*– its drive to optimize *information* flows within the supply chain. Specifically, the informational imperative drives the firm to maximize its profits *by simultaneously managing not just its own information endowment, but also those of its competitors and suppliers.* Moreover, a firm's operational and informational imperatives are often in conflict, as in our model, necessitating their joint management. Since optimizing just the material flows (while ignoring their impact on information flows) leads to sub-optimal performance, we posit the need for *Strategic Information Management– actively managing the firm's informational imperative, and making appropriate tradeoffs with the operational imperative should conflicts arise, in order to maximize profits.* Hence the central leitmotif of this paper, in the context of information leakage, is the importance of strategic information management for firms: Information may be acquired, shared, inferred or even leaked, and firms' strategies collectively determine their information endowments and profits.

2 Literature Review

Anand and Mendelson (1997) were among the first to explicitly model information flows in a supply chain. In their model, order quantities, production and sales are functions of the information acquired and disseminated within the supply chain; further, both *information acquisition* and *the extent of information dissemination* (within the supply chain) are decision variables. Their setting is a monopoly firm operating in multiple horizontal markets, with a 'Center' (headquarters) and branches selling in the individual markets. They model two types of information: 'data' (e.g. POS data) which are transferrable, and 'local knowledge' (such as intuition and expertise on local market conditions) which by their very nature cannot be shared in a timely or cost-effective manner in an organizational setting. The *organizational design* (whether centralized or decentralized) determines the decision rights ('Who decides what?') within the firm, while the *IT structure* determines the informational endowment ('Who knows what?') of the decision makers. They show that a firm's IT and organizational structures are intertwined, necessitating their joint optimization. Like Anand and Mendelson (1997), we too endogenize the information endowment of the supply chain. However, in our competitive setting, material and information flows interact through leakage of order quantities, and *(dis-)incentives* for sharing information play a central role.

While Anand and Mendelson (1997) synthesize the entire gamut of information flows, other papers isolate and study specific components of these flows, such as information sharing, leakage and acquisition. These are surveyed below.

Information Sharing

The supply chain literature on information sharing typically assumes that information is shared truthfully by all parties (ignoring the role of incentives) and emphasizes operational effectiveness, such as inventory control, alleviation of the bull-whip effect, or minimizing supply-demand mismatch costs (See Chen (2003) for a recent survey.). Thus the focus has been on material flow optimization for a *given* information endowment, rather than the joint, endogenous determination of material and information flows. However, Gavirneni (2002), while assuming truthful sharing of information, demonstrates that the optimal use of information flows may necessitate modifications in the firm's operating policies to maximize profits.

Representative papers on information sharing under *horizontal competition* include Li (1985, 2002), Gal-Or (1985, 86), Shapiro (1986), Vives (1984) and Raith (1996). These papers look at the effect of the types of competition (Bertrand or Cournot), the types of products (complements or substitutes) and the nature of information ('common' demand information or 'private' cost information) on the decision to share information. The consensus is that under Cournot competition with substitute products (a setting similar to ours), firms do *not* share demand information . Three key assumptions underlie these models: $(A1)$ *Firms receive demand signals, if any, by default, i.e., information acquisition is not a decision variable*; $(A2)$ *The decision to share or not share information is made ex-ante rather than ex-post, i.e., before the demand (or cost) signal is obtained*; and $(A3)$ *The information is shared either truthfully or by using a garbling function known to all players (and, typically, enforced by an outside agency).* We relax all three assumptions in our analysis.

A partial exception to the above is Ziv (1993), who relaxes assumptions $(A2)-(A3)$ (but not $(A1)$) in the context of a private-cost-horizontal-competition model. He explicitly considers *ex post* incentives to share private cost information with horizontally competing firms. Firms lie about their true costs, but enforcing appropriate (message-dependent) costs to signaling can induce truthful revelation. Similarly, in Lin *et al* (2005)'s model of inter-firm knowledge transfer, message-dependent costs are critical for an uninformed 'receiver firm' to distinguish among 'sender firms' who differ in their levels of knowledge.

Cachon and Lariviere (2001) consider *ex post* incentives for information sharing in a *vertical* contract. Our model includes both a vertical contract and horizontal competition. Like Cachon and Lariviere (2001), our incumbent 'signals' to the upstream supplier but, because of possible leakage, the signal gets transmitted to a horizontally competing retailer as in Ziv (1993).

Information Leakage

In Li (2002), retailers are engaged in Cournot competition under uncertain demand, and they procure an identical product from a common supplier. Each retailer operates under assumptions $(A1)-(A3)$, detailed earlier, while sharing demand information with the supplier. When the supplier sets the wholesale price (which is a function of the disclosed information), those retailers who choose not to share their private information with the supplier can infer the information of those who do from the wholesale price. Li calls this *information leakage,* and shows that no information is shared in equilibrium. One possible driver of this result is that *the supplier is not strategic:* His incentives to extract and disseminate retailers' demand information are not modeled (assumption ($A4$)).

Zhang (2002) extends Li (2002)'s model to partial substitutes and complements, with both Bertrand and Cournot competition. Li and Zhang (2007) study different types of confidentiality agreements in a setting similar to Li (2002).

Other contexts in which information leakage has been studied include Dye and Sridhar (2003), and Clemons and Hitt (2001). In Dye and Sridhar (2003), a firm facing investment risk in a new project can use outside consulting help to gauge project worthiness, but this leads to information leakage that reduces the value of the project. Clemons and Hitt (2001) identify conditions that can lead to leakage (which they call *poaching*) of information assets, such as product design specifications, and suggest mitigating strategies.

Another approach to prevent leakage is data encryption where firm-sensitive data and/or their sources are concealed, but summary measures like the mean and the variance are communicated (Domingo-Ferrer *et al*, 2004; Zhang and Li, 2006; Deshpande *et al* (2005) etc.). These methods are effective when such summary measures are sufficient statistics for decision making.

Information Acquisition

Academic models that endogenize information acquisition include Grossman and Stiglitz (1980), Daughety and Reinganum (1994) and Christen (2005). Grossman and Stiglitz (1980) model the incentives for traders to acquire information under perfect competition when the clearing price conveys this information to uninformed traders. They show that there is no pure strategy equilibrium with information acquisition as the outcome. Daughety and Reinganum (1994) model Cournot competition where firms can acquire demand information at a fixed cost. In equilibrium, one firm acquires information and produces first, followed by the uninformed firm. Christen (2005) models price competition where firms can acquire information on a common uncertain cost factor. He notes that "In a Stackelberg game [as against the simultaneous-move game that he modeled], the follower can infer the private information...this adds a signaling component, which complicates the equilibrium acquisition of information. This analysis is left for future research." In this spirit, our model considers acquisition of demand information by one of the firms in a Stackelberg setting, and explicitly factors in incentives for information acquisition and revelation, leading to a multi-stage embedded signaling game.

Summary

To summarize, much of the extant supply chain literature assumes that its information endowment is exogenously fixed – neglecting the role of incentives to acquire or disseminate information within the supply chain – and focuses on material flow optimization. We endogenize the information endowment of a supply chain by jointly determining the material and information flows within it, which interact through the potential for leakage of order quantity information to the competition. We relax all four assumptions ($A1-A4$) common to this literature. Specifically, in our model, *(i)* Information acquisition is not by default; it is a decision variable. For instance, firms conduct market research such as prelaunch trials to get information on the potential market. *(ii)* The decision on whether or not to share information is made *after* demand information is received. This sequence of events leads to equilibria that are *renegotiation-proof*.[1] *(iii)* Information may be *fudged*. We explicitly model the incumbent's incentives to share information truthfully. *(iv)* The supplier is a *strategic* profit-maximizer. He seeks to influence information and material flows by selectively leaking information[2].

The rest of the paper is organized as follows. The model formulation is detailed in Section 3. Section 4 analyzes information sharing in the supply chain under asymmetric information. Section 5 endogenizes information acquisition by the incumbent (potentially leading to the information asymmetry of Section 4), and the wholesale price set by the supplier. The impact of information leakage on the incumbent's sourcing strategy (whether to pick common or exclusive suppliers) is detailed in Section 6. Section 7 concludes. All proofs and other mathematical details are provided in the Technical Appendix.

3 The Model

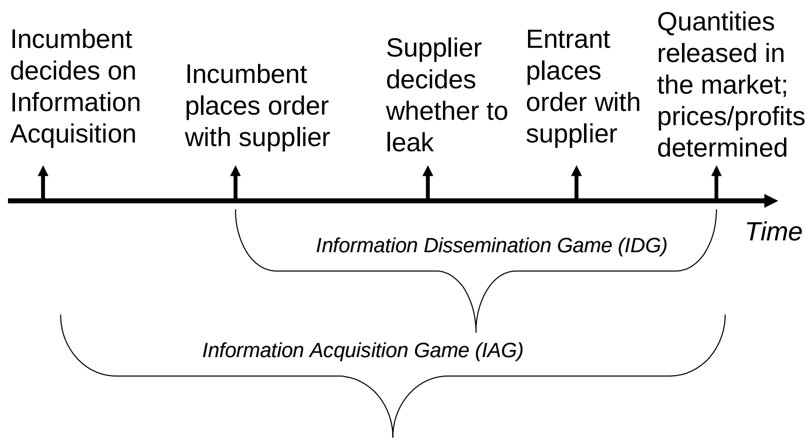

Figure 1: The Sequence of Events

Two firms– an 'incumbent' and an 'entrant'– compete in a market characterized by demand uncertainty. They source their product (or equivalently, a critical component for their product) from a common supplier. We index the three players– the *i*ncumbent, the *e*ntrant and the *s*upplier, by i, e and s respectively. The incumbent enters the market first as a Stackelberg leader followed by the entrant as

[1]Most extant academic models assume the *reverse* sequence of events, i.e., that the decision to share demand information precedes the receipt of that information (See assumption ($A2$) under 'Information Sharing' in Section 2). A serious criticism of this reverse sequence assumed in the literature is that the resulting equilibria are not renegotiation-proof (*cf* Bolton and Dewatripont 2005, pp 31-33). As Plambeck and Taylor (2007., pp 2-3) highlight, "The prospect of renegotiation undermines the credible transmission of private information [committed to *ex ante*]." Hence, a firm could decide, after observing demand, to renege on information sharing in spite of *ex ante* agreements. However, in our setting, all equilibria are renegotiation-proof.

[2]It is worth emphasizing here that much of the literature has either ignored the supplier's incentives to leak information (as in Dye and Sridhar, 2003) or considered unintentional (i.e., 'forced') leakage (Li, 2002). In our model, leakage is an endogenous decision variable.

the Stackelberg follower[3]. All firms are expected profit maximizers.

The sequence of events is as follows (see Figure 1). The incumbent firm decides whether to acquire market information to mitigate demand uncertainty. This marks the beginning of the 'Information Acquisition Game' (IAG). The incumbent then places an order with the supplier, knowing that the supplier might leak this order information to the entrant, who in turn can use this to tailor his order for the market. Thus a signaling game between the incumbent firm and the supplier/entrant is embedded within the larger model. Then the entrant places his order with the supplier. The supplier delivers the ordered quantities to the two firms, and prices and profits are realized. Since this is a dynamic (multi-stage) supply chain game under incomplete information among a supplier and two downstream competitors, we derive and analyze the Perfect Bayesian Nash Equilibria (PBNE) (*cf* Fudenberg and Tirole, 1991a.)[4] in terms of the information and material flows in this setting.

We assume that the demand curve is linear and downward-sloping, with an uncertain intercept. Specifically, the inverse demand curve is given by $P(Q) = \tilde{A} - Q$, where Q is the total quantity put in the market[5]. If the incumbent's order quantity is q_i and the entrant's order quantity is q_e, then $Q = (q_i + q_e)$. The intercept $\tilde{A}$ is random and can take one of two values: a *high* value A_H with probability p, and a *low* value A_L $(< A_H)$ with probability $(1-p)$;[6] these priors are common knowledge to all parties.[7] We assume that the wholesale price w is exogenously fixed, and without loss of generality, we normalize w to zero (We study the effect of endogenous wholesale prices in Section 5.1.). The mean demand intercept is $\mu = pA_H + (1-p)\,A_L$. Also define $\theta \equiv (A_H/A_L)$, where the parameter θ is a proxy

[3]Sequential moves arise naturally when some firms are better informed than others (*cf* Daughety and Reinganum, 1994), such as in settings plagued by information leakage (recall the case of Newbury Comics from the Introduction). Singer (1999) further argues that: "As a trendsetting retailer, you want to keep a product that you have introduced under wraps – so that customers can buy it, for a time at least, *exclusively* in your shop." The Stackelberg model is a stylized way of capturing such sequential moves.

[4]An alternate equilibrium construct used for dynamic games of incomplete information is Sequential Equilibrium (Kreps and Wilson, 1982). Fudenberg and Tirole (1991b) identify technical conditions under which a PBNE is also a Sequential Equilibrium. It is readily checked that our formulation meets these conditions.

[5]The linear demand curve has been widely used in the modeling literature (*cf* Ziv (1993), Daughety and Reinganum (1994), Anand and Mendelson (1997)). It has an appealing interpretation as the demand arising from the utility-maximizing behavior of consumers with quadratic, additively separable utility functions (Singh and Vives (1984)).

[6]The assumption of binary support for the intercept $\tilde{A}$ leads to binary incumbent 'types' in the embedded signaling game. Laffont and Martimort (2002; page 134) argue that, in many games of incomplete information, the assumption of continuous support generates very few additional insights. Moreover, since signaling games involve more sophisticated game-theoretic arguments than other games of incomplete information (*cf* Bolton and Dewatripont (2005), page 125), analyzing signaling models with non-binary support (either discrete or continuous) quickly runs into technical complexities. Milgrom and Roberts (1982), an influential work in the signaling literature, analyze a limit pricing game with both binary and continuous support and find that the insights gained are essentially the same, but with much more technical complexity in the game with continuous types. More recently, Kannan and Siebert (2007) utilize binary types in a repeated auction setting with similar justifications.

[7]The common knowledge assumption, first introduced by Lewis (1969) and later formalized by Aumann (1976), is ubiquitous in game-theoretic models, and implicit in justifications of the Nash Equilibrium and its refinements. Thus, while common knowledge assumptions are embedded in the solution methodology itself, here we invoke it explicitly.

for demand uncertainty as expressed by the coefficient of variation.[8]

The next Section analyzes the Information Dissemination Game (IDG), which assumes that the incumbent has invested in acquiring demand information and has an informational advantage. Section 6 analyzes IAG, in which information acquisition is a decision variable for the incumbent. In IAG, the subgame IDG arises when the incumbent acquires information.

4 The Information Dissemination Game

At the beginning of IDG, only the incumbent has access to demand information. This setting allows us to study the effect of (potential) information leakage on the incentives for information *revelation* and *dissemination*, i.e., the incumbent's incentives to share information with the supplier and the supplier's incentives to leak this information to the entrant.

To better understand the impact of leakage, consider the following two benchmark cases where information leakage is precluded: *(i)* The *perfect information benchmark*, where the true demand is common knowledge to all players at the beginning of the game, and *(ii)* The *exclusivity contract benchmark*, where *ex ante* measures (such as exclusive supply contracts) are put in place to prevent leakage by the supplier. In either case, the entrant's information endowment is exogenously determined, and outside the control of the incumbent. Hence the incumbent's decisions are driven purely by his operational imperative– he strives to maximize his own profits by optimizing material flows in the supply chain. Information revelation through material flows, if any, is irrelevant to the incumbent.

However, if there is information asymmetry (as in the present case, since only the incumbent knows the true demand state at the beginning of the game), the entrant's initial information endowment is simply his priors on the demand. If the supplier leaks the incumbent's order quantity, the entrant revises his *beliefs* on the true demand state based on this quantity[9]. The entrant's order quantity to the supplier, which determines his shipment to the market, is in turn a function of these posterior beliefs (his order quantity increases in the probability he ascribes to high demand). It can be shown formally that the incumbent's reaction-curve to the entrant's shipment is downward-sloping, and his profits are decreasing in the entrant's shipment quantity. *Hence, the incumbent seeks to maximize the entrant's beliefs in the probability of low demand*. Thus, leakage by the supplier sets the stage for the incumbent's *informational imperative*, where the possibility of *strategically altering the entrant's information endowment* in his own favor, to reap additional spoils, lures the incumbent to adjust his order quantity to convey demand information selectively. The entrant is of course aware of the incumbent's informational imperative, and factors this in the formulation of his posterior beliefs.[10]

[8]The standard deviation of demand, σ, can be shown to be $A_L(\theta-1)\sqrt{p(1-p)}$. Hence, the coefficient of variation of demand (σ/μ) is $\left((\theta-1)\sqrt{p(1-p)}\right)/(p\theta+(1-p))$ which is monotone increasing in θ.

[9]The incumbent's order quantity is increasing in the demand state realized. Consequently, in any reasonable belief structure, the probability that the entrant ascribes to high demand must increase (weakly) in the incumbent's order quantity.

[10]Conveying information through material flows renders the *signal* credible: The incumbent is forced to 'play out' the

The incumbent's order quantity is either a function of the demand state realized or independent of this realization (in the latter case, his order quantity is identical under both demand states).[11] These correspond to two kinds of pure strategy PBNE – *separation* and *pooling* – analyzed in Sections 5.1 and 5.2 respectively. We then integrate these results to derive a composite equilibrium in Section 5.3, which satisfies the Intuitive Criterion of Cho and Kreps (1987).

4.1 The Separating Equilibrium

In a separating equilibrium, the incumbent orders a distinct quantity in each demand state. Under leakage, the entrant's inferences about the underlying demand are a function of the incumbent's order quantity q_i. A reasonable belief structure ought to satisfy the following intuitive essentials: If q_i were 'high enough', the entrant ought to infer that the demand state is 'high'; similarly, if q_i were 'low enough', he would infer that the demand state is 'low' (see also footnote 9). The entrant's order quantity q_e increases in the probability he ascribes to high demand. If the supplier observes a high q_i, it is in his interest to leak, to encourage a high q_e and maximize his own profits. Hence, if the supplier does not leak,[12] the entrant fears the worst (i.e., low q_i implying low demand). The following proposition formalizes the entrant's belief structure, proves the existence of a separating equilibrium for all parameter values, and derives the equilibrium.

Proposition 1 *A separating PBNE exists for all θ, and is as follows:*

(i) The incumbent orders:

$$\begin{aligned} q_{iH}^* &= (A_H/2)\,, \text{ if demand is high, and} \\ q_{iL}^* &= \begin{cases} (A_L/2)\,, & \text{if demand is low and } \theta \geq 3; \\ \dfrac{2A_H - A_L - \sqrt{3A_H^2 - 4A_H A_L + A_L^2}}{2}, & \text{if demand is low and } \theta < 3. \end{cases} \end{aligned}$$

(ii) The supplier always leaks.

consequences of his informational signal through his order quantities. In contrast, any form of costless verbal signaling degenerates into non-credible 'cheap talk'. Both Ziv (1993) and Lin *et al* (2005) get around this problem in their models of firms with private information by imposing an exogenous message-dependent cost to signals, and show that a carefully chosen cost-structure can induce truthful revelation. In our model, a message-dependent cost emerges naturally (endogenously) as the cost incurred by the distortion of order quantities.

[11] Consistent with most of the literature, our analysis focuses on pure strategy equilibria wherein the incumbent's order quantities contingent on a known demand state are deterministic. Mixed strategies are particularly challenging to interpret or justify in our context. Such strategies would entail the incumbent's picking his order quantity from among multiple candidates through a random draw, even though he knows the demand state perfectly.

[12] PBNE requires that beliefs be specified for *all* possible outcomes in the strategy space even though many of these outcomes are 'off the equilibrium path', i.e., never realized in equilibrium.

(iii) The entrant orders

$$q_{eH}^{*} = (A_H/4)\,, \text{ if } Pr_e\left(\tilde{A}=A_H\right)=1, \text{ and}$$

$$q_{eL}^{*} = \begin{cases} A_L/4 & \text{if } \theta \geq 3 \text{ and } Pr_e\left(\tilde{A}=A_H\right)=0; \\ \dfrac{3A_L - 2A_H + \sqrt{(A_H - A_L)(3A_H - A_L)}}{4} & \text{if } \theta < 3 \text{ and } Pr_e\left(\tilde{A}=A_H\right)=0, \end{cases}$$

consistent with his beliefs that:

$$Pr_e\left(\tilde{A}=A_H\right) = \begin{cases} 0 \text{ if the supplier leaks } \underline{\text{and}} \ q_i \leq q_{iL}^{*}, \ OR \text{ the supplier does not leak;} \\ 1, \text{ otherwise.} \end{cases} \tag{1}$$

(iv) The profits of the incumbent and the entrant are as follows:

(a) The incumbent's earns a profit of

$$\pi_{iH} = A_H^2/8, \text{ if demand is high, and}$$

$$\pi_{iL} = \begin{cases} \left(A_L^2/8\right), & \text{if demand is low and } \theta \geq 3; \\ \frac{\left(-4A_L^2 + 12A_HA_L - 7A_H^2 + 4(A_H - A_L)\sqrt{(A_H - A_L)(3A_H - A_L)}\right)}{8}, & \text{if demand is low and } \theta < 3. \end{cases}$$

(b) The entrant earns a profit of

$$\pi_{eH} = \left(A_H^2/16\right), \text{ if } Pr_e\left(\tilde{A}=A_H\right)=1, \text{ and}$$

$$\pi_{eL} = \begin{cases} A_L^2/16 & \text{if } \theta \geq 3 \text{ and } Pr_e\left(\tilde{A}=A_H\right)=0; \\ \left(\dfrac{3A_L - 2A_H + \sqrt{(A_H - A_L)(3A_H - A_L)}}{4}\right)^2 & \text{if } \theta < 3 \text{ and } Pr_e\left(\tilde{A}=A_H\right)=0. \end{cases}$$

In order to better understand the impact of the informational imperative on the separating equilibrium, it is instructive to compare the equilibrium order quantities with those under the perfect information benchmark. In both scenarios, all parties are privy to demand information. However, under the perfect information benchmark, the informational imperative is superfluous, and the incumbent's order quantity ($\frac{A_H}{2}$ when the demand is high and $\frac{A_L}{2}$ when the demand is low) is driven purely by the operational imperative.

Now consider the separating equilibrium of Proposition 1. As noted earlier, in either demand state – high or low – the incumbent would like to convince the entrant that the demand is low, using his order quantity as an instrument. When θ is large (≥ 3), the high and low demand states are so widely separated that the penalty for the *high type* incumbent to mimic the *low type* (i.e., pretending that demand is low even though it is high) by ordering sub-optimally is prohibitively large. Hence, the informational imperative is dormant, and the order quantities, driven purely by the operational imperative, coincide with those under the perfect information benchmark: Both the high and the low types truthfully convey demand by ordering $A_H/2$ and $A_L/2$ respectively. Thus, when $\theta \geq 3$, a *natural* separation ensues whereby information is disseminated in the supply chain through undistorted material flows. However, when $\theta < 3$, if the low type incumbent were to order $A_L/2$, the high type would prefer mimicking the low type by ordering $A_L/2$ (thus signaling low demand to the entrant) to 'truthfully' ordering $A_H/2$ and revealing the high demand to the entrant. Hence, if the low type incumbent wants to send a *credible* signal of low demand to the entrant, he needs to order a quantity *sufficiently* smaller than $A_L/2$, to make it too costly for the high type to mimic him (even as deviating below $A_L/2$ is costly for the low type as well). Any quantity $q_{iL}^* \leq \left(2A_H - A_L - \sqrt{3A_H^2 - 4A_HA_L + A_L^2}\right)/2$ (which is strictly less than $A_L/2$ whenever $\theta < 3$) accomplishes this, and hence the optimal order quantity for the low type incumbent that ensures separation from the high type and is closest to $A_L/2$, is $q_{iL}^* = \left(2A_H - A_L - \sqrt{3A_H^2 - 4A_HA_L + A_L^2}\right)/2$, as stated in Proposition 1. In this scenario, the high type incumbent prefers ordering $A_H/2$ and revealing high demand truthfully to the entrant, to ordering q_{iL}^* in order to mimic the low type and mislead the entrant. Thus, demand information is still disseminated in the supply chain, but *material flows are distorted by the informational imperative* (in relation to both the perfect information benchmark and natural separation). The additional operational costs inflicted on the low type incumbent by the informational imperative are the difference in his profits, given by $\left(A_L^2 - \left(-4A_L^2 + 12A_HA_L - 7A_H^2 + 4\left(A_H - A_L\right)\sqrt{\left(A_H - A_L\right)\left(3A_H - A_L\right)}\right)\right)/8, > 0$ for $\theta < 3$. In fact, we find that both the incumbent and the supplier do worse under the separating equilibrium for $\theta < 3$ than under the perfect information benchmark, while the entrant is better off. Moreover, total supply chain profits fall due to the distortion in material flows caused by the informational imperative.

4.2 The Pooling Equilibrium

In a pooling equilibrium, the incumbent orders the same quantity from the supplier under either demand state. Hence the supplier (and by extension the entrant) cannot tease out any demand information from the order quantity. Under a pooling equilibrium, therefore, the incumbent successfully fudges his order quantity to prevent information revelation. The following proposition derives a *Pareto-dominant* pooling equilibrium.

Proposition 2 *I. When $\theta \leq \bar{\Theta}(p) = \frac{3+2p-p^2}{1+4p-p^2}$, a Pareto-dominant pooling equilibrium exists and is as follows:*

(i) The incumbent orders $q_{ip}^* = A_L - \dfrac{\mu}{2}$.

(ii) The supplier always leaks.

(iii) The entrant orders $q_{ep}^* = \dfrac{3\mu - 2A_L}{4}$,

consistent with his beliefs that:

$$Pr_e(\tilde{A} = A_H) = \begin{cases} 0, & \text{if the supplier leaks } \underline{\text{and}}\ q_i < \underline{q}_p, \text{ OR the supplier does not leak;} \\ p, & \text{if the supplier leaks } \underline{\text{and}}\ \underline{q}_p \leq q_i \leq q_{ip}^*; \\ 1, & \text{otherwise.} \end{cases} \quad (2)$$

where $\underline{q}_p = \left(A_H - \frac{\mu}{2} - \frac{1}{2}\sqrt{\left(A_H - \mu\right)\left(3A_H - \mu\right)}\right)$.

(iv) The profits of the incumbent and the entrant are summarized below:

(*a*) *The incumbent earns a profit of*

$$\pi_{ipH} = \left(A_H - \frac{\mu}{4} - \frac{A_L}{2}\right)\left(A_L - \frac{\mu}{2}\right) \text{ when demand is high, and}$$
$$\pi_{ipL} = \frac{1}{2}\left(A_L - \frac{\mu}{2}\right)^2 \text{ when demand is low.}$$

(*b*) *The entrant earns an expected profit of*

$$\pi_{ep} = \left(\frac{3\mu - 2A_L}{4}\right)^2$$

II. When $\theta > \bar{\Theta}(p)$, *there can be no pooling equilibrium.*

The results of Proposition 2 are driven by the incentives of the different incumbent types. The profits for both types of incumbent are *decreasing* in the entrant's order quantity, which is in turn increasing in the probability the entrant ascribes to high demand. Thus, the high type incumbent prefers pooling, leading to $Pr_e(\tilde{A} = A_H) = p$, to separation (in which case, $Pr_e(\tilde{A} = A_H) = 1$). By the same token, the low type incumbent prefers separation, so that $Pr_e(\tilde{A} = A_H) = 0$, to pooling.

A high θ $(> \bar{\Theta}(p))$ implies that A_H and A_L are far apart, and so it is too costly for the high type incumbent to emulate the low type's order quantity (Equivalently, it is easier for the low type incumbent to separate, by ordering a small-enough quantity.). Proposition 2 shows that under these conditions, the existence of any pooling equilibrium wherein the entrant's beliefs are 'reasonable' (in the sense of footnote 9) is precluded. Conversely, when θ is small $(\leq \bar{\Theta}(p))$, a pooling equilibrium with reasonable beliefs is possible; Proposition 2 employs the filter of Pareto-dominance in deriving a pooling equilibrium in closed-form.

On the equilibrium path, the entrant is conservative in his beliefs, and bases his order quantity on his priors for a broad range of revealed q_i. Information flow is *blocked* – only the incumbent knows the true demand state, and he successfully conceals his information from the rest of the supply chain. Thus, the information endowment of all players at the end of IDG is unchanged from that in the beginning of the game. However, the entrant interprets any deviation of q_i *outside* the range $\left[\underline{q}_p, q^*_{ip}\right]$ as a sufficiently strong demand signal that warrants overruling his own priors. Any $q_i > q^*_{ip}$ or $< \underline{q}_p$ is taken as conclusive evidence of high and low demand respectively. Since the supplier's incentives are to leak when he observes a high q_i, the entrant fears the worst (i.e., $q_i < \underline{q}_p$, implying low demand), if the supplier does not leak.

4.3 Composite Equilibrium

Our derivation of both kinds of pure strategy PBNE – pooling and separation – begs the question of which equilibrium is actually played when both are feasible (i.e., $\theta \leq \bar{\Theta}(p)$). The incumbent, as the first mover, *chooses* one of the two, based on the demand realization he observes and the profit-maximization motive. We find that the choice of equilibrium is determined by the value of θ, relative to a threshold $\bar{\bar{\Theta}}(p) = \frac{3-8\sqrt{p}+14p-8p^{3/2}+12p^2+2p^3+p^4}{1+14p^2+p^4}$. When $\theta \leq \bar{\bar{\Theta}}(p)$, the incumbent's profits under pooling dominate those under separation for both the high and low types; hence the pooling equilibrium is chosen by either type of incumbent. When $\bar{\Theta}(p) \geq \theta > \bar{\bar{\Theta}}(p)$, the incumbent's equilibrium preferences depend on his type. The low type incumbent's profits are greater under separation than under the pooling equilibrium; hence he orders q^*_{iL} (as specified in Proposition 1) in order to reveal his type. While the high type incumbent would prefer to pool with the low type at the quantity q^*_{ip}, this strategy would not work– the entrant would correctly infer high demand if the incumbent's order quantity deviates from q^*_{iL}. Thus the high type incumbent has two choices: He can order q^*_{iL} to pool with the low type, or order a different quantity and separate out. As per Proposition 1, the high type incumbent is better off ordering the profit-maximizing quantity q^*_{iH}, and consequently a separating equilibrium ensues. To summarize, the criterion of sequential rationality determines the choice of equilibrium: When $\theta \leq \bar{\bar{\Theta}}(p)$, the pooling equilibrium is observed, and when $\bar{\Theta}(p) \geq \theta > \bar{\bar{\Theta}}(p)$, the separating equilibrium is played. Of course, when $\theta > \bar{\Theta}(p)$, only the separating equilibrium is feasible. Proposition 3 provides the *composite* pure strategy PBNE consistent with sequential rationality as well as the Intuitive Criterion.

Proposition 3 *(I) There exists a pure strategy PBNE, composite of Propositions 1 and 2, which parses to the separating equilibrium of Proposition 1 when $\theta > \bar{\bar{\Theta}}(p)$ and to the pooling equilibrium of Proposition 2 otherwise. The incumbent's and the entrant's order quantities, the supplier's strategy and the entrant's beliefs in equilibrium are as specified in Propositions 1 (for $\theta > \bar{\bar{\Theta}}(p)$) and 2 (for $\theta \leq \bar{\bar{\Theta}}(p)$). The entrant's composite threshold belief structure is given by:*

(a) For $\theta > \bar{\bar{\Theta}}(p)$

$$Pr_e(\tilde{A} = A_H) = \begin{cases} 0 \text{ if the supplier leaks } \underline{\text{and}}\ q_i \leq q^*_{iL}, \text{ OR the supplier does not leak;} \\ 1, \text{ otherwise.} \end{cases} \tag{3}$$

(b) For $\theta \leq \bar{\bar{\Theta}}(p)$

$$Pr_e(\tilde{A} = A_H) = \begin{cases} 0, \text{ if the supplier leaks } \underline{\text{and}}\ q_i < \underline{q}_p, \text{ OR the supplier does not leak;} \\ p, \text{ if the supplier leaks } \underline{\text{and}}\ \underline{q}_p \leq q_i \leq q^*_{ip}; \\ 1, \text{ otherwise.} \end{cases} \tag{4}$$

(II) The composite equilibrium satisfies the Intuitive Criterion of Cho and Kreps (1987).

Proposition 3 establishes that the pooling equilibrium will be played only when $\theta \leq \bar{\bar{\Theta}}(p)$; else, the separating equilibrium is played. We can show (numerically) that the threshold $\bar{\bar{\Theta}}(p)$ is *decreasing* in p, and further, as $p \to 1$, $\bar{\bar{\Theta}}(p) \to 1$. When the priors are strong for high demand (i.e., p is large), the feasibility interval for the pooling equilibrium becomes vanishingly small. Under these conditions, the *mean* demand is close to its upper bound. Hence the entrant, basing his order quantity on the high mean demand, would release a large quantity into the market under pooling. The low type incumbent strongly prefers to prevent this and therefore favors separation by sufficiently lowering his order quantity. In contrast, when the priors are strong for low demand, (i.e., p is small), the entrant's order quantity (based on the low mean demand) would be relatively small under pooling, reducing the incentive of the low type incumbent to separate out. In fact, as $p \to 0$, $\overset{=}{\Theta}(p) \to 3$, meaning that the zone of costly separation shrinks. In either equilibrium (with the sole exception of natural or costless separation when $\theta \geq 3$), the informational imperative leads to operational losses through a distortion of material flows.

We showed formally that *the supplier, driven by his ex-post incentives, always leaks in equilibrium*– something that was often assumed in the extant literature (Dye et al. 2003, Li 2002). This fact is crucial to the analysis, for the incumbent's and the entrant's behavior would be very different, if the supplier could credibly commit not to leak. Further, there are two facets to information leakage by the supplier in relation to information flows in the supply chain. Obviously, leakage promotes information dissemination within the supply chain. But on the other hand, leakage tends to block information flows by encouraging information concealment by the incumbent.

The extant literature, both in economics (Raith 1996, etc.) and in operations management (Li 2002), has argued that demand information will not be shared between horizontally competing firms under similar conditions (quantity competition with substitutable products). In contrast, by explicitly considering incentives, we have shown that for a wide range of parameter values, demand information is both revealed to the supplier and in turn disseminated to the competition in equilibrium without any extraneous enforcement mechanism. We only require that signaling should be credible, through appropriate costs for example, and not degenerate into 'cheap talk' (see footnote 10).

5 Information Acquisition

Under IDG, the incumbent acquired demand information by default. In other settings, information acquisition is a choice variable for firms. In the Information Acquisition Game (IAG), analyzed in this Section, the incumbent first decides whether to acquire information. We assume that this decision is common knowledge (see also footnote 7). He then places an order with the supplier, and the rest of the events follow IDG (Recall Figure 1). IAG is applicable to settings where companies undertake special initiatives to acquire information, such as pre-season trials of fashion apparels. The following proposition derives the equilibrium for IAG.

Proposition 4 *There exists a pure strategy PBNE for the Information Acquisition Game, which depends on the value of* θ *relative to the threshold* $\Theta^*(p) = \frac{3-12p+p^2-8\sqrt{p}}{1-14p+p^2}$.

Case (i) $\theta < \Theta^*(p)$*: No information is acquired by the incumbent even when such information acquisition is costless. The supplier always leaks the incumbent's order quantity to the entrant. The order quantities of the incumbent and the entrant are* $q_i^* = \frac{\mu}{2}$ *and* $q_e^* = \frac{\mu}{4}$.

Case (ii) $\theta \geq \Theta^*(p)$*: The incumbent acquires information. Once information is acquired, the equilibrium of the continuation game (in terms of the incumbent's and the entrant's order quantities, the supplier's strategy and the entrant's beliefs) is given by the separating equilibrium of Proposition 3.*

In establishing Case *(ii)* of Proposition 4, we show that $\overset{=}{\Theta}(p) \leq \Theta^*(p) \leq 3, \forall\, p \in [0,1]$. Hence, when information is acquired, only the separating equilibrium of Proposition 3 is played – the incumbent's information is revealed to the supplier through his order quantities, and is in turn leaked by the supplier to the entrant. Thus, *all* parties (the incumbent, the supplier and the entrant) are privy to demand information. Of course, under Case *(i)*, none of the parties know the true demand. This leads to the following Corollary:

Corollary 1 *When information acquisition is a choice variable for the incumbent, there is no information asymmetry in equilibrium: Either all players know the true demand state (when the incumbent acquires demand information) or none do (when the incumbent avoids acquiring demand information).*

The intuition behind Proposition 4 is best understood as an outcome of the conflict between two components of the informational imperative itself. The first component, the *internal* informational imperative, strives to maximize the firm's *own* information endowment, and always favors information acquisition: An improvement in the firm's own information endowment, *ceteris paribus,* increases profits by enabling a better mapping of material flows to demand. However, such information acquisition also triggers the *external* informational imperative – the drive to control the information endowment of the firm's *environment* – which was the focus of IDG. In our setting, since order quantities carry information, the external informational imperative manifests as a distortion of material flows, leading to operational losses.

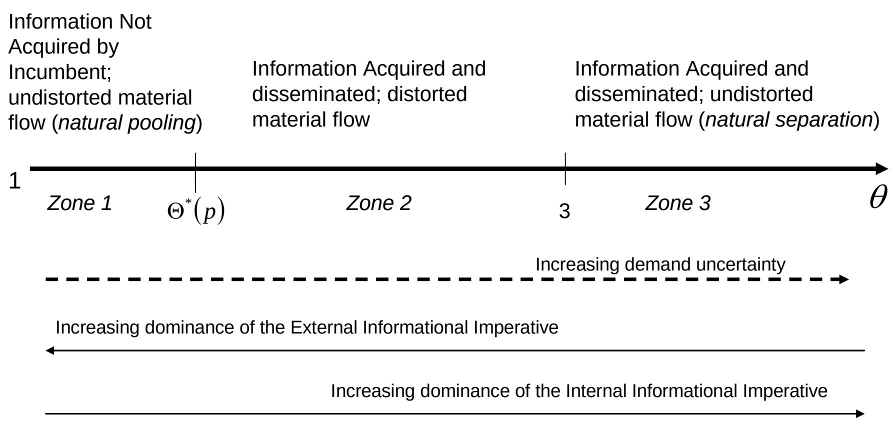

Figure 2: The equilibrium of the Information Acquisition Game.

The tradeoff between the internal and external informational imperatives, as a function of the demand uncertainty (θ), is summarized in Figure 2. For $\theta \geq \Theta^*(p)$ (high demand uncertainty), the gains accrued by the internal informational imperative dominate the operational losses inflicted by the external informational imperative, and the incumbent acquires information. The continuation game in this case (zones 2 and 3 in Figure 2 below) is the separating equilibrium of Proposition 1. For small enough θ ($\theta \leq \Theta^*(p)$), the operational costs induced by the external informational imperative are excessive, and override the direct benefits of acquiring information. In this range of θ, since information acquisition triggers these operational losses, and since the incumbent cannot credibly 'throw away' the acquired information, he prefers not to acquire information even if this is costless. Hence, all players have the same information endowment (that of priors on demand), leading to a *natural* pooling (zone 1 in Figure 2 below). Notice that in both zones 1 and 3, the material flows are undistorted, i.e., in accord with the operational imperative, contingent on the players' information endowment.

5.1 Impact of the wholesale price on information and material flows

Throughout our analysis, and consistent with much of the supply chain literature, we assumed that the wholesale price w was exogenously fixed. We had also normalized w to zero, but in fact, with θ *imputed* as $(A_H - w)/(A_L - w)$, the analysis of the previous sections is entirely applicable for *any* exogenously specified w. When the supplier controls and sets the wholesale price, he has a second instrument (other than leakage) by which to influence material and information flows, and hence to optimize his own profits. By adjusting w, the supplier can tweak the effective demand uncertainty for his customers (via the imputed θ) thereby shifting the equilibrium under IAG among the three zones of Figure 2. Since information is acquired and disseminated throughout the supply chain in Zones 2 and 3, but not acquired in Zone 1, the supplier can affect information flows using the wholesale price, and thereby also the material flows. Of course, the wholesale price also affects material flows directly, through the well-known *double marginalization* effect, and so these two effects would need to be disentangled. For a comprehensive study of the effect of double marginalization on a supply chain, see Anand *et al* 2005.

We illustrate these issues through a numerical example. A full-scale model with endogenous wholesale prices, focusing in particular on the relative impact of the informational imperative vis-à-vis double marginalization, merits a separate paper and is deferred to future research.

Example: Suppose that $A_H = 136$, $A_L = 100$ and $p = 0.15$. That is, the (inverse) demand curves $P(Q) = (136 - Q)$ and $P(Q) = (100 - Q)$ are realized with probabilities of 0.15 and 0.85 respectively. The threshold $\Theta^*(p)$ between Zones 1 and 2 is 1.74. Under the perfect information benchmark (recall Section 4), the supplier's optimal wholesale price is $w_{PI} = \left(\frac{\mu}{2}\right) = \$52.70$, and his expected profit is $\$2,083$. This benchmark is useful because it eliminates the incumbent's *informational imperative*, since the incumbent and the entrant have identical, exogenously pre-determined information endowments.

Now suppose the supplier 'naively' ignores the incumbent's informational imperative. He would then set the wholesale price that is optimal under the perfect information benchmark, i.e., $w = w_{PI} = \$52.70$. Then the imputed $\theta = 1.76 > \Theta^*(p)$; hence the supply chain operates in Zone 2, and demand information is both acquired and disseminated in the supply chain. However, the incumbent's *external* informational imperative exerts a downward pressure on material flows in the supply chain, and the supplier's expected profit is $\$1,933$, less than the $\$2,083$ he would have made under the perfect information benchmark. This suggests that the supplier may do better by tipping the supply chain to Zones 1 or 3 where, by natural pooling or natural separation, material flows are undistorted. Indeed, we find that the supplier's optimal wholesale price (taking the incumbent's informational imperative into account) is $w^* = \$50.50$, inducing $\theta = 1.73 < \Theta^*(p)$– the supply chain tips to Zone 1, and information flows are *blocked* in equilibrium. The supplier's profits move up to $\$2,079$, an increase of 7.6%, by taking the incumbent's informational imperative into account in setting his wholesale price.

This increase in supplier profits is due to changes in the supply chain's material flows, effected *indirectly* by using the wholesale price to control information flows. In addition, the wholesale price has a *direct* impact on material flows through double marginalization. We now attempt to disentangle these two effects in our example, and compare their relative impact on material flows and profits.

Informational Imperative versus Double Marginalization:

When $w = w_{PI} = \$52.70$, the supply chain operates in Zone 2, and the total expected quantity shipped by the supplier is 36.67. Under the optimal $w^* = \$50.50$, which tips the supply chain to Zone 1, the supplier's expected total shipment is 41.17 (an increase of about 12.3%). This increase is both through a reduction in double marginalization (when the wholesale price falls), and through the change in information flows. To isolate the former, we need to hold the information flow in the supply chain constant. Thus, even though the supplier announces a wholesale price of $w^* = \$50.50$ (which should block information flows by moving the supply chain to Zone 1), we will assume that information is acquired and disseminated, causing the supply chain to continue operating in Zone 2. In this case, we find that the total expected shipment is 38.20. Hence, the increase in material flow from 36.67 to 41.17, by moving from w_{PI} to w^*, can be parsed into two components: from 36.67 to 38.20 (an increase of 4.2%) *solely* due to a reduction in double marginalization, and from 38.20 to 41.17 (an additional increase of about 7.8%) due to a change in information flows induced through the incumbent's informational imperative. Thus, in moving from w_{PI} to w^*, the indirect effect of the wholesale price (through information flows) accounts for a full 65% of the change in total shipments in the supply chain, while the direct impact through double marginalization accounts for only 35%.

Profit comparisons reveal a similar story. Ignoring the impact of the wholesale price on information flows (by assuming that information is always acquired and disseminated in the supply chain), the supplier's profits *fall* slightly, from $\$1,933$ to $\$1,926$, when he moves his wholesale price from w_{PI} to w^*, on account of the change in double marginalization. However, when changes in information flows through the incumbent's informational imperative are also taken into account, the supplier's profits increase from $\$1,926$ to $2079.

Thus, in the context of this example, it is at least as important for the supplier to analyze the impact of his wholesale price on the supply chain's information flows, as it is for him to take double marginalization into account.

6 Exclusive sourcing strategies to counter leakage

Information leakage arises in our supply chain because the incumbent and the entrant have a *common* 'sourcing base' (the set of suppliers). To mitigate leakage, the incumbent could source all or part of his supply from *exclusive* suppliers, not shared with the entrant. Such exclusivity, though, comes at a premium, which we model as an increase in the unit sourcing cost. The exclusivity premium could be driven simply by the greater costs of doing business for the exclusive suppliers– for example, contractual restrictions on their seeking additional business, or the resultant lack of scale economies. In this section, we endogenize this sourcing decision for the incumbent: whether to select exclusive or common suppliers, or a mix of both.

The incumbent first decides on the mix of common and exclusive suppliers who constitute his sourcing base. Then he acquires information, and the rest of the events follow Figure 1. (If the incumbent does not acquire information, the threat of information leakage, and hence the need for exclusive sourcing strategies to counter this, is moot.) We denote the proportion of common suppliers in the incumbent's sourcing base by the parameter $\alpha \in [0, 1]$; hence, the proportion of exclusive suppliers is $(1 - \alpha)$. To capture the exclusivity premium, we model the incumbent's unit purchasing cost as $K(\alpha) = k_0 (1 - \alpha)$, where $k_0 \geq 0$ is a *scaling* parameter that reflects the *marginal cost* of additional exclusivity, and $(1 - \alpha)$ measures the *degree* of exclusivity. $K(1) \equiv 0$, i.e., the cost when the incumbent engages only common suppliers is normalized to zero. Since the entrant prefers leakage of the incumbent's information, he engages the cheapest suppliers at a sourcing cost of zero.

With the inclusion of exclusive suppliers in the incumbent's sourcing base, the common suppliers do not have a complete picture of the incumbent's demand, and hence leak an imprecise demand signal to the entrant. Specifically, contingent on the demand state ('High' or 'Low'), the entrant receives a signal s_e (through leakage) which is either 'High' or 'Low' with conditional probabilities $\Pr\left\{s_e = High/\tilde{A} = A_H\right\} = \Pr\left\{s_e = Low/\tilde{A} = A_L\right\} = (1 + \alpha)/2$. Thus the probability that the entrant receives a 'correct' signal in accordance with the true demand state is increasing in α, the proportion of common suppliers. At $\alpha = 0$, the signal is uninformative (i.e., pure noise), and at $\alpha = 1$, the signal is perfect. Upon observing a specific signal, the entrant's posterior beliefs on the demand state are derived from Bayes' Rule.[13]

6.1 Comparative statics

The incumbent's order quantities and profits are in turn a function of the entrant's posteriors, and their derivation involves tedious algebra. Moreover, as is readily observed from the mathematical details provided in the Technical Appendix, the expressions for these order quantities and profits are unwieldy and provide little insight. Hence, we study the behavior of the incumbent's expected profit ($E\pi_i$) numerically. We denote the α that maximizes $E\pi_i$ (i.e., the optimal proportion of common suppliers for the incumbent) by α^*. As we might expect, α^* increases in k_0 : Figures 3(a)-(d) illustrate this for $p = 1/2$, $A_L = 1$ and $A_H = 2$. At $k_0 = 0$, we get the corner solution $\alpha^* = 0$ (Figure 3a): With zero costs to exclusivity, the incumbent prefers a purely exclusive supplier base to prevent leakage and maximize his informational advantage. For $k_0 = 0.01$, $\alpha^* = 0.30$ (Figure 3b); for $k_0 = 0.05$, $\alpha^* = 0.82$ (Figure 3c); and finally for $k_0 \geq 0.25$, $\alpha^* = 1$ (Figure 3d). Hence, as the cost of exclusivity increases, the incumbent engages more common suppliers to save on the sourcing cost, but incurs informational losses on account of supplier leakage. Similar qualitative insights are obtained for other values of p, A_H and A_L.

[13] In an alternate model specification, we let α represent the *probability* of leakage: *if* leakage occurred, the entrant obtained perfect information. The qualitative insights obtained were very similar to those of the main model.

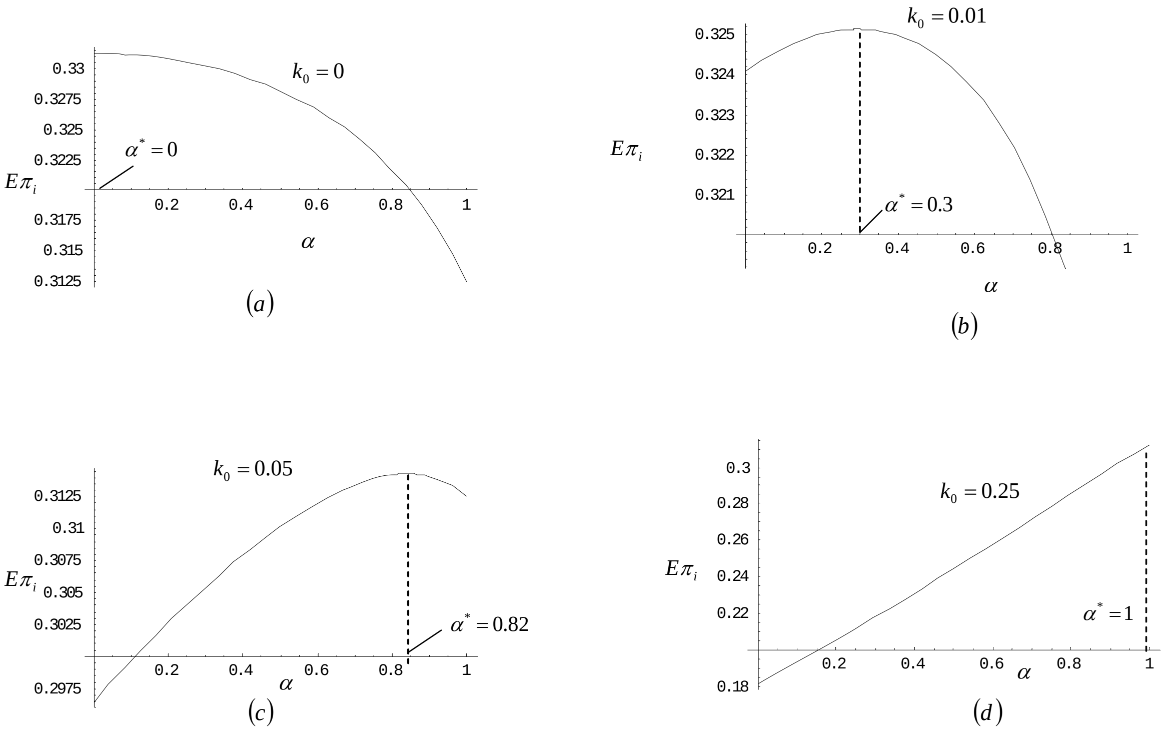

Fig. 3: Incumbent's expected profit $(E\pi_i)$ as a function of α and k_0 for $p = 0.5, \theta = 2$. α^*denotes optimal α.

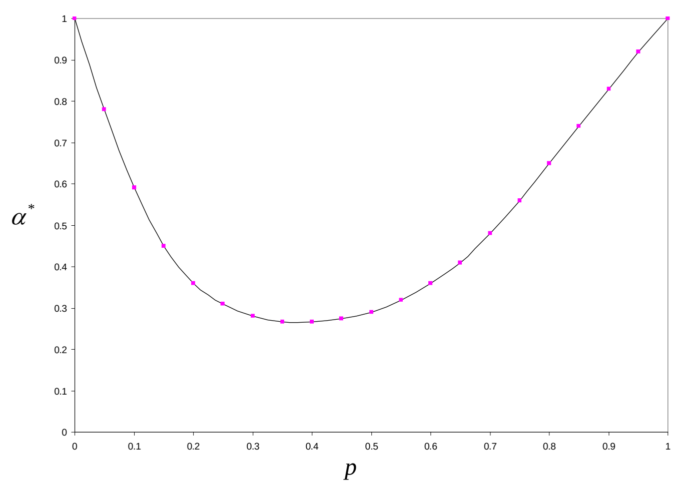

Figure 4: α^* as a function of p for $k_0 = 0.01, \theta = 2$.

Figure 4 illustrates the impact of p on α^* – the optimal proportion of common suppliers engaged by the incumbent – for $k_0 = 0.01$ (similar insights were obtained for other positive values of k_0). Here again, the tradeoff between sourcing costs and informational advantage comes into play. The entrant's uncertainty (demand variance) is maximized at $p = 1/2$, and falls as p moves away from $1/2$ (towards either 0 or 1). Since the entrant's uncertainty translates to the incumbent's informational advantage, we might expect that the curve $\alpha^*(p)$ is symmetric around, and minimized at, $p = 1/2$ (i.e., the incumbent's optimal α is lowest when the entrant's uncertainty is maximum, with the unit sourcing cost at its highest).

However, as Figure 4 shows, the curve $\alpha^*(p)$ is not perfectly symmetric around $p = 1/2$, nor is its minimum reached at $p = 1/2$. In fact, $\alpha^*(p)$ attains its minimum at $p = 0.4$, and increases more rapidly to the right of $p = 1/2$ (as p increases) than to the left (i.e., as p decreases). Mathematically, we find that $\alpha^*(1/2 + \epsilon) > \alpha^*(1/2 - \epsilon)$, for any positive $\epsilon < 1/2$; for example, $\alpha^*(0.9) \simeq 0.83$, but $\alpha^*(0.1) \simeq 0.59$ i.e., $\alpha^*(0.5 + 0.4) > \alpha^*(0.5 - 0.4)$. This can be understood as follows. The entrant's demand posterior is a weighted function of both his priors and his demand signal, where the relative weighting of each depends on the strength (precision) of the signal. Signal precision is in turn a function of the extent of leakage through the entrant's suppliers, measured by α. Two factors collude to drive the asymmetry of Figure 4: *(i)* The entrant's priors on high demand are weaker at $p = (1/2 - \epsilon)$ than at $p = (1/2 + \epsilon)$. Hence, for any signal strength α (i.e., any fixed loading on the demand signal), the entrant will ship a smaller quantity to the market at $p = (1/2 - \epsilon)$ than at $p = (1/2 + \epsilon)$. *Ceteris paribus*, smaller entrant shipments lead to greater incumbent profits. *(ii)* A smaller α (i.e., fewer common suppliers) translates for the entrant into a greater reliance on his priors. Thus, preventing leakage (meaning a lower α) is more beneficial to the incumbent at $p = (1/2 - \epsilon)$ than at $p = (1/2 + \epsilon)$. In other words, $\alpha^*(1/2 + \epsilon) > \alpha^*(1/2 - \epsilon)$, leading to the asymmetry of Figure 4.

To summarize, our analysis shows that the degree of exclusivity employed by the incumbent in his sourcing strategy trades off two key factors. The first factor is the cost premium for exclusivity: higher these costs, the lower the level of exclusivity employed by the incumbent. A second factor is the level of demand uncertainty, which drives the incumbent's informational advantage, and hence determines the value of protecting this advantage by employing an exclusive supplier base to prevent leakage.

7 Postscript

Our understanding of the notion of '*strategy*' in operations management is largely derived from an academic literature that spotlights inventory and material flow optimization (*cf* Zipkin 2000) and mechanisms to coordinate the supply chain under conflicting incentives (Cachon 2003). Incentive conflicts in managing information flows have largely been modeled in non-competitive settings, and where competition has been considered, the role of incentives has typically been restricted to *ex ante* information sharing decisions (Chen 2003). In essence, the role of the *informational imperative* – the necessity for a profit-maximizing firm to simultaneously manage not just its own information endowment, but also those of its competitors and suppliers – has been given short shrift in the literature.

Our paper is a first step towards a rigorous, modeling based, analytical understanding of *strategic information management.* This entails an active management of the firm's informational imperative, including making appropriate tradeoffs with material flow management in the event of conflicts, in order to maximize profits. Strategic information management is a *sine qua non* in particular for a firm operating in a competitive environment. In our model, demand information may be acquired, revealed, inferred and even leaked, and material and information flows intersect through leakage. Consequently, the supply chain's information endowment is not an exogenously fixed entity, but an outcome of 'strategic information management' undertaken by all firms in the supply chain.

The single-period, multi-stage setting of our model is appropriate where products with short life-cycles are sold over a concentrated season, as is the case with fashion apparels (Salmon and Blasberg, 1997), new music CDs (Singer, 1999) and many seasonal products. Previous academic research has shown that under demand uncertainty, *inventories, incentives* and *information* interact in subtle but important ways (Anand, 2008; Anand *et al* 2008). Extensions of our model along these dimensions are natural directions for future research, and underscore some of the limitations of the current model. First, it would be interesting to expand the scope of material flows to include inventories, which arise naturally in a multiperiod setting. In fact, supplier-mediated leakage of demand (order) information is one of several possible drivers of interactions between material and information flows. Other factors driving such interactions, and their repercussions for material flow management, need to be explored further. Second, when suppliers and retailers interact repeatedly (as in a multiperiod context), firms' reputations matter. Conceivably, such 'reputation effects' would partially inhibit a supplier's incentives to leak information, even if not completely preventing leakage. In the 1990s, General Motors (GM) routinely leaked its suppliers' design innovations to their competitors in order to trim its sourcing costs. In an attempt to restore its sullied reputation, GM recently reversed policy on leakage. Despite its best efforts, GM has been unable to curb leakage. GM's global Chief of Purchasing has even asked its suppliers to patent their innovations to legally preclude leakage (Murphy, 2007). Third and last, while the abstraction of information in our model enabled us to derive crisp, quantifiable results, 'information' itself varies in nature and kind. The nature of information ranges from 'hard data' that can be easily communicated in the supply chain (such as Point-of-Sales information) to nebulous, less easily communicable 'local knowledge' (Anand and Mendelson (1997)). Similarly, there are different kinds of information, ranging from demand information (modeled in our paper) to design specifications, quality and cost information. Future work could incorporate a richer, more fine-grained model of the nature and kinds of information.

References

[1] Anand, K.S. 2008. Can Information and Inventories be Complements? Wharton Working Paper Series, The Wharton School of the University of Pennsylvania, Philadelphia, PA 19104.

[2] Anand, K. S., R. Anupindi and Y. Bassok. 2008. Strategic Inventories in Vertical Contracts. *Management Science,* Forthcoming.

[3] Anand, K.S. and H. Mendelson. 1997. Information and organization for horizontal multi-market coordination *Management Science.* 43(1), 1609-1627.

[4] Aumann, R. 1976. Agreeing to Disagree. *The Annals of Statistics.* 4: 1236-1239.

[5] Bolton, P. and M. Dewatripont. 2005. Contract Theory. The MIT Press.

[6] Cachon, G. 2003. Supply chain coordination with contracts. Handbooks in Operations Research and Management Science: Supply Chain Management. Edited by Steve Graves and Ton de Kok. North Holland.

[7] Cachon, G.P and M. Lariviere. 2001. Contracting to assure supply: how to share demand forecasts in a supply chain. *Management Science*. 47(5). 629-46

[8] Chen, F. 2003. Information sharing and supply chain coordination. Handbooks in Operations Research and Management Science: Supply Chain Management. Edited by Steve Graves and Ton de Kok. North Holland.

[9] Cho, I.K. and D.M. Kreps. 1987. Signalling games and stable equilibria. *Quarterly Journal of Economics* 102: 179-221.

[10] Christen, M. 2005. Research Note-Cost uncertainty is bliss: the effect of competition on the acquisition of cost information for pricing new products. *Management Science.* Vol 51(4). 668-676

[11] Clemons, E.K and L.M. Hitt. 2001. Poaching and the misappropriation of information: an analysis of relationship risks in information-intensive production. Working paper, University of Pennsylvania.

[12] Daughety, A and J. Reinganum. 1994. Asymmetric information acquisition and behavior in role choice models: an endogenously generated signaling game. *International Economic Review*. 35(4)

[13] Deshpande, V., L.B. Schwarz, M.J. Atallah, M. Blanton, K.B. Frikken and J. Li. 2005. Secure Collaborative Planning, Forecasting and Replenishment (SCPFR). Working Paper, Purdue University.

[14] Domingo-Ferrer, J., F. Sebe, and J. Castella-Roca. 2004. On the security of noise addition for privacy in statistical databases. *Lecture Notes in Computer Science*. Vol. 3050, pp. 149-161, 2004. ISSN 0302-9743. Vol. Privacy in Statistical Databases, eds. J. Domingo-Ferrer and V. Torra, Berlin: Springer-Verlag.

[15] Dye, R. and S. Sridhar. 2003. Investment implications of information acquisition and leakage. *Management Science*. Vol 49 (6) pp. 767-783

[16] Fudenberg, D. and J. Tirole. 1991a. Game Theory. The MIT Press.

[17] Fudenberg, D. and J. Tirole. 1991b. Perfect bayesian equilibrium and sequential equilibrium. *Journal of Economic Theory* 53: 236-260.

[18] Gal-Or, E. 1985. Information sharing in oligopoly. *Econometrica.* Vol. 53(2), 329-343.

[19] Gal-Or, E. 1986. Information transmission - Cournot and Bertrand equilibria. *Review of Economic Studies,* Vol LIII, 85-92.

[20] Gavirneni, S. 2002. Information flows in capacitated supply chains with fixed ordering costs, *Management Science*, Vol 58(5), 644-651.

[21] Grossman, S.J. and J.E. Stiglitz. 1980. On the impossibility of informationally efficient markets. *American Economic Review.* Vol 70 (3), pp. 393-408.

[22] Hayek, F.A. 1945. The use of knowledge in society. *American Economic Review.* Vol 35(4), 519-530.

[23] Hays, C.L. 2004. What Wal-Mart knows about customers' habits. *New York Times,* Nov 14.

[24] Jensen, M.C and W. Meckling. 1992. Specific and general knowledge, and organizational structure. *Contract Economics.* Eds. L. Wein and H. Hijkander. Basil Blackwell, Cambridge, MA.

[25] Kannan, K.N. and R. Siebert. 2007. Effects of revelation policies under cost uncertainty. Working Paper, Purdue University.

[26] Kreps, D.M. and R. Wilson. 1982. Sequential equilibria. *Econometrica.* Vol 50(4), 863-894.

[27] Laffont, J. and D. Martimort. 2002. The theory of incentives. The principal agent model. Princeton University Press.

[28] Lee, H. and S. Whang. 2000. Information sharing in a supply chain. *International Journal of Technology Management.* Vol 20, 373-387.

[29] Lewis, D. 1969. Convention: A Philosophical Study. Cambridge: Harvard University Press.

[30] Li,L. 1985. Cournot oligopoly with information sharing. *Rand Journal of Economics.* Vol 16 (4), 521-536

[31] Li, L. 2002. Information sharing in a supply chain with horizontal competition. *Management Science*. Vol 48 (9) pp. 1196-1212

[32] Li, L and H. Zhang. 2007. Confidentiality and information sharing in supply chain coordination. Working paper, Yale School of Management.

[33] Lin, L., X. Geng and A.B. Whinston. 2005. A sender-receiver framework for knowledge transfer. *MIS Quarterly*, Vol. 29(2), 197-219.

[34] Milgrom, P. and J. Roberts. 1982. Limit pricing and entry under incomplete information: an equilibrium analysis. *Econometrica.* Vol.50(2). 443-459.

[35] Murphy, T. 2007. Protection in question. Survey: Detroit compromises intellectual property. *Wards AutoWorld*, August 2007.

[36] Plambeck, E. and T. Taylor. 2007. Implications of renegotiation for optimal contract flexibility and investment. Forthcoming, *Management Science.*

[37] Raith, M. 1996. A general model of information sharing in oligopoly. *Journal of Economic Theory.* Vol 71, 260-288.

[38] Salmon, W. and J. Blasberg. 1997. Liz Claiborne, Inc. Harvard Business School.

[39] Shapiro, C. 1986. Exchange of cost information in oligopoly. *Review of Economic Studies.* Vol. LIII, 433-446

[40] Singer, T. 1999. Sharer Beware: are you giving too much information about your business. *Inc.* March.

[41] Singh, N. and X. Vives. 1984. Price and quantity competition in a differentiated duopoly. *Rand Journal of Economics.* Vol 15 (4), 546-554.

[42] Tirole, J. 1988. The theory of industrial organization. The MIT Press.

[43] Vives, X. 1984. Duopoly information equilibrium: Cournot and Bertrand. *Journal of Economic Theory.* Vol 34, 71-94

[44] Zhang, C. and S. Li. 2006. Secure information sharing in internet-based supply chain management systems. *Journal of Computer Information Systems.* Vol 46(4).

[45] Zhang, H. 2002. Vertical information exchange in a supply chain with duopoly retailers. *Production and Operations Management.* Vol 11(4), 531-546.

[46] Zipkin, P.H. 2000. Foundation of inventory management. McGraw Hill.

[47] Ziv, A. 1993. Information sharing in oligopoly: the truth-telling problem. *RAND Journal of Economics.* Vol 24 (3), 455-465.