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Flow Coordination and Information Sharing in Supply Chains: Review, Implications, and Directions for Future Research

Funda Sahin
The University of Tennessee, MLT Department, 310 Stokely Management Center, Knoxville, TN 37996-0530, e-mail: fsahin@utk.edu

E. Powell Robinson
Texas A&M University, INFO Department, 322 Wehner Building, College Station, TX 77843-4217, e-mail: probinson@cgsb.tamu.edu

ABSTRACT

Advances in information technology, particularly in the e-business arena, are enabling firms to rethink their supply chain strategies and explore new avenues for inter-organizational cooperation. However, an incomplete understanding of the value of information sharing and physical flow coordination hinder these efforts. This research attempts to help fill these gaps by surveying prior research in the area, categorized in terms of information sharing and flow coordination. We conclude by highlighting gaps in the current body of knowledge and identifying promising areas for future research.

Subject Areas: e-Business, Inventory Management, Supply Chain Management, and Survey Research.

INTRODUCTION

A supply chain consists of suppliers/vendors, manufacturers, distributors, and retailers interconnected by transportation, information, and financial infrastructure. The supply chain's objective is to provide value to the end consumer in terms of products and services, and for each channel participant to garner a profit in doing so. In addition to the financial and information flows, there is a significant physical flow between supply chain members including raw materials, work-in-process inventories, finished products, and returned items. Managing these flows effectively and efficiently requires a systems approach to successfully identify, analyze, and coordinate the interactions among the entities. However, attaining supply chain integration is not an easy task. The often-conflicting objectives of the channel members and the continuously evolving dynamic structure of the supply chain pose many challenges for effective system integration.

A better understanding of the benefits of supply chain integration promotes organizational relationships that foster the sharing of technological and strategic efforts. Forrester (1958, 1961) introduces the theory of Industrial Dynamics, which anchors our current understanding of supply chain coordination. A key component of Forrester's management concepts rests on understanding the dynamics of how the delays, amplifications, and oscillations in the flow of demand information adversely affect supply chain operations, most noticeably inventory levels and production rates. Forrester states that management is on the verge of a major breakthrough in understanding how industrial company success depends on the interaction between the flows of information, materials, money, manpower, and capital equipment. The way these five flow systems interlock to amplify one another and to cause change form a basis for anticipating the effects of decisions, policies, organizational forms, and investment choices. Only through this understanding and the continued development of the 'tools of progress,' such as today's advances in information technologies, can new management concepts be implemented.

Forrester's concepts were largely neglected until the co-emergence of e-business and supply chain management philosophies in the early 1990s. This renewed interest was precipitated by several successful industry initiatives that exploited the advances in information technology, particularly electronic data interchange, to restructure their supply chains. An early example is Wal-Mart's Retail Link program that connects their suppliers with point-of-sales (POS) data (Stalk, Evans, & Shulman, 1992). In the grocery industry, Kurt Salmon Associates (1993) project a potential $30 billion in supply chain savings from the implementation of Efficient Consumer Response (ECR) strategies. HEB (Clark & Croson, 1994), Campbell Soup (Clark & McKenney, 1994; Cachon & Fisher, 1997), Procter & Gamble (Clark & McKenney, 1995) and Spartan Stores Inc. (Schiano & McKenney, 1996) are innovators in ECR. Quick Response (QR) in the apparel industry is occurring at J.C. Penney (Apte, Lane, Sample, & Vaughn, 1993) and numerous other retailers. Dell Computer's Direct Sell model revolutionized the computer industry (Magretta, 1998). Other national retailers such as Dillard's and J.C. Penney are exploring Vendor Managed Inventory (VMI) programs and report 20-25 percent sales increases with a 30 percent improvement in inventory turnover (Buzzell & Ortmeyer, 1995). While each of these initiatives focuses on improving supply chain performance through information sharing and physical flow coordination, they fail to provide sufficient insight into the underlying principles necessary for theory development.

There is a growing stream of literature attempting to better understand information distortion and physical flows in supply chains. However, there is no systematic framework for organizing these diverse efforts. Hence, we are left with a disjointed scattering of research activity that fails to clearly represent what we currently know and what we still need to learn. Unless we can assimilate these efforts and use them as a platform for continued research, our endeavors toward understanding the underlying principles of supply chain integration and building basic theory will be hampered.

The objective of this research is to consolidate existing research efforts concerning the value of information sharing and physical flow coordination in supply chain management, and to identify promising areas for study. In order to make any progress in such a broad topic area, we focus our attention on the interfaces between information sharing and physical flow coordination at the operational level. As such, we do not review the vast research base that addresses multi-stage inventory planning and control in isolation from information sharing. The reader is referred to Axsater (2000), Clark and Scarf (1960), Graves (1996), Collier (1982), Gao and Robinson (1994), and Silver, Pyke, and Peterson (1998) for an algorithmic treatment of multi-echelon inventory modeling. Thomas and Griffin (1996), Beamon (1998), Ganeshan, Jack, Magazine, and Stephens (1999), Erenguc, Simpson, and Vakharia (1999), and Frohlich and Westbrook (2001) provide a broader review of the supply chain management literature.

There is also a rapidly emerging literature examining supply chain coordination utilizing price and non-price competition and contracting as coordinating mechanisms. For the most part, this literature does not consider information sharing and physical flow coordination at the operational level, and consequently is outside the focus of this research. However, we briefly characterize this broader literature base so that the position of our work within the larger context is clearly understood. We begin with a definition of supply chain coordination and then provide a taxonomy for the supply chain coordination literature.

Supply Chain Coordination

A supply chain is fully coordinated when all decisions are aligned to accomplish global system objectives. Lack of coordination occurs when decision makers have incomplete information or incentives that are not compatible with system-wide objectives. Even under conditions of full information availability, the performance of the supply chain can be sub-optimal when each decision maker optimizes her individual objective function. The classic example is the "double marginalization" result of Spengler (1950) in which the retailer does not consider the supplier's profit margin when setting his order quantity, so he orders too little product for system optimization.

Two methods for accomplishing coordination are centralized decision making and decentralized decision making utilizing coordination mechanisms (see Whang, 1995; and Lee and Whang, 1999). Under the centralized decision-making approach, a single entity optimizes the network. This philosophy is taken in Clark and Scarf (1960), where optimal policies for a multi-echelon inventory problem are studied.

In lieu of a centralized decision maker, coordination mechanisms seek to align available information and incentives such that decentralized decision makers act in the best interests of the system. Lee and Whang (1999) and Chen, Federgruen, and Zheng (2001) argue that this approach is in keeping with currently accepted management practices. Often, however, decision makers have private information, which they may not share with others, resulting in sub-optimal system performance. Hence, the supply chain may resort to contracts ensuring coordination through appropriate provisions for information and incentives such that channel performance is optimized, or at least Pareto-improving solutions are achieved (Anupindi & Bassok, 1999). Coordination mechanisms include price and non-price strategies, and performance measurement schemes such as transfer pricing arrangements between sites, performance metrics, and operational constraints.

Tsay, Nahmias, and Agrawal (1999) and Cachon (1999a) provide extensive surveys of the supply chain contracting literature. Below we summarize the major research categories.

Price coordination using quantity discounts

Using price to coordinate buyers and sellers is common in the marketing literature. Jeuland and Shugan (1983), Moorthy (1987), Lal and Staelin (1984), Lee and Rosenblatt (1986), Weng (1995), Corbett and de Groote (2000), Corbett and Tang (1999), Tsay and Agrawal (2000), and Chen, Federgruen, and Zheng (2001) explore quantity discount pricing schemes under a variety of scenarios including asymmetric and symmetric information sharing among channel members. The objective is to insure that the manufacturer's pricing structure aligns the retailers' purchasing incentives to seek system optimization. Lee and Staelin (1997) explore vertical strategic interaction and implications for channel pricing strategy. Mahajan, Radas, and Vakharia (2002), on the other hand, examine the implications of this type of coordination on the supplier's distribution strategy (inclusive or selective/exclusive) and the retailers' stocking decisions in the existence of unlimited or limited capacity.

Non-price coordination

Iyer (1998) and Tsay and Agrawal (2000) examine non-price coordination mechanisms such as exclusive service territories, quantity forcing, and service differentiation.

Buy-back and returns policy

A buy-back contract that allows a retailer to return any portion of his initial order at a pre-specified price can coordinate pricing and quantity decisions for short shelf life and seasonal demand products. Pasternack (1985), Kandel (1996), and Lariviere (1999) determine optimal pricing and return policies using one-period newsvendor type models. Weng (1995) develops a two-part tariff policy to achieve similar results.

Quantity flexibility

A quantity flexibility contract defines the terms under which the quantity a buyer ultimately obtains may deviate from a previous estimate (Lariviere, 1999). Representative research in this area includes Bassok and Anupindi's (1997) analysis of a minimum-purchase quantity contract; Eppen and Iyer's (1997) study of backup agreements allowing the buyer to purchase certain quantities in excess of his initial forecast; and Tsay's (1999) consideration of a contract which couples the customer's commitment to purchase no less than a certain percentage below the forecast with the supplier's guarantee to deliver up to a certain percentage above the forecast.

Allocation rules

Competition for scarce capacity can lead retailers to distort their orders leading to supply chain inefficiencies (Lee et al., 1997a). Cachon and Lariviere (1999a, 1999b) study product allocation strategies as a coordination mechanism, while determining capacity levels is addressed in Cachon and Lariviere (1999c, 2001).

The above literature addresses supply chain coordination from a strategic and tactical perspective. The focus of this research is at the operational level on demand management and stock replenishment policies. As such, we are particularly interested in the impact of real-time information and decision-making coordination on information distortion, demand variability, forecast accuracy, inventory policy cost and investment, and related factors in a multi-echelon and multi-period planning environment.

Method of Study

This paper reviews the literature in academic journals, books, and case studies. The objective is to collect, organize, and synthesize existing knowledge relating to supply chain information sharing and physical flow coordination. The surveyed papers span several disciplines including management, marketing, management science, operations management, supply chain management, and industrial engineering. Due to the lack of precise key words defining the topic, we spent substantial time in the traditional and electronic library system sorting through the academic and business journals reviewing titles, abstracts and manuscripts. We examined each article's reference list to identify any potentially relevant research or journal title. We also contacted several researchers working in the area to identify working papers or efforts awaiting publication. In total, we collected over 100 articles and culled them into the focused set discussed in this paper. A substantial subset of the culled articles is cited above in the discussion of the coordination literature, or referenced within these articles, while others provided insufficient research contribution to warrant inclusion in this study.

A variety of potential classification schemes for structuring the literature emerged during the research. Prominent alternatives are:

- Channel structure: the breadth and depth of the supply chain.
- Channel focus: the scope of the integration effort including either upstream (supply side) or downstream (distribution side) of the manufacturer, or both.
- Research methodology: analytical models, simulation, case study, mathematical programming, and empirical analysis.
- Performance metrics: total system cost or profit, individual channel members' costs, demand variance, and capacity requirements.
- Number of products: varied from one in most studies to multiple.
- Demand pattern: typically stationary, stochastic, and identically distributed among retailers.
- Degree of information sharing: the timing and specific data shared ranged from only sharing the immediate replenishment order to sharing all POS, inventory, and cost data.
- Degree of decision-making coordination between trading partners: varied from independent decision-making by channel members to fully centralized.
- Planning horizon: infinite and short sales season planning horizons.

Information Sharing and Flow Coordination

From the above dimensions, the degree of information sharing and physical flow coordination best categorize prior research and provide a structure for guiding future efforts. Information sharing can occur at several levels. Under "no information sharing," the only demand data the supplier receives are actual orders from his immediate customer. At the "full information sharing" level, complete information is available to support the specific decision-making environment. This could include one or more of the following: production status and costs, transportation availability and quantity discounts, inventory costs, inventory levels, various capacities, demand data from all channel members, and all planned promotional strategies. Partial information sharing occurs between these two extremes.

Information sharing is often considered as a generic cure for supply chain ailments (see Forrester, 1958; Lee et al., 1997a and 1997b; Simchi-Levi, Kaminsky, and Simchi-Levi, 2000; Chen, Drezer, Ryan, and Simchi-Levi, 2000). Our experiences in administering "The Beer Distribution Game" to supply chain executives confirm this general belief, in which the most frequent suggestion for improving system performance is to provide each channel member with the final customer's POS data and the inventory levels of adjacent channel members. However, further experimentation reveals that this does not completely solve the problem when players are evaluated based on their individual performance versus system performance (a typical industry practice).

The remainder of the paper is organized into five major sections. The next three sections review the literature and classify it within the information-sharing and physical flow coordination categories. Section 2 examines research characterized by no information sharing and no physical flow coordination between channel members. This section examines supply chain dynamics including its causes, effects, and the counter measures for controlling it and also reviews efforts to quantify the impact of the bullwhip effect. Section 3 categorizes the research studying partial and full information sharing and no physical flow coordination. Section 4 studies the literature on full information sharing and full system coordination. In Section 5, we provide the conclusions and implications of the research, and suggest future research directions.

NO INFORMATION SHARING AND NO SYSTEM COORDINATION

The 1950s and 1960s were banner years for the development of single installation inventory models, where the tradeoffs among ordering and setup costs, inventory holding costs, and shortage costs were balanced to provide optimal ordering policies. Classic work includes extensions of Harris' (1913) economic order quantity model, the Wagner and Whitin (1958) dynamic, deterministic demand inventory model, and the stochastic demand (s, S) inventory model (Arrow, Harris, & Marschak, 1951; Scarf , 1960). However, as Forrester (1958), Clark and Scarf (1960) and Lee, Padmanabhan, and Whang (1997a,b) warn, optimizing each installation's inventory separately in a multi-stage system does not guarantee efficient system performance. In this section, we examine the dynamics of information and product flows in traditional supply chains, often referred to as "industrial dynamics."

The Bullwhip Effect—Causes and Effects

Forrester (1958) identifies the supply chain's natural tendency to amplify, delay, and oscillate demand information, and demonstrates its effect in a serial supply chain consisting of a retailer, distributor, warehouse, and factory. This phenomenon, known as the 'Forrester' or the 'bullwhip' effect, is apparent in the operations of traditional industry channels. In this environment, the supplier first receives an order and then makes a replenishment decision based on its quantity. The replenishment order includes sufficient quantity to restock the actual units sold, plus any adjustments to safety stock and pipeline inventory necessary to compensate for a possible shift in the demand pattern. These adjustments, which are passed to the distributor in the form of an overstated order, amplify the distributor's perception of system demand. Replication of this process at each stage of the supply chain amplifies the information distortion, causing all channel members upstream of the retailer to lose track of the actual customer demand pattern so that system-wide inventory control suffers.

Potential causes of demand amplification are seasonal retail sales variation, random fluctuations in sales, advertising and price discount policies, factory capacity limitations that encourage over-ordering in times of shortages, order cycle lead-time that delays transmittal of timely demand information, and traditional purchasing and inventory policies that over-react to perceived changes in the demand pattern. Strategies for managing the bullwhip effect are (Forrester, 1958): shorten the order cycle lead-time, share the retailers' point of sales data with all channel members, and alter inventory control procedures to provide a more gradual correction to demand changes.

The "Beer Distribution Game," a role-playing simulation game of a serial production and distribution system, captures these key concepts. Later, research provides empirical evidence of the bullwhip effect in industry through analysis of economic data (Baganha & Cohen, 1998), case studies (Houlihan, 1987; Fransoo & Wouters, 2000; Taylor, 1999), and industry observations (Lee et al., 1997a).

Sterman (1989) utilizes the Beer Distribution Game to explore decision maker behavior and its impact on demand amplification in the supply chain. His results explain the bullwhip phenomenon as a consequence of the players' systematic irrational behavior induced by misconceptions of informational feedback.

Lee et al. (1997a) provide several industrial examples of the bullwhip effect, refine its potential causes, and discuss more comprehensive strategies for counteracting its effect. Lee et al. (1997b) mathematically examine the causes of the bullwhip effect and demonstrate that rational independent decision making, increased order cycle lead-time, and synchronized (simultaneous) ordering by retailers increase demand amplification. Lee et al. (1997a,b) shift the focus toward modifying the supply chain's infrastructure and related processes, and away from the individual decision makers' behavior as suggested by Sterman (1989). Combined, the work by Forrester (1958, 1961) and Lee et al. (1997a,b) lay the foundation for understanding industrial dynamics and the impact of information distortion in the supply chain. Other researchers fill in some of the gaps by clarifying basic principles and testing the concepts in a variety of problem environments.

Baganha and Cohen (1998) propose a normative model to analyze the stabilizing effect of distribution inventories in a network of a single factory, one distribution center, and multiple retailers. While demand at each retailer is stationary, independent, and identically distributed, the network environment is characterized as nonstationary (correlated) demand due to the periodic review stock replenishment procedures used at each echelon of the network. Analytical results support earlier findings by showing that a firm's inventory policy can increase the volatility of demand moving up the supply chain. However, under certain conditions, the variance of demand faced by a manufacturer is less when filtered through a distribution center than when the retailers submit their orders directly to the manufacturer. These results are counter to those provided by Forrester (1958, 1961) and Lee et al. (1997a,b) for a single retailer environment, and are attributed to the consideration of multiple retailers with nonsynchronized ordering patterns. Furthermore, the model does not include a fixed ordering cost at the distribution center, which would increase the size and variability of the distributor's orders on the factory.

Whereas most researchers assume the demand process at the retailer is stationary, Graves (1999) considers an adaptive base-stock policy for a single-item inventory system with deterministic lead-time but subject to a stochastic nonstationary demand process. The author finds that for a single-stage and multi-stage supply chain setting, the safety stock requirements for the nonstationary demand case is much greater than for the stationary demand case. Furthermore, the relationship between safety stock and the replenishment lead-time is convex when the demand process is nonstationary, quite unlike the concave relationship for the case of stationary demand. In the multi-stage case, demand becomes more variable moving upstream, has more inertia, and cannot be mitigated by sharing information about the exogenous demand or about the ordering procedures at the downstream customer. Further analysis indicates that reducing the downstream lead-time impacts both the downstream and upstream safety stocks.

Cachon (1999b) studies demand variability in a one supplier and N identical retailer environment with stochastic, stationary demand. The retailers follow scheduled ordering policies in which they order an integer multiple of a fixed batch size Q every T periods. Assuming balanced orders, this research shows that the supplier's demand variance, and, hence, inventory policy costs are reduced when the time interval between retailer orders is lengthened and when the retailers' fixed batch size is decreased. However, these actions may have an adverse impact on retailer costs. Increasing T results in higher retailer inventory and backorder costs, while smaller fixed batch sizes lower the retailer's inventory levels and increases his ordering costs. Hence, Cachon (1999b) recommends a *flexible strategy* of increasing T and reducing the batch size Q to balance the supplier's demand variability against system costs. This research demonstrates that the supplier's demand variability by itself provides an imperfect proxy for measuring supply chain performance. Multiple metrics such as demand variance, cost, and profitability provide a clearer picture of system effectiveness. Additional results in the paper support the findings in Lee et al. (1997b) that balanced ordering by retailers provides lower supplier demand variability than synchronized ordering.

Quantifying the Bullwhip Effect

To better understand the specific causes of the bullwhip effect and the economic benefit of eliminating them, several authors attempt to quantify the inventory amplification attributed to each cause. Fransoo and Wouters (2000) study the bullwhip effect in two convenience food supply chains, defining it as the ratio of the coefficient of variation of demand generated by the facility echelon and the coefficient of variation of demand received by the same echelon. Empirical estimates of demand amplification in the food services supply chain for meals (salads) are 1.67 (2.09), 1.26 (2.73), and 1.75 (1.23) for the retail, distribution center, and production facility, respectively.

Taylor (1999) quantifies the bullwhip effect in an upstream automotive component supply chain, finding increased demand variability (standard deviation of daily order sizes) moving up the supply chain with values of 0.88, 1.63, 2.17, 3.64, 3.05, and 13.76 at OEM demand, final assembly, pressing, blanking, service center, and steel mill, respectively. The causes of the demand amplification are demand variability originating at downstream customers as a result of order batching, and replenishment lead-time variability from upstream suppliers due to equipment downtime, process throughput variability, and indivisibility in the units of supply.

Chen, Drezner, Ryan, and Simchi-Levi (2000) analytically quantify the bullwhip effect associated with demand forecasting and order cycle lead-time in a two-stage serial system. In each time period, the retailer utilizes an order-up-to inventory policy and employs a simple moving average forecast procedure. Replenishment lead-time is constant, demand is correlated across time periods, and any excess inventory at the retailer is returned to the manufacturer without cost. The results include amplification in order variability moving up the supply chain, increasing the number of periods included in the moving average forecast decreases demand variability, increasing the order cycle lead-time increases demand variability, and less demand variability is associated with a higher correlation between demand in successive time periods.

While others attempt to quantify the bullwhip effect in terms of demand variance, Metters (1997) examines the impact of forecast error and induced sales seasonality on profits in a serial supplier, manufacturer, wholesaler, and retailer network. He argues that by identifying the inefficiencies of the bullwhip effect in monetary terms, its significance is better illuminated and its causes are more likely to receive managerial attention. For a periodic, time-varying stochastic demand problem with capacitated production, this research compares the profitability of various levels of demand distortion against optimal policies as determined by dynamic programming. They report that eliminating the self-induced seasonality improves profits by 10-20%, whereas the improvement from eliminating the forecast error is 5-10%. The potential interaction between the two factors is not investigated.

Observations and Implications

The existence of the bullwhip effect in industry is well documented through case studies and economic data analysis. In addition, its major causes and the counter measures are also well-known. However, the magnitude of its impact is highly dependent upon the specific problem environment including the retailer's ordering pattern (i.e., synchronized versus balanced orders), the demand process (i.e., stationary versus nonstationary), the channel structure (serial network versus one supplier with multiple retailers), and the inventory policy applied by the channel members, among others. This highlights the need to investigate a wide variety of problem environments and inventory control systems in order to clearly understand industrial dynamics.

In addition, the bullwhip effect appears to be the result of a combination of interacting causes, not the sum of isolated factors. Thus, studying each of these factors independently may mask important interactions among the causes of the bullwhip effect and their remedies. Considering these limitations, enlarging the problem scope to include multiple products, more complex network structures, more realistic demand structures, and the interactions among the causes and remedies of the bullwhip effect appear worthwhile. This expanded problem scope would most likely require a shift from simple analytical models to simulation-based research. Additional case research quantifying the bullwhip effect is also well justified, particularly with a longitudinal focus, in which current operations and "remedied" processes are compared.

PARTIAL AND FULL INFORMATION SHARING AND NO SYSTEM COORDINATION

Electronic Data Interchange (EDI) and other advanced information technologies are making it less expensive to capture POS data, transmit it to a centralized storage and processing site, and provide real-time data to all members of the supply chain. This allows each inventory stocking point to use actual customer demand information in their forecasting systems versus the more highly variable orders from downstream channel members. This section considers the economic value of real-time information sharing and advanced order commitments. Infinite time horizon and short sales season problem environments are considered.

Infinite Time Horizon Research

Chen, Drezner, Ryan, and Simchi-Levi (2000) examine information centralization in a multistage serial supply chain employing order-up-to inventory policies at each echelon and fixed replenishment lead-times. They find that even with real-time sharing of retailer demand data, and all stages using the same forecasting and inventory control procedures, the demand variability still increases at each stage of the supply chain. Other findings reveal that the increase in variability at each stage is an additive function of the lead time and the lead time squared, while for supply chains without centralized information, the increase in variability at each stage is multiplicative.

Bourland, Powell, and Pyke (1996) study the impact of timely demand information in a single-product, make-to-stock supply chain consisting of an independent component supplier and a final assembly plant facing probabilistic demand. Both firms utilize a periodic base-stock order-up-to inventory policy with identical cycle lengths. The supplier must satisfy a maximum expected probability of stock out during an order cycle. The research examines the inventory levels of the system under a no-information-sharing and information-sharing environments. In the no-information-sharing case, the assembly plant places orders with the supplier one at a time without any advanced knowledge of its actual customer demand. Under information sharing, the assembly plant transmits its realized demand at the end of each day. When the order cycles of the supplier and the assembly plant are equal length and each channel member replenishes on the same day, information sharing has no effect on inventories. However, when the replenishment periods are not synchronized, information sharing improves the supplier's forecast accuracy. The research reports an inventory reduction ranging from 26.2% to 62.2% at the supplier and an inventory increase ranging from 0.0% to 4.2% at the assembly plant under information sharing. The counter-intuitive increase in inventory at the assembly plant is attributed to the specific inventory policies modeled in the research. Other findings are that the value of information sharing increases as the supplier's service level, the supplier's holding costs, customer demand variability, and the offset time between supplier and final assembly replenishments increase, and as the length of the order cycle decreases. This paper is one of the first ones to isolate each partner's potential benefit from information sharing.

Gilbert and Ballou (1999) examine the operations of a steel distributor in a multiple customer make-to-order environment to capture the benefits of advanced customer order commitments (information sharing) and develop pricing strategy guidelines for encouraging advanced orders. Advanced orders benefit the distributor by reducing raw material inventory and overtime production costs. The authors study the impact of advanced order commitment on raw material inventory costs using a continuous review (s, S) inventory policy that considers ordering, shortage, and inventory holding costs. A queuing model is applied to examine the impact of advanced orders on overtime production costs. The findings indicate that the higher the fraction of demand that is committed and the earlier the time commitment, the greater the potential cost reduction is for the distributor. However, advanced order commitments longer than the replenishment lead-time offer no economic advantages. Viewing this research from a contracting perspective suggests that the distributor can optimize his profits by using a price discount contract to encourage the customer to submit advanced order commitments. As such, it complements the pricing literature on quantity discount contracts discussed earlier. However, the research falls short of coordinating the supply chain because the customer's cost associated with a loss of ordering flexibility due to advanced order commitments is not considered. In addition, joint consideration of the distributor's upstream supplier would shed light on the multi-echleon impact of advance order commitments.

Hariharan and Zipkin (1995) consider supplier-customer relationships in a make-to-stock environment in which customers provide advanced warning of their demands. The authors define two lead-times: demand lead-time and supply lead-time. Demand lead-time is the time duration from when the customer places an order until the specified delivery due date. Supply lead-time is the supplier's replenishment lead-time from his vendor. The authors develop single-stage and multiple-stage base-stock and (s, S) inventory policies that incorporate both demand and supply lead-time dimensions under a variety of constant and stochastic lead-time assumptions. Basic results indicate that demand lead-times have an identical impact on system performance as a reduction in supply lead-time.

Gavirneni, Kapuscinski, and Tayur (1999) apply infinitesimal perturbation analysis to study the value of information sharing in a two-echelon supply chain with a single retailer and a capacitated supplier. The research examines three levels of information sharing—no sharing, partial sharing, and full sharing. In the no sharing environment, the supplier receives orders, one at a time, from the retailer and no other demand information. Under partial information sharing, the supplier knows the (*s, S*) inventory policy used by the retailer as well as the end-item demand distribution. In the full information scenario, the supplier knows the inventory position of the retailer and receives daily demand data. Replenishment decisions are not coordinated in any of the scenarios, and the retailer is assumed to follow an order-up-to (*s, S*) policy. The supplier uses a modified order-up-to policy to reflect capacity constraints. The authors explore the relationships among information sharing, total cost, capacity, ratio of shortage penalty to holding cost, and demand distribution. Savings range from 10% to 90% with an average of 50% when moving from a no-information-sharing to a partial-information-sharing environment. The savings are inversely related to capacity utilization. At high capacity utilization levels, the supplier obtains almost no benefit from information sharing since he must produce at full capacity each time period. When capacity is not binding, the supplier's cost savings range from 1% to 35%, moving from partial to full information.

The findings are limited to serial systems because prior work in single supplier and multiple retailer problems indicate that balanced ordering among retailers mitigates the bullwhip effect when compared to synchronous ordering patterns (Cachon, 1999b). Considering that two-stage serial environment is analogous to a multiple retailer synchronous (balanced) ordering environment, the impact of information sharing in these two environments is expected to be quite different. Further investigation of the multiple product case deserves attention.

Lee, So, and Tang (2000) quantify the value of information sharing in a single-product, two-stage serial supply chain assuming demand processes are autocorrelated over time. Both stocking points use a periodic review system, in which inventory levels are reviewed and replenished every period. In the event the supplier stocks out, he is charged with expediting costs from an alternate source to meet the retailer's demand. The authors develop order-up-to levels for each supply chain member and approximations for average inventory levels. As expected, for the case of independently distributed demand, information sharing does not yield any benefit to the system because there is no difference between the retailer's demand and the order placed with the supplier. However, information sharing reduces the supplier's cost and inventory when the demand correlation over time is high, the demand variance within each time period is high, or lead times are long. Other results indicate that the supplier's inventory and costs increase exponentially with an increase in the correlation coefficient, and linearly with an increase in the standard deviation of demand. The authors provide limited results for the multi-retailer case. Suggested extensions include in-depth analysis of the multiple retailer case, comparing an information-sharing environment with a vendor-managed inventory environment, and developing cost-sharing strategies that encourage information sharing.

Short Sales Season Environment

Two studies examine Quick Response (QR) strategies for short sales season environments in the apparel industry (see Hammond, 1990, for a detailed description of QR). While traditional newsvendor problems encompass only a single replenishment opportunity at the start of the sales season, QR hinges on shortening the manufacturer's replenishment lead-time, which allows the retailer to start the seasonal sales cycle with a small initial inventory allocation, observe early demand, generate a posterior demand distribution, and choose an optimal replenishment quantity to maximize expected profits given the posterior distribution. The manufacturer receives the early sales data and utilizes it to increase forecast accuracy and fine tune his production schedules. QR implementation at Sport Obermeyer is discussed in Fisher, Hammond, Obermeyer, and Raman (1994).

Iyer and Bergen (1997) compare traditional approaches and a variation of QR in a single product manufacturer-retailer environment with unlimited manufacturing capacity. Each channel participant operates independently, seeking to maximize their own self-interest. In the traditional system, the retailer places orders at time 0, which are delivered at the beginning of the sales season, L time units later. In the QR system, at time 0, the retailer starts collecting sales data on related products (e.g., color, fabric, style, etc.,) until time L_1 ($< L$) and uses this information to decrease the forecast error for the item to be ordered. An order is then placed with the manufacturer for delivery $L_2 = L - L_1$ units of time later at the beginning of the sales season. For each approach, the authors develop newsvendor type inventory models and examine the anticipated benefits to the retailer and supplier. QR enables the retailer to decrease leftover inventory and yet increase the customer fill rate, but the manufacturer does not always benefit from the QR strategy. However, under relatively low customer service levels, consignment inventory, high markdown allowances, wholesale price commitments, and volume commitments, QR can provide a Pareto-improving solution whereby both the retailer and the manufacturer benefit.

Fisher and Raman (1996) analyze QR at a fashion skiwear manufacturer. Traditionally, the firm incurs high stock out and inventory obsolescence costs due to long lead-times and a concentrated selling season. The authors provide a two-period replenishment procedure in which a manufacturer supplies an initial inventory for each product, observes demand, and then produces a second amount of each product based on improved forecasts. The production planning decisions are formulated as two-stage stochastic programming problems and solved using relaxation methods. Multiple products, production capacity constraints, and minimum production quantities of each item are included in the model. The authors implement the procedures at Sport Obermeyer reducing stock out and markdown costs by 1.82% of sales.

Observations and Implications

The major focus of the infinite horizon category is on the value of information sharing through either real-time sharing of customer demand data or by customers providing advanced order information. In each situation, information sharing mitigates demand uncertainty, but does not totally eliminate it. More comprehensive treatment of capacity issues deserves attention.

Specific results from Lee et al. (2000) indicate that when the demand process is more complex than the *i.i.d.* case, information sharing is of greater value. Analysis assuming stationary demand may therefore be insufficient to capture the benefits in high-tech, grocery, or other industries, where autocorrelated demand is prevalent. These findings highlight the general limitations of current research and provide guidelines for the future. The most far reaching is the potential danger of building simplified mathematical models for the purpose of obtaining closed form analytical results, and then assuming they are broadly applicable. The disparate research findings indicate that it is necessary to expand research scope to consider a wider variety of problem environments with more comprehensive models.

The research also demonstrates that system improvements may impact each channel member differently. Hence, it is important to evaluate the impact of information sharing both at the system level and at the individual channel member, and look for Pareto-improving solutions or a mechanism for allocating system benefits equitably among channel members.

FULL INFORMATION SHARING AND SYSTEM COORDINATION

Frohlich and Westbrook (2001) empirically investigate the relationship between the degree of supply chain integration and operational performance. Utilizing data on 322 firms drawn from the 1998 round of the International Manufacturing Strategy Survey (IMSS), the authors define five degrees of integration ranging from an "inward-facing internal" focus to an "outward-facing supply chain" focus. Eight different integration activities are measured including access to planning systems, sharing production plans, joint EDI access/networks, knowledge of inventory mix/levels, packaging customization, delivery frequencies, common equipment/containers, and common use of third-party logistics. Performance metrics include competitive advantage in the marketplace, productivity improvements, and non-productivity benefits such as quality improvements. The research findings suggest that an outward-facing supply chain focus is associated with higher performance than strategies biased toward either suppliers or customers. However, the general nature of the research does not allow for the impact of information sharing and coordination to be isolated, thus calling for additional research examining specific supply chain interactions.

Anand and Mendelson (1997) study the impact of coordination structures on firm performance, where a coordination structure is composed of two components—decision authority and information structure. While this particular research project does not directly address physical flow coordination, we include it in the survey due to its rich conceptual underpinnings, which link information sharing and coordination. Decision authority is classified as either decentralized or centralized decision-making. Information structure consists of two components—knowledge that cannot be transferred among market areas and data that can be transferred. The research considers four coordination structures: (1) centralized, the center makes all the decisions using all the data but none of the local knowledge; (2) decentralized, each market makes its own decisions using its local knowledge and data; (3) fully distributed, all data are shared and hence each branch makes its decisions based on both its own local knowledge and all system data; and (4) no information, only local knowledge is used in a decentralized decision environment.

The authors model a central manufacturer that produces a single product, where the total production cost is an increasing and a quadratic (convex) function. There are multiple retailers operating under a profit maximizing objective function, each facing an independent and uncertain market demand function. Without knowing total system demand, the retailers do not know the marginal product cost prior to order placement. Hence, there is economic incentive to centralize the production and product allocations for the system. However, a centralized decision maker does not have local knowledge, which lowers the accuracy of his plan. The fully distributed coordination structure does better than both the decentralized system, where branches cannot share their data, and the centralized system, which fails to exploit local knowledge. In a variety of cases, the performance of the decentralized system dominates that of the centralized coordination structure in spite of the latter's superior coordination. In the situation, where local knowledge is of little value, the centralized system does better for a small number of markets.

Chen (1998) studies the value of centralized demand information in a serial inventory system of N stages with random customer demand at the last stage. Each stage controls its inventory position using a reorder point/order quantity policy (R, nQ). Two models of the inventory system are compared. One is based on echelon stocks, which requires centralized demand and inventory information, while the other is based on installation stocks, requiring only local demand and inventory data. An extensive study reveals that the centralized information system's costs are on average 1.75% lower than the decentralized information system, with a maximum 9% savings. As expected, the relative value of centralized demand information grows larger with an increase in the number of facility stages, lead-time length, and order batch sizes. A counter-intuitive result is that the value of information is lower in more highly variable demand environments. This paper provides the first extensive numerical evidence on the value of information sharing and physical flow coordination in multi-stage supply chains. Its limitations relate to the single item assumption, no consideration of transportation fixed charges, and the assumption that both the echelon-stock policy and the installation-stock policy use the same base quantities, Q.

Cachon and Fisher (2000) compare the value of sharing real-time demand information with two other information-technology-related sources of supply chain improvement: reducing order cycle lead times through electronic transaction processing and reducing shipment batch sizes as a result of lower transaction processing costs. They study a single supplier and N identical retailer environment with stochastic stationary demand under both a no-information-sharing scenario and an information-sharing scenario, where the supplier has real-time access to the retailers' demand and inventory status. The retailers and the supplier use an (R, nQ) reorder point system in the no-information-sharing setting. Under full information sharing, retailers use reorder point policies, while the supplier monitors echelon inventory levels at each retailer and utilizes this information in determining the replenishment batch size and inventory allocation across retailers. Experimental results reveal that full information sharing provides an average 2.2% system cost reduction, with a maximum of 12.1% savings. The authors also develop a lower bound for supply chain costs over all feasible inventory policies for the full-information-sharing case. The gap between the no-information-sharing policy cost and the lower bound is an upper bound on the value of information sharing. Its value for the test problems is 3.4% on average, with a maximum of 13.8% improvement.

Further analysis suggests that operational improvements associated with electronic order processing may exceed those associated with real-time information sharing. Cutting the batch size in half yields a 22% cost reduction, while reducing order cycle lead time from 5 to 3 time periods provides a 21% savings. These levels of operational improvement mirror those reported in industry (see Cachon and Fisher, 1997; and Kurt Salmon Associates, 1993). The authors conclude that while information sharing reduces costs, simply flowing goods through the supply chain quicker and in smaller batches produces an order of magnitude greater savings.

VMI Research

Waller, Johnson, and Davis (1999) study the potential benefits of VMI (also known as continuous replenishment and supplier managed inventory) in a retail supply chain. Under VMI, the supplier monitors the retailer's inventory levels and makes periodic replenishment decisions involving order quantities, delivery mode, and the timing of replenishments. The supplier's main advantage from implementing VMI is the mitigation of demand uncertainty, thereby allowing a specified service level to be maintained at minimal inventory and production cost. VMI benefits the customer by providing a better balance between the conflicting performance measures of inventory holding cost and customer service.

The authors utilize simulation to study VMI systems under various supply chain structures with different levels of demand variability, manufacturing capacity, and channel adoption rates to identify the key performance drivers. More frequent inventory reviews and deliveries are the main sources of inventory reduction. However, the results on demand variability are inconclusive, with low and high demand volatility offering almost equal savings. The authors report the greatest benefits from wide channel adoption of VMI, whereas the benefits are significant for manufacturers even at low rates of adoption.

Fry, Kapuscinski, and Olsen (2001) compare the performance of traditional retailer-managed inventory (RMI) systems and vendor-managed inventory (VMI) systems under full information sharing. In the RMI environment, the retailer uses a periodic review order-up-to policy minimizing his inventory holding and backorder costs. The vendor receives full information concerning the customer's demand distribution and current orders, and applies a periodic review order-up-to policy to minimize his inventory holding and outsourcing costs. In the VMI environment, the supplier makes replenishment decisions under a (z, Z) contract in which the retailer sets a minimum inventory level, z, and a maximum inventory level, Z. The supplier minimizes his inventory and outsourcing costs, and the penalty amount b^- (b^+) paid to the retailer for every unit of the retailer's inventory that is less than z (more than Z) after customer demand. This relationship is best characterized as independent decision making since each party sets their own policy parameters.

However, establishing the optimal values of the contract parameters (b^-, b^+, z, and Z) would coordinate the supply chain permitting it to achieve the optimal system performance level.

Numerical results indicate that a (z, Z)-type VMI contract can perform better or worse than RMI depending on the scenario and the chosen contract parameters. However, the authors provide intuitive guidelines for determining 'good' parameter values. Experimental results indicate a 10% to 15% savings when moving from RMI to VMI and that savings increase with higher levels of demand variance. Since both the RMI and VMI systems receive real-time demand data, the savings represents a lower bound on the value of coordination. The value of information sharing in this VMI environment is not explored. It is worth noting that in situations where VMI performs poorly, the supplier bears the brunt of the additional costs. This reinforces the need to isolate the potential benefits and risks among channel members and take these into consideration during system design.

Aviv and Federgruen (1998) analyze the benefits of information sharing and vendor-managed inventory (VMI) programs in a single product, single supplier, and N retailer environment. Demand is stochastic and independent across retailers who face a fixed replenishment cost. Retailers use an (m, S) policy, observing their inventory positions once every m periods and increasing it to S. Supplier orders are not charged a fixed cost, but are capacitated presenting a stock allocation problem across retailers when inventory is insufficient to meet all replenishment requests. Three different coordination structures are studied: (1) traditional systems, where no sales or inventory policy information is shared between retailers and the supplier, (2) information sharing without coordination, where the retailers instantaneously share their demand data with the supplier and each firm makes his own replenishment decisions, and (3), VMI, where the supplier receives all demand and inventory data and is the centralized decision maker for the system.

The analysis considers four experimental factors: replenishment lead-time, smooth versus peak retailer loading on the supplier, supplier capacity, and the ratio of shortage penalty cost to inventory holding cost. General results indicate that information sharing without system coordination, when compared to traditional systems, yields an average improvement of 2%, ranging from 0 to 5%. The improvement is sensitive to the ratio of backorder to inventory holding costs. For high backorder/holding ratios, the relative benefits increase with lower capacity utilization (supporting results in Gavirneni et al., 1999), greater numbers of retailers, and higher retailer replenishment costs. These savings are related to supplier cost reductions. However, under the VMI strategy, the total system costs are uniformly lower than those under information sharing by an average of 4.7%, with a 0.4%-9.5% range. The benefit of VMI increases significantly with higher levels of capacity utilization. Results also support that the system performs better under balanced as opposed to synchronized ordering environments.

Short Sales Season

This section reviews the literature on short sales season environments. Since our focus is on physical flow coordination in a multi-period setting, only models with at least two replenishment opportunities are discussed. Readers interested in a single-replenishment newsvendor environment are referred to Pasternack (1985) and

Kandel (1996), who promote using a return provision to coordinate buyer-supplier relationships, and Weng (1995), who proposes a two-part tariff.

Parlar and Weng (1997) examine a situation in which a retailer receives an initial inventory allocation at the beginning of the sales season and a single subsequent replenishment. Each replenishment has different cost structures. The model assumes that after observing early sales, perfect demand information is available for planning the second replenishment. The authors develop optimal replenishment schedules under decentralized (no information sharing and no coordination) and centralized (information sharing and full coordination) control, finding that the centralized system is superior to the decentralized approach under relatively high replenishment costs. In addition, information sharing and coordination dampens the adverse impact of increases in backorder cost, unit sales prices, mean demand, and unit salvage values.

Donohue (2000) studies the two-phase replenishment problem in which the initial replenishment is relatively inexpensive but requires a long lead-time, while the subsequent replenishment is expensive but has a short lead-time. A contract of the form (w_1, w_2, b) coordinates the system, where w_i is the wholesale price offered by replenishment i, and b is the return price paid to the retailer for each unsold unit at the end of each the sales season. Prior to the second replenishment, the supplier updates his forecast accuracy utilizing early demand data. In this system, double marginalization threatens to impact both the total replenishment quantity and the proper allocation of supply between periods. In order to evaluate the benefit of system coordination, two-stage newsvendor models are developed to evaluate both a centralized and decentralized control system. In the centralized model, the pricing scheme aligns the supplier and the buyer to act in the best interest of the channel. Pareto-improving conditions with respect to the traditional single-replenishment contract approach are identified. A surprising result is that as the predictive power of the new market information increases, the supplier is able to choose from a wider combination of efficient prices and extract more of the economic benefits such that a Pareto-improving solution is not always possible.

Fisher, Rajaram, and Raman (2001) consider the problem of determining initial and subsequent replenishment quantities that minimize the total lost sales, backorder, and obsolete inventory costs in a seasonal demand retail environment. They model the problem as a two-stage stochastic dynamic program and propose a heuristic solution procedure. Problem assumptions include stochastic demand, a finite selling period, multiple production stages, fixed replenishment lead-time, constant price, information sharing between channel members to update demand forecasts between planning periods, and centralized planning. Implementation of the procedures at a catalog retailer improved profits as a percent of sales from 2.23% to 4.92%, thereby documenting the potential value of coordination and information sharing prior to the second replenishment.

Observations and Implications

Recent studies are beginning to clarify the benefits of full information sharing and coordination in supply chains with infinite and short sales season planning horizons, and under a variety of control structures including centralized, decentralized, contract, and vendor-managed inventory systems. Frohlich and Westbrook (2001) provide empirical evidence of the value of supply chain integration identifying "outward-facing supply chain" firms as leading performers. Chen (1998) and Cachon and Fisher (2000) find information sharing and physical flow coordination to be worth 1.75% and 3.4%, respectively, in system cost improvements. These results hold for the specific problem environments studied and encourage further analysis of alternative and more complex supply chain structures.

Waller et al. (1999), Fry et al. (2001), and Aviv and Federgruen (1998) document the value of traditional VMI arrangements in which POS data is provided to the vendor, who then schedules all replenishments. However, an in-depth interpretation of the research direction leads to what we define as "extended-VMI," a relationship under which both the vendor's replenishment system and the retailer's inventory system are fully coordinated to eliminate any system externalities. While Aviv and Federgruen (1998) touch on this system type, extended-VMI is largely unexplored in the literature, presenting numerous research opportunities.

Parlar and Weng (1997), Fisher et al. (2001), and Donohue (2000) consider two-stage newsvendor situations for short sales season planning horizon problems assuming that after observing early sales, forecast accuracy is improved for the second replenishment. Fisher et al. (2001) provide a centralized planning model based on full information sharing, while Donohue (2000) proposes a two-price contract with a buyback clause that coordinates the system under decentralized decision making. The short sales season research strengthens the argument for increased information sharing and coordination in retailing environments. Promising extensions of the work include extending the scope further upstream in the channel, designing coordination mechanisms that insure benefit sharing, and developing improved methods for updating the forecast for the second replenishment. Harpaz, Lee, and Winkler (1982), Braden and Freimer (1991), and Lariviere and Porteus (1999) provide initial research efforts in this area.

Overall, current research in this area is fragmented and findings are tied to specific problem parameters. Generalization of the problem scope to include capacity constraints, multiple products, multiple echelons, and replenishment fixed cost structures is needed. Furthermore, with the exception of Fisher, Rajaram, and Raman (2001), there is very little research that addresses the level of problem complexity encountered in industry.

CONCLUSIONS, IMPLICATIONS AND RESEARCH DIRECTIONS

Tables 1, 2, and 3 summarize the literature review by grouping the "core research" articles by research objective and methodology.

Anchored by Forrester's visionary work, a substantial block of the articles addresses the bullwhip effect including its definition, causes, effects, countermeasures, and procedures for quantifying the effect. The case study, simulation, and analytical research complement each other in providing insight into the principles underlying information distortion. These articles are summarized in Table 1.

The second set of articles, presented in Table 2, investigates the benefits of partial and full information sharing in the absence of coordinated decision making. In the infinite planning horizon environment, the focus is on POS data sharing as a potential countermeasure to the bullwhip effect. For short sales season problems,

Table 1: Research on no information sharing and no coordination in supply chains.

Reference	Research Objective	Research Methodology
No Information Sharing and No Coordination		
Forrester, J. W. (1958)	Define basic principles of industrial dynamics including information distortion, its causes and possible solutions.	Computer simulation of a serial system consisting of a factory, factory warehouse, distributor, and retailer.
Sterman, J. D. (1989)	Study the impact of decision makers' behaviors on supply chain performance.	Use of a lab study (Beer Distribution Game).
Metters, R. (1997)	Study the profitability impact of the bullwhip effect due to demand seasonality and forecast error in a serial supply chain.	Dynamic programming model with probabilistic retailer demand and capacitated production.
Lee, H. L., Padhamanabhan, V., and Whang, S. (1997a)	Define bullwhip effect, its causes and prescriptions to counter the effect.	Consolidation of literature and industry observations.
Lee, H. L., Padhamanabhan, V., and Whang, S. (1997b)	Analytical analysis of the causes of the bullwhip effect and possible countermeasures.	Mathematical explanations (Inventory model development and analysis) of the causes of the bullwhip effect.
Baganha, M. P., and Cohen, M. A. (1998)	Study of the stabilizing effect of inventories in multi-echelon manufacturing/distribution systems.	Periodic review stock replenishment procedures in a single factory, single DC, multiple-retailer system. Performance metric is demand volatility at the plant.
Cachon, G. (1999b)	Study supplier's demand variance under synchronized, balanced, and flexible (assuming balanced ordering) policies.	Development of optimization methodology. Numerical analysis of scheduled ordering policies in a single supplier *N* retailer system. Performance metrics are demand variability and total system cost.
Graves, S. C. (1999)	Analytical analysis of the bullwhip effect for a single-stage and a multi-stage case with non-stationary demand.	Adaptive base-stock policy for a single-item inventory system with deterministic lead-time, but subject to a stochastic non-stationary demand process.
Taylor , D. (1999)	Develop procedures for quantifying the bullwhip effect in supply chains.	Use of a lab study (Beer Distribution Game).

Table 1: (cont.) Research on no information sharing and no coordination in supply chains.

Reference	Research Objective	Research Methodology
No Information Sharing and No Coordination		
Chen, F., Drezner, Z., Ryan, J. K., and Simchi-Levi, D. (2000)	Quantify the bullwhip effect due to forecasting and lead-time in a two-stage serial system with and without centralized demand information.	Analytical models based on order-up-to inventory models with results supported by a simulation study from an earlier work of the authors.
Fransoo, J. C. and Wouters, M. J. F. (2000)	Discussion of the conceptual measurement problems associated with quantifying the bullwhip effect.	Case based effort to document and define ways of measuring the bullwhip effect in two supply chains.

information sharing provides a mechanism for implementing quick response strategies, thereby reducing the financial and market risk associated with bringing new or seasonal products to market. The research encompasses a wide variety of supply chain structures, inventory models, demand processes, information-sharing strategies, facility characteristics, and research methodologies. Each effort contributes to the overall understanding of information sharing and its potential value in supply chain management. However, the bottom line is that information sharing alone does not eliminate the bullwhip effect. Coordination among the trading partners is also required.

Table 3 consolidates the research, studying information sharing and system coordination. The infinite and short sales season planning environments are carried forward as subcategories in this research block. In addition, we add a separate category for VMI. While we recognize that VMI could be incorporated into the infinite and short sales season research, we represent it separately, reflecting the significant body of work that is emerging under this heading (Fry et al., 2001).

This review also highlights the evolution of the research area. Earlier research focused on understanding the complexities of supply chain management including information distortion and the bullwhip effect. The second phase targeted the role of information sharing as a possible remedy for supply chain ailments. Finally, the critical role of physical flow coordination in supply chain management is addressed. Building upon these accomplishments calls for additional research documenting the value of physical flow coordination and the drivers of the associated benefits. Only through a clear understanding of the economics of channel integration can industry move forward with the development and implementation of new information-technology-based supply chain strategies.

Implications and Directions for Future Research

The literature addresses a variety of supply chain structures, demand processes, and operational environments. Each characteristic potentially plays a significant role in supply chain performance and must be clearly understood. A common research approach is to simplify the problem so that the basic underlying tradeoffs can be understood analytically. Unfortunately, this may compromise the validity of the results when applied in an industrial context. Broadening the problem scope to

Table 2: Research on partial/full information sharing and no coordination in supply chains.

Reference	Research Objective	Methodology
Partial/ Full Information Sharing and No Coordination		
Infinite Time Horizon		
Hariharan, R. and Zipkin, P. (1995)	Study of the impact of advance warning of customer demand on system inventory performance in a make-to-stock environment.	Basic inventory models are extended to consider the placement of advanced orders. Analytical results indicate that advance warning impacts performance identically to a reduction in supply lead-time.
Bourland, K.E., Powell, S.G. and Pyke, D. F. (1996)	Study of the impact of timely demand information on inventory and service levels both at the manufacturer and the customer firm.	Analytical analysis of a two-stage system with each firm using a periodic base-stock inventory policy with offset, but identical cycle lengths. Total system and player benefits are reported.
Gavirneni, S., Kapuscinski, R. and Tayur, S. (1999)	Explore the relationship between information sharing, supplier capacity, and inventory in a supplier-retailer supply chain.	Order-up-to (s, S) and modified order-up-to inventory models are applied to study the total cost impact of alternative information-sharing strategies. Infinitesimal perturbation analysis is applied to study the value of information sharing.
Gilbert, S.and Ballou, R. (1999)	Study potential benefits of sharing advanced order commitments in a two-stage make-to-order environment.	Development of (s, S) inventory models to study inventory and excess capacity costs. A queuing model examines the impact of advanced orders on overtime production costs.
Chen, F., Drezner, Z., Ryan, J. K. and Simchi-Levi, D. (2000).	Examine the impact of information centralization on a multi-stage serial supply chain.	Analytical models based on order-up-to inventory models with results supported by a simulation study from an earlier work of the authors.
Lee, H. L., So, K. C. and Tang, C. S. (2000)	Quantify the value of information sharing in a single-product, two-level supply chain with auto-correlated demand	Expressions for optimal order-up-to inventory policies are developed. Numerical analysis and simulation are applied to quantify savings versus demand correlation, order cycle lead-time, and demand variability.

Table 2: (cont.) Research on partial/full information sharing and no coordination in supply chains.

Reference	Research Objective	Methodology
Partial/ Full Information Sharing and No Coordination		
Short Sales Season		
Fisher, M. and Raman, A. (1996)	Develop methods for improving forecasting and production planning in a single capacitated supplier, multiple-retailer, and multiple-product seasonal demand environment to improve system performance.	Improved procedures for forecasting seasonal demand items. Developed a capacity-constrained newsboy model and Lagrangian solution procedure for production planning.
Iyer, A.V. and Bergen, M. E. (1997)	Study of the impact of QR strategy on production and marketing in a single product, manufacturer-retailer supply chain.	Development of newsboy type inventory models to examine anticipated benefits to both the retailer and supplier. Numerical analysis supports the results.

include more realistic problem environments such as multiple products and multi-echelon supply chains with multiple players at each echelon could provide additional insights not gleamed from simple models.

We also caution that a problem's specific assumptions and parameter values significantly influence the experimental results. Assumptions on balanced versus synchronized ordering by the retailers, stationary versus nonstationary demand processes, alternative forecasting and inventory policies, and single versus multiple products are shown to have a different impact of the system's response to integration efforts. It is dangerous to draw broad conclusions from a specific problem environment or a limited set of experiments. While numerous studies have explored the causes of the bullwhip effect and obtained similar findings, insufficient effort has been directed at the value of information sharing and physical coordination for these issues to be well understood.

The typical problem environment assumes that customers face a continuous demand process and that all members of the supply chain apply statistical based inventory control procedures. While these assumptions fit well for the distribution side of the supply chain, they are not reflective of many upstream supply processes in a make-to-order, batch, or other lumpy demand environment. In these cases, stochastic end-item demand is converted into production batch sizes during master production scheduling and further aggregated into larger batches during the material planning process. Here, deterministic dynamic-demand inventory models and material requirements planning approaches are more appropriate than statistical based procedures. However, in spite of its common occurrence in industry, the unique opportunities for sharing planned order releases and net requirements data are not addressed in the literature. Similarly, channel coordination opportunities between manufacturers and vendors to reduce system costs associated with the vendor's equipment changeover costs, transportation delivery charges, and transaction charges are unexplored.

Table 3: Research on full information sharing and system coordination in supply chains.

Reference	Research Objective	Methodology
Full Information Sharing and System Coordination		
Infinite Time Horizon		
Anand, K.S. and Mendelson, H. (1997)	Study alternative coordination structures and levels of information sharing on firm performance.	Theoretical framework and numerical analysis to study the impact of alternative coordination structures on firm performance.
Chen, F. (1998)	Study the value of information sharing and coordination in an *n*-stage serial supply chain. Identify the relationship between environmental factors and supply chain performance.	(R, nQ) inventory models are developed to solve echelon and installation stock multi-echelon systems. Heuristic algorithm to determine the reorder point for installation stock policy. Numerical analysis of a variety of problem parameters provides insight.
Cachon G. P. and Fisher, M. (2000)	Analysis of the value of information sharing, lead-time reduction, and reduced batch sizes in a supplier-*N* identical retailer environment.	Develop (R, nQ) inventory models to study information sharing, lead-time, and batch sizes.
Chen, F., Federgruen, A. and Zheng, Y-S. (2001)	Study of the value of coordination in a single supplier-multiple retailers supply chain.	Analytical and numerical analysis
Short Sales Season		
Parlar, M., and Weng, Z. (1995)	Studies the impact of perfect information on a two-stage supply chain under decentralized and centralized control.	Development of a two-stage newsvendor model. Numerical results support the superiority of centralized systems over decentralized with given problem parameters.
Donohue, K. (2000)	Study of a two-period, two-mode replenishment problem in a manufacturer-retailer environment. The system is coordinated by a contract.	Two-stage newsvendor problems are developed to evaluate the centralized and decentralized control.
Fisher, M., Rajaram, K., and Raman, A. (2001)	Study of a seasonal demand retail environment to determine the initial product stocking quantities and replenishment order quantities.	Development of a two-stage stochastic dynamic program and a heuristic solution procedure.
Frohlich, M., and Westbrook, R. (2001)	Measure the relationship between the level of supply chain integration and performance improvement.	Analysis of data from the International Manufacturing Strategy Survey.

Table 3: (cont.) Research on full information sharing and system coordination in supply chains.

Full Information Sharing and Centralized Decision-Making		
Vendor-Managed Inventory		
Aviv, Y., and Federgruen, A. (1998)	Analysis of the inventory and distribution cost benefits of information sharing and VMI in a single, capacitated supplier, *N* non-identical retailer supply chain.	Development of (*m, S*) policies for replenishment. Numerical analysis of no information and full information sharing in VMI control systems.
Waller, M., Johnson, E., and Davis, T. (1999)	Description of VMI, discussion of the sources of savings from VMI, and the technologies needed to make it work.	Simulation analysis of VMI and alternative environmental factors to determine savings drivers.
Fry, M., Kapusicski, R. and Olsen, T. (2001)	Performance comparison of the traditional retailer-managed inventory systems (RMI) and vendor-managed inventory systems (VMI).	Development of periodic order-up-to inventory policies for RMI and (*z, Z*) type inventory replenishment for VMI. Numerical analysis indicates superior performance from VMI over RMI.

The primary focus in physical flow coordination research is on demand variability and inventory planning and control. Recently Cetinkaya and Lee (2000) and Cetinkaya, Tekin, and Lee (2000) broadened the VMI problem scope to include transportation delivery issues, but ignored the potential benefits of real-time information sharing and physical flow coordination. Joint consideration of these issues provides significant research opportunities of potential benefit to industry.

While information sharing and physical flow coordination are viewed as prerequisites for effective supply chain integration, several hurdles to establishing inter-organizational relationships exist. These include identifying the magnitude of the anticipated benefits and who in the channel receives them. Infinite horizon and VMI research indicates the primary benefits are to the supplier, while short sales season supply chain integration tends to benefit the retailers. Furthermore, information sharing and coordination may require substantial investment in information technology for data capture, transmission, storage, analysis, and site maintenance. Exploration of strategies for sharing the costs and benefits among channel members deserves more research. These may include benefit-sharing plans, incentive systems, transfer pricing, and other agreements concerning long-term working relationships. Economic analysis, as well as case study and empirical research addressing these issues, are well justified.

The impact of alternative information-sharing technologies and strategies on system performance and cost structures is another relatively unexplored area. Alternatives such as extranets, electronic marketplaces, JIT-II, EDI, and traditional forms of information exchange such as fax, e-mail, and telephone provide unique cost and performance tradeoffs. Understanding the impact and benefit of each alternative on the channel is necessary to insure effective and efficient system integration. Technology interoperability among channel members is also a growing concern. The advances in business-to-business e-commerce are directing industry's attention to these areas, but rigorous academic research is slow in materializing.

B2B hubs provide one such opportunity for research. The current research on the impact of removing a channel member, such as a distributor through disintermediation, is limited and conflicting. Most findings support the contention that removing a distributor reduces the bullwhip effect. Others argue that in addition to sales support, distributors provide a variety of value-added services such as technical support, product mixing, forward position inventory, and others. There is an emerging research area exploring disintermediation, but it needs to be more fully examined.

Another implementation issue relates to how the system will be coordinated. The initial work in multi-echelon inventory control by Clark and Scarf (1960) assumes a centralized planner with system-wide information. However, the common operating mode in industry is decentralized decision making. Hence, the development of decentralized planning models that provide each decision maker with local information and performance measurement schemes that result in globally optimal solutions is needed. For example, Federgruen and Zipkin (1984) illustrate that by constructing cost functions appropriately, a decentralized system can perform as well as a centralized one for some multi-echelon systems. Cachon (1999a), Cachon and Zipkin (1999), Chen (1997), Lee and Whang (1999), and Porteus (1997) provide transfer payment approaches for two-stage serial supply chains with stationary demand, holding and backorder costs, fixed lead times, and information sharing. Additional work in more general supply chain structures is necessary to support supply chain coordination in practice.

As a final research initiative, we call attention to the inventory planning and control "best practices" incorporated into leading enterprise resource planning (ERP) software packages. These systems are based on procedures dating back to the 1950s and 1960s, and include economic order quantity and reorder point models, material requirements planning systems, and distribution requirements planning systems. While they are valid when optimizing a single echelon of the supply chain, their propensity to amplify and distort information in the supply chain is now well understood. Yet, in spite of these shortcomings, they remain "standard issue" in ERP software systems, and are implemented by numerous vertically integrated manufacturers and distributors. Hence, while the ERP database has full information sharing capability, current decision models do not effectively utilize this capability. This is especially unfortunate in view of the potential savings that could accrue from full information sharing and coordinated decision making. The development and testing of multi-echelon inventory control procedures based on POS data capture and full information sharing is a pressing research area. However, due to the computational complexity of the problem, we envision incremental progress in this area with research shifting away from closed form analytical models to embrace heuristic and hierarchical planning approaches. Simulation studies could also contribute to understanding alternative decision rules. Existing work in the multi-echelon inventory, hierarchical production planning, and vendor managed inventory literature provide a solid foundation for these efforts. [Received: September 21, 2001. Accepted: November 15, 2002.]

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Funda Sahin is an assistant professor in the Department of Marketing, Logistics, and Transportation at The University of Tennessee. She received her PhD in operations management from the Mays Business School, Texas A&M University. Her teaching and research interests are in operations and supply chain management, e-business, inventory planning and control, and information intensive supply chain management. Her publications have appeared in *Decision Sciences* and *Production & Inventory Management Journal.* She is a member of the Decision Sciences Institute, POMS, CLM and INFORMS.

E. Powell Robinson, Jr. is an associate professor of supply chain management at the Mays Business School, Texas A&M University. He received his PhD from the University of Texas at Austin and was previously a faculty member at Indiana University. His primary research interests are in information technology applications in supply chain management, design of production/distribution networks, multi-echelon inventory control and e-business. His publications have appeared in *Decision Sciences, Management Science, Journal of Operations Management, Naval Research Logistics*, and *Interfaces*, among others.