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Supply Chain Management Research and *Production and Operations Management*: Review, Trends, and Opportunities

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We reviewed the manuscripts focused on Supply Chain Management that had been published in *Production and Operations Management (POM)* over roughly 15 years (1992 to 2006). The manuscripts covered dealt with topics including supply chain design, uncertainty and the bullwhip effect, contracts and supply chain coordination, capacity and sourcing decisions, applications and practice, and teaching supply chain management. In the process of this review, we highlight the significant contribution of *POM* to the field of supply chain management, and illustrate how this body of work has served to further the mission of the journal. We then highlight works from this group along with the discussion of selected papers from other top journals in an effort to provide a reasonably complete overview of important issues addressed in recent supply chain management research. Using our research survey and conceptual overview of the area as a foundation, we offer comments which highlight opportunities and suggest ideas on how to usefully expand the body of work in the supply chain management area.

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1. Introduction

The first 60 issues of *Production and Operations Management* (*POM*) included 49 manuscripts accepted by the Supply Chain Management department. This constitutes a relatively small portion of the 399 papers printed in the pages of *POM* over this 15 year period. However, only one of these papers dates prior to 1997, while 18 appeared in the nine issues from Spring 2004 to Spring 2006. Consideration of the pages of other top journals in our field reveals a similar pattern. This strongly suggests that supply chain management (SCM) has recently become the dominant theme in operations management research. This paper begins with a survey of many of the papers on supply chain management published in *POM*, including those accepted by other departments. It is useful to organize these papers by topic in Sections 2 to 6. These sections focus on supply chain dynamics and the Bullwhip Effect (BWE), supply chain capacity and sourcing decisions, supply chain management (SCM) applications and practices, supply chain planning and scheduling, and approaches to teaching SCM.

Obviously, the review of such a small number of papers cannot provide or even suggest a complete overview of the literature on supply chain management that has emerged over the past 15 years. We also believe it to be unwise to attempt a complete overview of this literature in this limited space. In fact, one can argue that the collective reviews appearing in edited supply chain management research books by deKok and Graves (2003), Simchi-Levi, Wu, and Shen (2003), and Tayur, Ganeshan, and Magazine (1998) still miss some works in the area, even though they collectively consider over 1,000 manuscripts. Therefore, we have decided to use several papers from *POM* as springboards into discussions of selected topics which have attracted well deserved attention in other research venues. Specifically, we will focus on supply chain coordination with contracts, coordination issues involving internet channels, postponement, and the role and value of operational hedging in managing supply chains. To reiterate, by no means do we imply that this is an exhaustive list. Rather, our intent is to highlight a number of major areas that are arguably at the forefront of supply chain research at the present time. Further, we hope to go beyond an outline of the SCM research landscape and to suggest open areas in the field that seem ripe for significant contributions by the POM community.

2. Supply Chain Dynamics and the Bullwhip Effect

The "Bullwhip Effect" (BWE) refers to the phenomenon that order variability increases as orders move upstream along the supply chain. This phenomenon is so well known that it is sometimes referred to as, "the first law of supply chain dynamics." This effect is well documented by researchers both in theory and practice and has several important implications. The BWE can lead to excess inventory as well as unused or overused capacity. It dramatically increases the operating costs of the supply chain system and often leads to serious supply and demand mismatches and deterioration in customer service levels. A variety of causes of the BWE have been identified in the literature. These factors have been effectively classified in the seminal articles of Lee et al. (1997ab) into four major categories: (a) Informational inefficiencies and accentuating factors (e.g., propagation of distorted demand information via erratic orders, long and/or variable lead times, uncontrollable product production, etc.); (b) Order batching effects (e.g., pervasive impact of fixed costs and other economies of scale considerations in batching orders, periodic reviews, and "hockey-stick" phenomena in sales behavior etc.); (c) Dynamic pricing and promotional campaigns (provide incentives for customers to wait and place large orders, thus creating hard to predict "peaks" and "valleys"); and (d) System gaming behaviors (often in environments where capacity and/or material constraints might lead to order rationing, thus leading to order inflations/deflations as perception about system constraints change over time).

Warburton (2004) captures the systemic nature of the BWE by studying the fundamental differential delay equations that describe the evolution of the retailer's inventory level in the supply chain, which were originally described by Forrester (1961). In particular, he considers the impact of a single jump in demand. This work finds analytical solutions for the resulting equations. With these solutions in hand one can explicitly quantify the BWE, consider various policies exactly without the use of simulation, and predict the impact of specific changes to the chain's structure or practices.

Based on a case study of the machine tool industry, Anderson, Fine, and Parker (2000) investigate the amplification of demand variability by presenting a system dynamics simulation model. This work highlights a phenomenon which they label the "investment accelerator effect." For machine tools, there is a fairly stable demand for replacement units, but when durable goods producers invest in anticipation of even a small surge in their demand, this often shows itself as a huge increase in the orders placed with machine tool manufacturers. For example, a plant may use 100 machine tools and replace 5% of them in a typical year. If this firm anticipates a 5% increase in sales, it may plan to buy 10 machine tools this period; 5 new and 5 replacements. Thus, a 5% surge in expected sales at one level becomes a 50% surge for the supplier. This is particularly problematic for machine tools because this pattern is correlated across the entire customer base. The authors recommend that forecasting policies which tend to produce smoother orders be adopted by downstream customers to reduce the variability seen by the upstream suppliers.

Our experience suggests that the most intuitive response to the BWE is some form of information sharing to help coordinate the supply chain. Chatfield, Kim, Harrison, and Hayya (2004) present a simulation study to evaluate causes of the BWE. Their results include the following insights: (1) without forecast updating there is no BWE if simple ordering rules are adhered to, (2) lead time variability is a significant cause of the BWE, (3) information sharing is the most direct way to reduce the BWE, and (4) making use of information without sharing it is typically worse then ignoring the information completely. This last point is related to the first one. It is the updating following the receipt of new information that leads to the amplification of orders, and particularly so when customer orders are the only data available to a buyer when placing orders with his supplier. These results suggest that policies which stimulate information sharing and coordination are critical mitigants to the BWE.

3. Supply Chain Design, Capacity, and Sourcing Decisions

Supply Chain design involves strategic decisions and plans regarding where to locate facilities (for production, storage, distribution, retail, etc.), how to allocate capacities or assign production tasks to the various facilities, how to choose and develop supplier and distribution channels, and how to organize the interfaces among the various parties in the supply chain. Supply chain design is not stationary and in order to be effective has to be integrated with the processes of product (service) and manufacturing (delivery) system design. By studying the supply chains of fast-clockspeed industries (such as Internet service, personal computers, and multimedia entertainment), Fine (2000) concludes that the ultimate core competency of an organization is supply chain design, which is defined as "choosing what capabilities along the value chain to invest in and develop internally and which to allocate for development by suppliers." This work advocates the concept of "three-dimensional concurrent engineering", i.e., integrating supply chain design, product development, and process development. Product development includes architectural choices (e.g., integrality vs. modularity decisions) and detailed design choices, while process development includes unit process and manufacturing systems development. Supply chain development encompasses decisions on whether to make or buy a component, sourcing and contracting decisions, and logistics and coordination decisions.

When facing either demand or supply uncertainty, it is often valuable to have multiple sources of inputs or of finished items. Consequently questions regarding the optimal number and types of sources are studied in a number of *POM* papers. For example, Agrawal and Nahmias (1997) focuses on the optimal number of suppliers when demand is known and the yield from the supplier's production system is normally distributed. Given their formulation, increasing the number of suppliers reduces the variability of delivered quantities but increases the cost of managing the supplier relationships. The objective is to maximize profits considering holding, shortage, and supplier management costs. Sodhi (2005) considers a tactical planning model that uses linear programming. First a deterministic model is solved to generate a production plan. Second a stochastic problem is solved to devise an "ideal" replenishment plan in the face of demand uncertainty. The gap between the outputs of the two models can be used to reallocate capacity among different products as a plan to deal with the demand/inventory risks.

Agrawal, Smith, and Tsay (2002) develops a methodology for capacity planning and vendor management when the retailer places orders with two vendors who differ in lead times, costs, and production flexibility. The model uses multiple demand scenarios and captures several supplier attributes to populate an LP formulation of the planning problem. The system is developed in cooperation with a retail chain that ultimately used the model as part of a decision support system.

Yan, Liu, and Hsu (2003) studies how an updated demand forecast affects a manufacturer's ordering decisions when sourcing raw materials in a dual-supplier system. Their model includes the ability to place two raw material orders before the selling season: one at a low cost from a slow supplier, and one at a high cost from a fast supplier. The manufacturer puts effort into updating his demand forecast and demand forecast accuracy increases with time. Consequently, the buyer faces a tradeoff between the increased cost of fast delivery and the value of the information gained between the ordering points. A two-stage stochastic programming model is established and the manufacturer's expected cost function is proved to be convex under the assumption that the optimal order level is a linear function with respect to the mean of the demand forecast.

Increasing the flexibility of production capacity can provide an effective response to uncertain demand and reduce the cost induced by that uncertainty. Fisher, Hammond, Obermeyer, and Raman (1997) develop the idea of "accurate response" as a way to manage demand uncertainty. One critical notion here is to increase effective response capability by dividing production capacity into two distinct parts: speculative production capacity used before the observation of demand, and reactive production capacity, used after an early demand indicator. Other approaches include increasing total capacity, reducing lead times, throughput times, and/or transportation times, gathering market data earlier, improving market intelligence, and reducing minimum lot sizes. The authors then use data from a fashion/sporting goods producer to discuss the feasibility and relative impacts of these mechanisms on supply chain responsiveness.

Hazra, Mahadevan, and Seshadri (2004) model an electronic market where a buyer conducts an online reverse auction to select suppliers to meet his capacity requirements. The reverse auction mechanism described in the paper works as follows: the buyer selects a subset of suppliers from the enlisted pool and then equally allocates his capacity requirements among the selected suppliers at the uniform price of the lowest bid among the unselected suppliers. The contracts awarded through this electronic market are long term. The suppliers can also sell their capacity in a traditional open market with a fixed historical price, but incur a selling expense (e.g., searching cost, administrative cost, and negotiating cost, etc.) and face the risk of unsold capacity. The authors derive the suppliers' bidding price as a function of their available capacity and show that suppliers with larger capacities would quote a lower price in the electronic market. Based on the derived supplier's capacity-price curve, the authors model a scenario where the buyer announces the number of suppliers to be selected for award of a contract that minimizes the cost for meeting his capacity requirements.

As firms become increasingly global, they are exposed more and more to the policies of foreign governments. Many governments (or regional trade agreements, like NAFTA) have set local content rules for companies that wish to operate in their country (or within the region protected by the trade agreement). Local content rules require manufacturers to purchase a certain amount of components from suppliers located in that country (or the protected region). Munson and Rosenblatt (1997) formulates and solves a mathematical programming model to select suppliers while satisfying local content provisions. In their numerical studies, Munson and Rosenblatt consider a single plant producing several components under local content constraints. As the required local content percentage goes up, the plant increasingly prefers sourcing from local suppliers and the chances become much greater that we shall see high values of the local content percentage. However, if the government sets the local content percentage too high, it may cause companies to shift production to other countries. Such policies eventually become detrimental to local suppliers rather than helpful as they lead to reduced production and investment in the country.

The issue of designing a global facility network is examined in Kouvelis and Munson (2004). The authors develop a structural equations model, using the global sensitivity approach of Wagner (1995), based on a mixed integer program that captures the facilities network design complexities and tradeoffs. The presented work can be used both as a conceptual framework and as a decision support tool for global supply chain design. Other work emphasizes the robustness of global supply chain designs in the presence of significant uncertainty. The designed supply chain is robust in the sense that it hedges the firm's performance against the worst contingencies in terms of uncertain factors (demand, exchange rates, commodity prices, etc.) over a planning horizon. The work of Gutierrez and Kouvelis (1995) formally introduces many of these concepts and presents effective algorithmic procedures for the solution of the related mixed integer programs. The wide applicability of the approach is further illustrated in the work of Lowe et al. (2002) and illustrated in the popular case, Applichem (Flaherty 1996). This work addresses supply chain design in the face of exchange rate uncertainty and makes the material easier to transfer into MBA and Executive classrooms.

4. Supply Chain Management Practice: Vendor Managed Inventory and Reengineering Programs

The literature review by Cohen and Mallik (1997) points out that the theoretical studies in supply chain management often suggest policies that are impractical and hard to implement. This work argues that due to the gap between theory and practice, there is a need for research which reflects the complexity of real supply chains and highlights important practices and applications. Several papers published in *POM* do rise to this challenge.

Campbell Soup's continuous replenishment program (CRP) is a notable innovation to improve the efficiency of inventory management throughout the supply chain. It is a successful Vendor Managed Inventory (VMI) program for "functional products." Use of the term "functional products" stems from the original reference of Fisher (1997). Cachon and Fisher (1997) describes Campbell Soup's program. This system involves a combination of 'Every Day Low Pricing' (EDLP), daily transmissions of store inventory levels and sales for each SKU, and decisions by Campbell's concerning shipments to the retailer's distribution center. The authors also use data from this system to develop improved inventory management rules to implement continuous replenishment. They show that implementation of these rules would greatly increase the impact of the CRR approach.

Kreipl and Pinedo (2004) discuss how to integrate medium term production planning models and short term scheduling models in the design and implementation of decision support systems which help manage supply chains. Production planning models described in this paper optimize several consecutive stages in a collaborative supply chain. Particularly, the production planning model is designed to allocate production of different products to the various facilities in each time period in order to minimize the systematic production costs, holding costs and transportation costs under the given capacity (production and transportation) constraints. The output of the planning models is an input to the detailed scheduling process, which has considerably narrower scope in terms of time and space and aims at minimizing the total setup time on the machines at the bottleneck as well as the total weighted tardiness. Their ideas are operationalized through a real application in Carlsberg A/S, a Denmark-based beer brewer with global distribution.

The pages of *POM* have included several survey studies, which address the application and practice of supply chain management in industry. Through a survey of 30 ongoing partnerships, Kopczak (1997) investigates the interaction between the formation of logistics partnerships and supply chain restructuring in the U.S. computer industry. Logistics partnership is defined as a business relationship involving the outsourcing of a set of logistics activities, which involve more than one logistics function and are of a long-tern nature. Restructuring is defined as involving significant changes in the structure of the outsourced part of the supply chain via the partnership. These changes may include a change in the warehouse structure (number of tiers, number of warehouse, etc.), reassignment of tasks between tiers, redistribution of inventory between tiers (centralized vs. distributed stocking), a structural change in the transportation network, designating new consolidation points, and reassignment of roles and responsibilities among supply chain entities. The investigation found that both restructuring and non-restructuring organizations were common in the computer industry and that both types of organizations use outsourcing, but for different reasons. Restructurers are driven by the desire to restructure the supply chain while the non-restructurers are driven by a desire to focus on the firm's core business. The survey results support the hypothesis that relationships which involve efforts to restructure the supply chain are likely to provide greater benefits.

Clark and Hammond (1997) discusses the relationship between business process reengineering and channel performance for firms implementing electronic data interfaces (EDI) in the U.S. grocery industry. They combine data on inventory turns, stockouts, and sales with variables indicating the use of EDI, EDLP, and CRP to isolate the effects of each practice. They find that EDLP alone provides statistically significant benefits, while EDI alone does not. Their work suggests that the process reengineering required to implement CRP is the largest driver of value, while EDI is a common enabler of the process improvement.

The emergence of the internet has had a significant impact on how firms interact with each other and their customers. Johnson and Whang (2002) provides a detailed review of the existing literature on the impact of e-business on supply chain management. The authors categorize the various forms of e-business applications into *e-commerce*, *e-procurement* and *e-collaboration* and examine research in the three forms of e-business. Basically, e-commerce uses the internet to facilitate supply chain partners' interaction with customers, while e-procurement provides e-enabled firms efficient material procurement. E-collaboration is defined as business-to-business interactions facilitated by the internet, which go beyond transactions and may include information sharing and integration, decision sharing, process sharing, and resource sharing.

Klassen and Vachon (2003) take an interesting perspective on supply chains. In particular, the authors investigate how the supply chain management activities (specifically, the collaborative activities and upstream evaluative activities) affect the plant-level environmental investment through a survey conducted among plant managers from selected manufacturing sites in Canada. This work finds that the collaborative activities such as site visits, exchange of personnel, and technical assistance, etc., significantly impact environmental investment while the evaluative activities including assessing supplier performance, relying on supplier certification to reduce the need for inspection, recognizing supplier achievements, and offering feedback has limited influence on the environmental investment.

5. Supply Chain Planning and Scheduling

In a supply chain, entities such as suppliers, manufacturers, distributors, and retailers, can belong to a single organization or independent organizations. However, the distinction between centralized and decentralized systems is more properly related to the incentive structures within the chain. At the most basic level, in a centralized supply chain, there is a central planner who makes decisions for the entire system, while each entity in a decentralized system functions as an autonomous unit. Decentralized control policies can be easily implemented and analyzed at the local level (function, department, firm, etc.), however coordinated planning of the individual entities in a way that optimizes the value of the overall supply chain (system) is a difficult undertaking. Research tools that are used for planning such systems include network flow models and Mixed Integer Programming (MIP) models.

Chen, Zhao, and Ball (2002) present an MIP model which allows a decision maker to specify suppliers of inputs and production resources on a job by job basis in a make to order environment. Their model also accommodates order rejection if the supply chain cannot meet order requirements. The model simulates settings in which firms accept orders, make tentative promises, then make final schedules by planning batches of orders on an hourly, daily, or weekly basis. The authors point out that such policies are quite common in firms that gather orders via the internet. They also experiment with the approach using industry data to answer questions about how often the orders should be scheduled as a batch.

Souza, Zhao, Chen, and Ball (2004) develop a model using data on Toshiba's global notebook supply chain. This paper uses an MIP model to investigate whether a global manufacturer wants to pass temporary component price discounts offered by an upstream supplier on to the final customers. The analysis accounts for the fact that this component is included in multiple products made in various locations and delivered through a range of channels. The resulting model includes as many as a million variables because it is necessary to account for each path that a part may take through the system. The resulting model leads to interesting conclusions on the extent to which it is optimal to pass raw material discounts on to consumers. For example, short-term raw material discounts may require longer term end-item discounts in order to increase total supply chain profits. Additionally, the merits of passing on the discount are intimately related to the elasticity of the demand curve as well as the correlations of demand across multiple items.

Even when multiple parts of a supply chain are within the same organization, it is still attractive to operate the system in a decentralized way due to the ease of implementing site-specific control policies. It is also easier to evaluate an independent site rather than an integrated system. These factors drive much research in the field. Zhang (1997) studies a decentralized assemble-to-order system with multiple components and multiple products facing correlated demands. Inventories are kept at the component level and are used to support service level targets for final products. Each component has a deterministic replenishment lead time, and the assembly time for the final products is assumed to be negligible. An independent order-up-to policy is employed for each component and a product-type-based priority rule is used to allocate the components to final products. Given fill rate targets for final products the author uses an optimization model to find the optimal order-up-to levels for components.

Andersson, Axsäter, and Marklund (1998) apply a decomposition approach to coordinate a system with one central warehouse and an arbitrary number of retailers. Two main techniques are employed to enable the decentralized near-optimal order quantity decisions for the system. One is cost approximation for each retailer via replacing the random ordering lead time from the warehouse by its expected value. The other is to modify the warehouse's cost structure to include stockout penalty costs for late deliveries to the retailers. An iterative approach is used starting with a set of expected lead times for retailers. It is shown that in the case of normally distributed lead time demand the existence of a Nash Equilibrium for the decomposed problem is guaranteed. The proposed policy is shown to be quite close to optimal in several useful cases and has the advantage of being easy to implement.

Urban (2000) analyzes the multi-period inventory ordering policy of a retailer who is offered a "periodic, stationary commitment "contract, in which the buyer commits to purchase a certain quantity every period but will incur a cost each time a change in the order quantity is made. This type of commitment contract aims to reduce the variability faced by a supplier with low volume flexibility, by making it costly for the buyer to pass along the variability of market demand. A solution approach for the stochastic demand model is presented and several specific demand distributions are considered. For the case of deterministic demand, two alternative models are employed: one is a mixed-integer linear program and the other is a network model.

6. Teaching Supply Chain Management

As the demand for supply chain expertise exploded in industry, many teaching tools have been developed by business and engineering school faculty. Undoubtedly, the "Beer Game" has gained the most popularity among the simulation games used as teaching tools in undergraduate as well as graduate programs. The setup of the game involves students playing four roles within a single supply chain; Retailer, Wholesaler, Distributor, and Factory. Customers' demand for "Beer" arrives at the retailer. Material flows from upstream to downstream is often represented by some physical proxy such as chips or cards. Information flows upstream through the placement of orders. In each period, each player in the chain decides how much to order from their respective supplier and the factory must decide how much to produce. Order processing, transportation, and production lead times are built into the game. Each member experiences a holding or backlog cost in each period and the objective of the team is to minimize the sum of these costs without any communication between levels of the chain other then orders moving upstream and material moving downstream.

While many instructors have students play the game using some physical tokens to symbolize material flows, computerized versions of the game facilitate a wide array of variants. Chen and Samroengraja (2000) present a variant known as of the stationary beer game. This version of the game models the material and information flows in a production-distribution channel serving a stationary market where the customer demands in different periods are independent and identically distributed, and each player is aware of the distribution. This modification addresses students' most common criticism of the game (that, in reality, we must have some a'priori sense of demand even if we do not know it exactly) and retains the game's major teaching points. Playing the game using PC's or the web allows the instructor to deliver the game's lessons without sacrificing much class time.

A computer program was also developed for the purpose of playing the stationary beer game. Jacobs (2000) describes a internet version of the beer game, in which students work at personal computers in a classroom using a web browser to play the game while the instructor keeps tract of the game using software residing on the web server. The instructor determines the pace of the game and manually triggers the update of the system. Besides the obvious advantage of saving time, the internet version of the beer game can easily incorporate some of the major causes that lead to the bullwhip effect. For example, by inputting alternative demand files, the game can simulate the buying pattern influenced by price fluctuation.

Johnson and Pyke (2000) argues that teaching supply chain management is much more than repacking topics taught in "Operations management" or "logistics" courses since "integration" is the essential theme of supply chain management. While the planning and management of procurement, conversion and logistics functions are indispensable components, supply chain management emphasizes the importance of *integration*, which comprises the functional integration within the company (e.g., the integration of operations, logistics, marketing, and finance) as well as the coordination and collaboration with channel partners across company boundaries.

By examining the curricula used by many top engineering and graduate business schools for courses in supply chain management, Johnson and Pyke (2000) present a framework consisting of 12 components (areas) of a typical supply chain management course. Besides a description on how to teach each component, the authors provide extensive lists of cases and business news stories and categorize using the framework they propose. Several abbreviated class syllabi are also listed. Vollmann et al. (2000) present approaches for teaching supply chain management specifically to business executives. They argue that the chain focus should start with the customer and work backwards, instead of starting with the supplier and working forward. Therefore, they propose the term "demand chain management" to replace "supply chain management" in order to reflect their point of view. The authors believe that the following four managerial concerns are particularly important to executives: flawless execution, a move from supply to demand chain management, outsourcing and supply base development and, implementing demand chain partnerships. For each concern, the authors provide one or two cases that are appropriate for illustrating the underlying ideas and concepts. Kopczak and Fransoo (2000) share their supply chain management teaching experience through a Master's level offering called Global Project Coordination Course (GPC) in which project teams composed of three students from each of two overseas universities execute company-sponsored projects dealing with global supply chain management issues. A detailed course schedule and discussion of the logistics involved are reported. A project focused on the reverse logistics at Quantum is used to illustrate the scope and nature of the projects in the course. The authors conclude that, in conjunction with lecture and case-based approaches, the GPC course successfully trained students' project management and consulting skills. The course also enhanced the students' knowledge and understanding of supply chain management and information system theory. Finally, the course helped enable the students to apply the theory in a real setting and to work effectively in a global, cross-cultural project team.

Mehring (2000) describes another supply chain simulation game: the Siemens Brief Case Game (BCG), used extensively within Siemens. Compared with the beer game, the BCG has more details and complexity, which enables the instructors to develop learning exercises that focus on a wider range of supply chain management issues. The BCG supply chain consists of 9 activities: receiving a customer order, sales order processing, plant order processing, plant procurement, subassembly, final assembly, managing plant traffic and warehousing, managing sales traffic and warehousing, and dealing with a supplier. The paper describes two typical exercises. One targets the undergraduate audience and aims to provide a concrete example of typical activities in a supply chain and their interactions. The other is tailored for a graduate level audience and leads students to discover what creates a need for coordination, what activities require coordination, and what types of methods are more likely to be effective.

Anderson and Morrice (2000) propose a simulation game designed to teach service-oriented supply chain management principles. The authors argue that the Beer Game is not an accurate reflection of many service settings because service providers typically cannot hold inventory and can only manage backlogs through capacity adjustments. This game simulates the processing of a mortgage application. Each application passes through 4 stages: initial processing, credit checking, surveying the property that the applicant wants to purchase, and title checking. During each period, each player sees the backlog of jobs at his position. He then makes decisions to hire or fire in an effort to manage this backlog. Lags are built into the game to simulate the time it takes to find new workers and train them, or the notice that is given to workers being released. The objective of the team of 4 positions is to minimize the total costs of capacity adjustments and service delays. The behavior of the system can become quite complex due to the lags between capacity adjustment decisions and their realization at each position. Campbell, Goentzel, and Savelsbergh (2000) shares their experiences with use of supply chain management software in teaching, and presents many useful ideas on how to integrate popular software into the classroom.

7. Supply Chain Coordination: Information Sharing, Incentives, and Contracts

Actions or approaches which lead supply chain partners to act in ways that are best for the chain as a whole are known as supply chain coordination. One of the most obvious means to achieve this coordination is the use of contracts, whose terms lead to the desired actions. Such a mechanism is valuable when these actions are not in the best interest of the individual members of the chain unless some type of transfer payment is built into the scenario. Several works in *POM* have attempted to show the effectiveness of various supply chain coordination mechanisms and contracts. This is particularly important in a competitive environment in which entire supply chains are competing for customers.

POM included one of the earliest contributions on incentive alignment in decentralized supply chains. Ernst and Cohen (1992) introduces a stochastic model of a decentralized distribution system consisting of a dealer (who controls the stock policy) and a manufacturer (who is responsible for the delivery of the product through regular or expedite shipment modes). They derive optimal inventory control policies under three different scenarios: the dealer is dominant, the manufacturer is dominant, and the system is under centralized control. It is shown that the expected profit for a dominant decision maker is higher under decentralized control than the expected profit he can get in the centralized system.

Extensive reviews of the more recent literature on supply chain coordination are available in Whang (1995), Cachon (1998), Lariviere (1998), Tsay, Nahmias, and Agrawal (1998) and Cachon (2003). Supply chain coordination with internal markets is discussed in Porteus and Whang (1991) and Kouvelis and Lariviere (2000). For illustrative purposes, let us consider a simple form of the most commonly treated class of problems in the supply chain coordination area. Consider a simple chain with one supplier and one retailer. There is one selling season with uncertain demand, and a single opportunity for the retailer to order before the selling season begins. If the contract consists only of a wholesale cost per unit, it is easy to show that the retailer does not order enough to maximize the supply chain's total profit because he ignores the impact of his action on the supplier's profit. Hence, coordination requires that the retailer be given an incentive to increase his order. This incentive can follow from a wide variety of contract types and terms. For example, the supplier can offer the buyer a wholesale price plus some adjustment that depends on realized demand, such as a promise to buy back leftover inventory. In effect, this presents the retailer with a salvage value which increases his optimal order quantity. See Pasternack (1985) for a detailed analysis of buyback contracts.

Another commonly used approach involves a quantity flexibility contract. Under quantity flexibility contracts, the retailer is allowed to change the quantity ordered from the supplier after observing early demand or a demand signal. These contracts are similar to buy-back contracts in that the supplier shares some of the risks of having excess inventory with the retailer. Quantity flexibility contracts may induce the retailer to purchase larger quantities, thereby increasing total supply chain profits. See Tsay (1999) for a detailed study of supply chain coordination with this type of contract. Another common approach exists when the supplier charges some amount per unit purchased and the retailer gives the supplier a percentage of his revenue. This effectively splits both the benefits of coordination and the risks related to market uncertainty. Cachon and Lariviere (2005) provide an analysis of these contracts in a general setting. A related approach is known as the sales-rebate contract. Under this approach the supplier charges an amount per unit purchased, but then gives the retailer a rebate per unit sold above a threshold level.

A more complex setting exists when retail prices are not taken as given. If demand is a function of retail prices, then the contract types just discussed may not coordinate the chain, especially if salvage values or goodwill penalties are present. For these settings a price-discount contract is often used. It is essentially a buyback contract with parameters that are set only after the retailer chooses his price.

The general topic of supply chain coordination was the focus of a special issue of *POM* in 2004. As part of this issue, Boyaci and Gallego (2004) present a game-theoretic approach to modeling competition between 2 supply chains consisting of one wholesaler and one retailer. In the depicted scenario, market share is based strictly on customer service levels. The resulting model shows that supply chain coordination is an equilibrium strategy for both firms, but not necessarily one that increases supply chain profits. This is true because, in some instances where service is the only order winner, the consumers extract all of the benefits resulting from coordination. This suggests that coordination may be paramount to survival even though industry profits may not rise as a result of the coordinating activity.

Gerchak and Wang (2004) study two distinct contract schemes involving an assembler and its suppliers in a decentralized assembly system with uncertain demand. One scheme combines vendor-managed inventory (VMI) with revenue sharing. The other scheme is a simpler wholesale-price driven contract. In the VMI system the downstream assembler offers shares to the suppliers who then select the components production quantities. It is shown that with the assembler as the leader, the revenue shares are chosen such that all suppliers produce the same quantity and this amount is independent of the other supplier's production cost. To achieve channel coordination, the authors also propose a revenue-plus-surplus-subsidy scheme where, in addition to a share of revenue, a supplier is partially paid by the assembler for his unsold delivered components. In the more conventional wholesale price contract, the suppliers first simultaneously choose their individual component wholesale prices, then the assembler chooses the order quantity from each suppliers. It is shown that the production quantity and the system profit are decreasing in the number of suppliers. Similarly as in the single-supplier-single-buyer system, by adding a buy-back policy to the wholesale price contract, the multi-supplier, decentralized assembly system can be coordinated. The authors also provide one example to show that the VMI with revenue sharing system dominates the wholesale-price-based system in terms of the channel profit.

An asymmetric incentive structure can follow from the way in which the damage resulting from a lost sale is split among the channel partners. Kraiselburd, Narayanan, and Raman (2004) consider such a case via analysis of a scenario in which the retailer carries substitutable products from different manufacturers and customers make substitution decisions. In this case, an individual wholesaler feels the impact of lost sales even though no impact is felt by the retailer. The authors propose VMI as a solution to such a misalignment of incentives problem, but the performance of this approach depends on the manufacturer's effort which is 'non-contractible' meaning contracts regarding this level of effort are not fully enforceable because the retailer lacks perfect information. This leads to scenarios in which VMI can actually increase channel inefficiency when there is a high likelihood of substitution and the manufacturer's effort has little impact on product demand.

The coordination of supply chains with risk-averse agents is studied by Gan, Sethi, and Yan (2004). Based on the concepts used in group decision theory, this work defines a coordinating contract as one that leads to a Pareto-optimal solution acceptable to each agent in the supply chain. The decisions faced by the group include external choices and the internal split of the payoff among the group members. In supply chains with risk-averse agents, each Pareto-optimal solution is characterized by a pair: the optimal channel's external action and the corresponding Pareto-optimal sharing rule. A coordinating contract is then defined as one with a specific set of parameters that achieves the selected Pareto-optimal solution. The authors demonstrate how to find the set of Pareto-optimal solutions and how to design a contract to achieve the solutions for three specific cases: (1) the supplier is risk neutral and the retailer maximizes his expected profit subject to a downside risk; (2) the supplier and the retailer each maximizes his own mean-variance tradeoff; (3) the suppler and the retailer each maximizes his own expected utility. For general concave utility functions, it is not always possible to get the Pareto-sharing rule in closed form. Therefore, the authors consider the special case of exponential utility functions, for which the Pareto-optimal sharing rule and the optimal external action are derived and explicit coordinating contracts (revenue sharing contract and buy-back contract) are designed.

Poundarikapuram and Veeramani (2004) present a distributed decision-making framework for the players in a supply chain or a private e-marketplace in which players have limited information about each other but they do collaborative planning. The players have a global goal that is dependent on some common variables and their unique local private objectives that are dependent on local variables. Based on the Integer L-shaped method, the authors propose an iterative procedure to address the collaborative decision making problem in the decentralized system. In this approach a master problem (modeled as a mixed-integer program) is solved to propose global solutions and each player solves his local problems (modeled as Linear programs) to construct cuts on the feasible space of the master problem. This model enables the distributed decision-making process to achieve near-optimal global performance if the players are willing to disclose limited information.

Zhang (2002) considers a single manufacturer and two competing retailers. The retailers may compete by selecting either prices or output quantities. They also must decide whether to share signals regarding demand prior to receiving the signal. The major results are that the manufacturer is always better off with more information and that each retailer is damaged if he shares information, while his competitor does not. Consequently, the unique equilibrium is to avoid information sharing in the supply chain unless some mechanism exists to induce sharing such as a side payment or a guarantee that your rival will share truthful information along with you.

A quantity discount can serve as an inventory coordination mechanism between buyers and suppliers. Shin and Benton (2004) study the effectiveness of quantity discounts under different conditions. They show that the link between quantity discounts and the performance of the chain is influenced by several other factors including the variability of demand, the relative inventory cost structures, and the buyer's economic reorder intervals.

In the context of high-tech industries, Erkoc and Wu (2005) study capacity reservation contracts between a manufacturer, who faces convex capacity expansion cost, and her OEM customer. They share the stochastic demand information but the OEM places orders when the demand is realized. In the absence of a capacity reservation, the manufacturer bears all demand risk. To mitigate the manufacturer's capacity expansion risk and to encourage the manufacturer to expand capacity aggressively, the OEM may engage in a capacity reservation contract, in which, the buyer reserves capacities upfront by paying a deductible fee. However, such a contract is not always desirable for both parties. There is a threshold for the reservation fee that the buyer will accept, and such a reservation is only beneficial for the supplier when the product margin is sufficiently high. Consequently, the fully deductible reservation fee contract rarely coordinates the chain. The authors propose two coordination mechanisms: a partially deductible reservation fee contract, and a cost-sharing contract. Supply chain coordination is also discussed for cases in which the manufacturer under-expands capacity, and cases where demand information can be partially updated.

8. Multi-Channel Coordination Challenges: Coordinating Offline and Online Procurement and Distribution

The emergence and development of the internet, and its role in information management, marketing, and supply chain coordination has opened the door to a host of research and business opportunities. The internet offers manufacturers and retailers new avenues to conduct their business and most, if not all established firms are at least considering expanding on their historic business practices and relationships to include some internet enabled component. In this section, we will focus on the unique issues that arise when one needs to coordinate the activities of an online and offline approach to procurement, sales, and delivery. We will also highlight a few research efforts in these areas as examples of the styles of analysis used so far and types of questions present which have not been fully addressed.

In our exposition, we follow the classification scheme of the review paper by Cattani, Gilland, and Swaminathan (2003). Focusing mainly on the manufacturer, they identify three areas of research focus; procurement, pricing, and distribution and fulfillment. Specifically, firms find themselves evaluating options to use the internet in procurement to either enhance or replace traditional practices. *POM* published one of the earliest works on the topic by Peleg, Lee, and Hausman (2002). This work develops a two-period model with uncertain demand in which the decision maker has options to use long-term contracts, simple auctions, or some combination of the two. The attraction of the long term contract is that the supplier is willing to promise reduced prices in the second period of a two-period game, if the buyer commits at the start of period 1 to some minimum order quantity in period two. This is rationalized as a learning effect in that the promised price in the second period is $p(1 - \Delta)$, where p is the first period price, and Δ is essentially a discount rate which reflects supplier learning. The attraction of using auctions is the opportunity to get lower prices. However, the manufacturer does not know a'priori what price will be realized in the auction. The model assumes that he does have some prior distribution describing the realized auction price. The buyer can also apply a combined strategy in which he has a contract to cover most of his expected needs but has the option to use the auction to cover any shortfall or buy additional units from the supplier at the agreed upon price.

Peleg et al. (2004) shows that there exists a value of Δ beyond which it is optimal for the buyer to prefer a strategic long term partnership as opposed to utilizing an auction in the second period. They also show that the combined strategy of using a contract and an auction in the second period to meet higher than expected demand may be either superior or inferior to a pure auction strategy, depending upon the distribution of prices obtained from the auction. This model also allows the authors to consider the impact of the number of players in the auction in that more players should result in lower prices, but including additional players involves some coordination cost. They conclude that the optimal number of suppliers depends on the variance of demand in the first period, and it increases with the mean demand level in the second period.

The growing literature on supply contracts which integrates markets in various contexts (storable vs. non-storable goods, various types of long term supply contracts, negotiation etc.) is surveyed in Kleindorfer and Wu (2003). Among the seminal works in this area is Lee and Whang (2002). This paper studies how internet based surplus (or secondary) markets serve as mechanisms through which inventory can be pooled and balanced among participants in reaction to demand information. The market price in their two-period model is determined as the equilibrium price that clears the market under the assumption of a large number of market participants. They show that an open secondary market increases the allocation efficiency though it has an unclear effect on the monopolistic supplier's sales. Recent work of Milner and Kouvelis (2006) elucidates some aspects of how speculative online exchanges with a small number of participants might behave and the impact they have on the use of long term contracts for supply. The authors show that participating buyers accrue network benefits as the number of participating firms increases through the inventory pooling effects, resulting in reduced cost for them. However, a strategically acting supplier will counteract such benefits by restricting availability of goods to the spot market, sacrificing short term spot market revenue for long term contract volume.

The work of Granot and Sosic (2005) considers the benefits of joining a consortia of industry players, using a model with three firms. In this work, each firm may form alliances with none, one, or two other firms. A variety of issues are involved which increase the complexity of the decision. This work focuses largely on the substitutability of the products of the firms considering the formation of an alliance. If the products are not substitutes, then the optimal strategy is to join and the authors argue that this outcome is relatively easy to sustain. On the other hand, if two firms have substitute products then the third firm is likely to value the alliance differently then either of them and some 2 firm alliances in which a seller of a substitutable product connects with the party not making such a product may be more stable. In settings in which all three players have substitutable products, a three firm alliance may be stable, but it is not likely. This follows from the fact that the benefit of such an alliance is very unlikely to be uniformly distributed across the three firms. The problem is also complicated by the fact that firm A may wish to form an alliance with firm B simply to keep firm C from forming such a 2-firm alliance. The authors point out that their work suggests much future research that considers different demand functions and information states for the players involved.

The consideration of a manufacturer exploring or being presented with a new "e-tail" channel presents at least four possibilities. The manufacturer may simply find himself as the supplier to two competing channels (an E-tailer, and a retailer.) He may decide to forward integrate by creating an e-tail channel which competes with a pre-existing retail channel. He may find himself serving a combined online and offline re-seller. In some cases, he may even decide to become both a retailer and an e-tailer himself. These four cases present a plethora of new research topics. In an effort to better frame the broad research issues involved, we discuss some representative work outside *POM* in the area, and then proceed to position *POM* publication contributions to this field.

Considering a manufacturer supplying a retailer competing with an e-tailer, the issue of product pricing is paramount. One obvious concern of manufacturers is that the end users' added ability to compare prices on line will result in reduced profits for the entire chain as buyers select the low cost provider for more and more goods, especially those that are not obviously differentiated between online and offline offerings. While much work remains to be done analyzing the ultimate impact of internet sales on manufacturers, some research has suggested that the fear that all buyers will simply select on price has proven to be overblown. Brynjolfsson and Smith (2000) consider the prices paid for items easily advertised online. This work considers the pricing and sale of CD's and books. They found that the internet offered a price discount of 15.5% over traditional channels on books, and 16.1% on CD's, and that these discounts are 9% and 13%, respectively, after considering sales tax, shipping and handling, and transportation charges. This work also found that price changes are much more common with online retailers as opposed to traditional brick and mortar stores.

The work of Smith and Brynjolfsson (2001) extended this analysis and found that customers do not always opt for the lowest price. In fact, when considering online book sales they found that the majority of customers do not chose the lowest price offered even when they are fully informed about the range of prices available. Among the customers that do not chose the lowest priced version of the product, the average price of the selected offer is 20.4% higher then the lowest price available. Surprisingly, they found that buyers were willing to pay $1.72 more for an item from one of the "big three" online booksellers (Amazon, Barnes and Noble, and Borders) when compared with other vendors. The authors suggest that this result shows that the online vendor is perceived as a brand by the potential buyers, and they are willing to pay a premium for the brand if this is associated with some notion of quality, reliability, or performance.

The issues which determine the optimal price become even more complex when the same item is being offered online and offline by the same firm. This "bricks and clicks" approach raises several difficult questions whose complete answers are still forthcoming from academic researchers. For example, Lal and Savary (1999) model scenarios in which competing products are offered in both retail stores and online. They assume that some attributes of the products are easily conveyed digitally while others are not. They also account for the cost of searching for items with which the customers have insufficient prior experience. The customers can get digital information online but must travel to stores to get non-digital information such as feel and fit. When no internet outlet exists, customers must get all information by store searches. After the internet channel is introduced, customers can get some info with much less effort. This work shows that, depending on the customer search cost, the addition of an internet option may result in lower, or higher average prices paid. Thus the intuition that an internet outlet must drive prices down does not necessarily hold. It depends on how much relevant information can be conveyed online, the customer search cost, and the probability that the search will result in an unfavorable evaluation.

The work of Chiang, Chhajed and Hess (2003) considers a manufacturer selling through traditional retail channels while contemplating a move to integrate forward by creating an online option for end users to purchase their products. They focus on the issue of double marginalization that occurs when both the manufacturer and the retailer behave in a manner that is locally optimal. They consider a customer specific parameter $0 < \theta < 1$, such that the customer's utility for the product purchased online is θ times the utility received when purchased in a retail store. This work shows that differing equilibria exist depending on the value of θ. When this value is low, the internet offering has no impact on the supply chain. There exists a range of moderate values of θ such that the presence of the internet channel serves to drive prices down at both the manufacturer and retail levels even though no sales actually take place online. In this case, the margins of both the manufacturer and retailer are affected but both parties may actually be more profitable as the reduced price increases sales. Finally, for relatively high values of θ, the manufacturer's profits increase but the retailer's profits decline as the online channel becomes a very effective competitor with the retailer.

An influential dual channel conflict and coordination work in the *POM* journal is by Tsay and Agrawal (2004). This paper develops a model where a traditional and an internet retailer compete against each other and the customer purchase decisions are driven by both price and the effort that each channel puts forth. Their findings include the surprising result that the apparent conflict created is not necessarily detrimental to the retailer because there is asymmetry in the cost structures of the different channels. Thus, both a reseller and its supplier can be better off when the supplier implements a direct sales channel. This follows from the fact that the price charged by the manufacturer to the retailer is driven down by the competition, but the determination of the optimal price at the retail level is more complex because he now has more options in offering a response.

A consideration of channel coordination involving internet outlets would be incomplete without some discussion of distribution and fulfillment issues that arise in this more complex environment. One excellent example of the work in this area was recently published in *POM*. Cattani and Souza (2002) consider a scenario in which the firm takes advantage of the fact that internet customers display a greater willingness to wait for the delivery of a product when compared with retail customers. This is evidenced by the fact that the internet customer must wait for product delivery in any case, and he does not know the inventory status of the item at the time of purchase. This suggests that a seller offering both retail and internet channels should dynamically allocate inventory between them. This work suggests a continuous review inventory management policy for a single product. It modifies the standard approach to such inventory management systems by determining three critical values. Specifically, they determine a reorder point, a target inventory position, and a third value which is the cutoff point for internet sales. In this system, once inventory drops below a determined level, all internet orders are backlogged even if inventory still exists in the system and is available to retail shoppers. The results show that the increase in the seller's profits depends on the fraction of total demand that is in the form of retail sales. Obviously, if this fraction is close to 0% or 100%, then the policy has no application. However, if this fraction is significantly different from these end points, then the seller's profits may increase by as much as 7%. Recently research work on rationing of inventories with dynamic discounts appeared in Ding, Kouvelis, and Milner (2006). The presented model considers a single period stochastic demand problem with variable ordering costs and multiple demand classes. The period is divided into multiple stages, allowing updating of demand information and making inventory allocation decisions. The authors argue on the effectiveness of rationing policies in lowering inventory levels and improving profitability for such settings, as well the use of dynamic discounts to "keep" lower class customers around and meet service level constraints.

9. Design for Supply Chain Management: Postponement and Product Variety

One can use the design of a product, as well as the design of the manufacturing and supply chain process, to delay the point of product differentiation such that it is closer, both in terms of physical location and time, to the final customer demand. This increases the firm's ability to handle the uncertain and continuously changing demand for one or multiple products. This approach was first termed postponement by Alderson (1950). The value of postponement lies in the reduction of inventory related costs due to a better matching of supply to demand. For complete reviews of important works in the design for supply chain management and postponement literature we refer readers to Lee (1993), Lee (1996), Garg and Tang (1997), Garg and Lee (1998), and Swaminathan and Lee (2003).

Swaninathan and Lee (2003) cite three specific enablers of postponement—process standardization, process resequencing, and component standardization. One classic process standardization example is found in the description of Hewlett Packard's DeskJet Printer business given in Lee, Billington, and Carter (1993). This printer line had distribution centers in the

U.S., Europe, and the Far East. The earlier strategy had been to make region-specific models all in the U.S. and to ship these completed items to each area as finished goods. The variability of demand within each region, and the one month lead time in shipping led to significant costs for the system. HP decided to redesign the product so that standardized steps in the production process could all be done in the U.S., but steps which make a model specific to one area such as power supply installation, and inclusion of manuals was deferred until after customer orders arrive in each region. The documented success of this approach at HP became the prime instigator of subsequent design for supply chain management practices at the company as discussed in Feitzinger and Lee (1997), Lee and Sasser (1995), and Lee et al. (1997).

A general model of this type of arrangement is presented in Garg and Tang (1997). In this work, the authors consider a system with two points of differentiation. The first is the family differentiation point, and the second is the product differentiation point. In other words, the process consists of three stages. In stage 1, steps common to the production process of the entire group of products are undertaken. In stage 2, steps which differentiate one family from another are taken. The steps which define a specific product are deferred until stage three. This work shows that when inventory is stored at the end of each stage, significant savings in inventory costs can be achieved when compared to a system that only stores finished products. They also discuss problem characteristics that increase the value of later postponement such as when product demand across a family is more negatively correlated.

Related work appeared in *POM* in Graman and Magazine (2002). This model considers postponement until the second of a 2-stage process, with capacity constraints for each stage where the differentiating steps take place in the second stage and inventory can be stored between the two stages. This is sometimes referred to as a 'vanilla box problem' because generic modules are produced in stage one and demand is realized for specific models after the additional steps of stage 2. This model derives analytical expressions for service measures and inventory levels. The authors also use a numerical study to show that very little postponement capacity can provide virtually all of the benefits related to inventory reduction. Some of the original work on delayed product differentiation through vanilla boxes appeared in Swaminathan and Tayur (1998).

A story frequently used in MBA classrooms which displays the value of process resequencing can be found in Dapiran's (1992) description of Benetton. In this scenario, sweaters had traditionally been produced by dyeing yarn to the appropriate colors, and then weaving them into the selected styles and sizes. The managers at Benetton observed that the major source of uncertainty was not over sizes and styles as much as it was over color. In other words, which color would be "hot" this season was very difficult to predict. As a result, Benetton found it profitable to change its traditional production sequence to allow for the weaving of uncolored sweaters, thus postponing the point in the process at which a unit became differentiated by color.

Lee and Tang (1998) formally considers a simplified version of the problem by modeling a two-stage system where a distinct feature is introduced into the product at each stage. Specifically, they consider two stages and two possible features at each stage. Thus, there are four possible products available to a customer. In this formulation, changing the sequence does not alter either the raw material or finished goods inventory levels. However, it may alter the variance of the buffer levels between the stages. This highlights the fact that the notions of holding and shortage costs for finished goods may not reflect all of the costs associated with managing inventory in the supply chain. This paper argues that the cost of manufacturing, such as overtime charges or the disruption caused by expediting, is often linked to the variances of inventory levels and production requirements within the system.

An excellent example of the use of a component standardization strategy involves Lucent Technologies and is relayed in Hoyt and Lopez-Tello (2001). In 1998, Lucent recognized a huge sales opportunity for telecommunications equipment in Saudi Arabia. However, to take advantage of this opportunity, Lucent needed to be able to offer a short lead time that would make it impractical to perform the usual detailed site engineering work that had always preceded product configuration. In addition, the Spanish plant which was closest to the customer did not have the capacity to fill the order, even if all specifications were known at once. Lucent ultimately decided to redesign the product so that it had common building blocks. This enabled them to pre-build these common blocks without full knowledge of the final configuration, and to use capacity in other plants to help generate the required output.

These approaches are closely related to earlier work focused on the benefits of component commonality. The bulk of the formal modeling which deals with component commonality focuses on inventory cost at the component level. One notable exception is in Van Mieghem (2004). This model considers two products where each product is assembled from two components and both common and product specific components are stocked. This work derives conditions under which commonality should be adopted. This determination is driven by the level and nature of demand correlation for the two end items, and the cost required to achieve commonality. When this cost is high, postponement and the use of common components may not be attractive. A strategy in which each product is assembled using a common component is only optimal if the cost to manage components is increasing in the number of different components in play. Finally, this work shows that while the value of the commonality strategy decreases in the correlation between product demands, commonality is optimal even when the product demands move in lockstep if there is a sufficient profit differential between the two products.

10. Operational Hedging and Risk Management in Supply Chains

Due to the inherent uncertainties/risks in SCM, Supply Chain Risk Management (SCRM) was virtually born alongside the concept of supply chain management itself. Even though many articles in the literature do not articulate the term "risk management" they are motivated by the need to deal with the management of uncertain demand, uncertain supply, and uncertain costs. Supply chain risks can be categorized into two basic levels: operational risks, and disruption risks (Tang 2006). Kleindorfer and Saad (2005) refer to them as supply-demand coordination risks and disruption risks. Operational risks are directly associated with the day to day management of the supply chain, while the term "disruption risks" is generally reserved for natural or purposeful man-made disasters (earthquakes, hurricanes, terrorism, etc.).

Tang (2006) offers an extensive and excellent review of various quantitative models in the literature dealing with the risks associated with supply chains and presents a unified framework for classifying SCRM articles. Tang (2006) first defines SCRM as "the management of supply chain risks through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity." By "profitability," the above definition implicitly assumes that the supply chain members are risk-neutral and consequently, this work basically reviews those articles that provide cost effective solutions for managing supply chain risks. Based on the above definition of SCRM, Tang (2006) classifies the risk management approaches appearing in the supply chain management literature into four groups: supply management, demand management, product management, and information management. As implied by the definition, these four approaches are all intended to improve supply chain operations via coordination or collaboration among supply chain members. Accepting the definition, we would like to highlight the relevant issues in several approaches that are used to mitigate supply chain risk.

There are five intertwined issues in supply management: supply network design, supplier relationships, supplier selection, supplier order allocation, and supply contracting. Tang (2006) discusses three approaches for demand management: shifting demand across time, shifting demand across markets, and shifting demand across products. That work also highlights three product management strategies: postponement, process sequencing, and product substitution. The author argues that postponement is an effective way to reduce variability in a supply chain. Researchers note that this variability can also be reduced by reversing the sequence of manufacturing processes in a supply chain. An example of using the process sequencing strategy is the reengineering effort at Benetton, which pioneered the knit-first-dye-later process instead of the traditional dye-first-knit-later sequence in the woolen garment industry. For information management, Tang (2006) classifies the work into strategies for fashion products (shorter life cycle and higher demand uncertainty) and strategies for functional products. The author reviews information sharing, vendor managed inventory, and collaborative forecasting. It is also pointed out that there is a lack of quantitative models which consider disruption risks in an explicit manner and therefore the author proposes several ideas for future research to close the gap between the literature and actual practices.

Note that few works reviewed by Tang (2006) explicitly address risk identification, risk measurement, or risk hedging. It seems fair to say that Tang (2006) provides an operational perspective of SCRM. However, many firms are deeply concerned about the variability of their profits and need insights regarding the management of this variability. Substantial academic research in the corporate finance literature has explained why firms should hedge risks. Violations of the assumptions underlying the Modigliani-Miller (Modigliani and Miller (1958) irrelevance theorems motivate corporate risk management. From a practical perspective risk management is indeed relevant due to a number of factors including tax laws, financial distress costs, managerial risk aversion (Smith and Stulz 1985), capital market imperfection and costs incurred when accessing external capital markets (Froot, Scharfstein, and Stein 1993). Consequently, we have seen the rigorous development of risk management concepts and techniques in the finance literature including both the quantification of risks and the development of risk hedging tools in the past two decades. Recently, there has been rapidly growing recognition that risk management concepts and techniques developed in the finance field can be applied to supply chain risk management. This has spawned several new research streams in operations management.

One such research stream is the incorporation of a supply chain agent's risk aversion into operational decision rules. A fundamental theoretical framework for modeling risk-sensitive decision makers is expected utility theory (see Mas-Colell, Whinston, and Green 1995, Chapter 6). The literature in financial economics offers a quite general and analytically tractable approach based on the mean-variance model developed by Markowitz (see Markowitz 1952; Markowitz 1987; and others). Both the general utility function and mean-variance approach have been employed in risk-aversion inventory management models (see Bouakiz and Sobel 1992; Chen and Federgruen (2000). However, there are fewer papers in supply chain management that incorporate risk aversion. Several papers appearing in POM contribute to this burgeoning research direction. Gan, Sethi, and Yan (2004) first consider the supply chain coordination problem with risk-averse agents. In a companion paper (Gan, Sethi, and Yan 2005), they specialize the definition of coordination for a supply chain with a risk-neutral supplier and a downside-risk constrained newsvendor. The authors illustrate that the buy-back contracts and revenue sharing contracts that coordinate the supply chain in the risk-neutral case will not always coordinate the channel in the presence of risk aversion if the downside risk of the retailer is higher than his acceptable level. In this case, the retailer prefers to order less than the coordinating quantity. A risk-sharing contract then is proposed, based on the buy-back/revenue-sharing contract. The basic idea of the risk-sharing contract is to provide the downside protection to the retailer by refunding a certain amount of unsold units. Some other notable research in the use of risk sharing contracts between retailers and suppliers in the presence of price uncertainty appeared in Li and Kouvelis (1999).

Another rising research stream explores the value of operational hedging, as well as the benefit of integrating operational hedging and financial hedging in the context of a global supply chain. As noted in Boyabatli and Toktay (2004), there are two essentially similar definitions of operational hedging in the operations management literature. One stems from a real options view (Huchzermeier and Cohen 1996), while another builds upon a counterbalancing-action view (Van Mieghem 2003). The real options view considers the operational hedging strategies as real options that are exercised in response to demand, price, and exchange rate contingencies. A variety of types of operational hedging strategies have been explored in the literature. Kogut and Kulatilaka (1994) consider the operating flexibility to shift production between two manufacturing plants located in different countries under exchange rate uncertainty. Huchzermeier and Cohen (1996) explores the value of global manufacturing strategy options including international supply flexibility and manufacturing and distribution flexibilities via maintaining multiple plants globally and switching production and distribution among the global supply chain network. Ding, Dong, and Kouvelis (2006) study the strategy of postponing the allocation of capacity to specific markets until currency and demand uncertainties are resolved.

Though it is clearly recognized that financial and operational options should be integrated in order to effectively manage exposure to exchange rate fluctuations (Hodder 1982; Flood and Lessard (1986), few quantitative models exist to help accomplish this. One such work is Ding, Dong, and Kouvelis (2006). This paper develops a structural model to integrate the capacity allocation option with financial hedging strategies for a risk-averse multinational firm. It is assumed that the firm uses a production facility in its home country and sells to markets in both its home country as well as a foreign market. Their investigations show that both the operational flexibility and financial hedging have an impact on value-creation and the control of the variance of the firm's profits. The firm with an allocation option tends to increase overall capacity after adopting financial hedging. Firms using financial hedging are less affected by volatilities and their own risk attitude when compared to firms not using financial hedging. Dong, Kouvelis, and Su (2006) expand this burgeoning research line by incorporating the competitive exposure faced by a global firm which sells to both a domestic market and a foreign market while competing with a local incumbent in the foreign market. The authors compare three operational strategies: one with involves no operational flexibility but assumes matching currency footprints ("natural hedge.") The second includes postponement flexibility. The third strategy includes both postponement and allocation flexibility. It is shown that the natural hedge strategy is outperformed by strategies which take advantage of operational flexibility in terms of both profit and downside risk. This work also finds that operational flexibility will sometimes benefit the competitor in the sense that the global firm may decide not to participate in the foreign market when the exchange rate is not favorable.

Several papers in POM address the issue of the supply chain disruption risk. Hendricks and Singhal (2005) conduct an empirical analysis of the effect of supply chain disruptions on long-term stock price performance and equity risk of the firm based on a sample of 827 disruption announcements made during 1989 to 2000. They found that the average abnormal stock return of firms that experienced disruptions is nearly −40% and furthermore, firms do not quickly recover from the negative effects of disruptions. Kleindorfer and Saad (2005) offer a conceptual framework for managing disruption risks in supply chains. This work discusses the need for continuous and concurrent efforts along three dimensions. They argue that firms must focus on "specifying" the sources of disruption risks and vulnerabilities. Firms also need to quantify the risks through a disciplined approach to risk "Assessment." Finally, the firms need to design policies and plan actions which serve to "Mitigate" these risks. The author's elaboration on their framework is supplemented with data from an empirical study on the U.S. Chemical industry.

Martinez-de-Albeniz and Simchi-Levi (2005) consider the sourcing problem for commodity products that are supplied by a variety of suppliers as well as a spot market. A multi-period inventory management model with uncertain demand, a supply contract in which the purchasing cost is convex in the purchase quantity, and a spot market is analyzed. The authors specialize the model to consider the case of a portfolio consisting of option contracts and the optimal replenishment policy is characterized for a selected portfolio of option contracts.

11. Future Research Directions

While we have made every effort to consider a rich set of topics thus far in this review, we must concede that we have omitted a great many research streams simply due to the lack of space. However, we would be sorely remiss if we did not at least mention three more emerging areas in the field. Recent months have seen a surge in the efforts of many researchers in the area of risk management related specifically to supply chain disruptions stemming from man-made or natural disasters. (Consider the many presentations on the topic at the Annual meeting of POMS in May 2006.) For some influential work in this area, we refer our readers to Tomlin (2006) and references therein. More attention has been paid to this topic following experiences with hurricanes Katrina and Rita, which hit the gulf coast of the U.S. in 2005. There is also a growing effort to cover topics involving closed loop supply chains (see Flapper et al. 2005 for a recent review). These supply chains typically involve previously sold or produced items which are "looped" back to a manufacturer and used, either partially or completely, to produce new units or models. This work is also related to works in the SCM area which focus on environmental or "green" issues (Rao and Holt 2005). Upcoming issues of *POM* will direct specific focus to each of these topics.

In the limited space which we have remaining, we would like to call attention to a number of areas through a broader style of argumentation. While the breadth of SCM research in *POM* and similar journals is quite impressive and far beyond what we have discussed here, we would like to bring attention to dimensions along which we perceive an opportunity for significant improvement in the near and intermediate term. First and foremost, judging from the plethora of anecdotes about poor service, large inventory levels, and friction between suppliers and manufacturers, it seems quite safe to say that SCM researchers still need to do a better job of packaging the insights derived from SCM research for SCM professionals. This issue itself is multi-dimensional. First, many of the complex decisions rules and contract structures developed in SCM research are simply not comprehensible to most managers. For example, Narayanan and Raman (2005) report that their straw polls of Senior Executives reveal that almost all of them admit that they had not even thought that incentive alignment might be a problem in their supply chains. Apparently, researchers have developed a large literature on coordinating contracts and other mechanisms while many practitioners are yet to even recognize the problem that these contracts seek to address. Narayanan and Raman (2005) also point out that supply chain incentives are often mis-aligned due to issues not easily addressed in contracts, such as hidden efforts which effect supply chain performance, and hidden information which can make contract formulation or enforcement impossible. Unfortunately, even when contract formation is possible it is not clear that researchers have conveyed the significance of contract terms in clear ways that managers understand. We can argue that this is natural in the sense that this research stream is still relatively young and that it takes time for these ideas to filter to the scattered army of SCM professionals. But the glaring inefficiencies which remain in fields such as Health Care, Transportation Logistics, and Disaster Relief demonstrate the great and immediate need for SCM researchers to find better and faster ways to help translate research findings into firm behavior. Applied projects that address implementation difficulties of new supply chain initiatives, and offer creative and well tested ways to overcome them, might deserve publication when well documented and clearly written to demonstrate both understanding of state-of-the art theory and the specifics of their application context.

While the stream of empirical work focused on SCM has grown steadily over the past decade, it still remains insufficiently developed. For example, Chang and Grimm (2006) argue that many of the 40 strategy papers which focus on SCM issues and use secondary data are reporting results from the analysis of data gathered 10 or more years ago. Given the relatively recent emergence of SCM as a discipline and the dynamic nature of the field, findings based on such data must be interpreted with great caution. Again, this is not a criticism of the researchers involved. Rather, it is a recognition that vast opportunities exist in this area because the efforts to gather relevant data which reflects the application of SC improvement efforts are still quite young. Some influential empirical research in the SCM field has recently appeared in Hendricks and Singhal (2005ab) connecting supply chain execution and firm operating and financial performance. Empirical testing of the "bullwhip effect" is currently under study by Cachon, Randall, and Schmidt (2006). Pioneering work on explaining the wide variations in inventory turnover performance, and the link between operational and financial performance in retail operations has recently appeared in Gaur, Fisher, and Raman (2005).

Much research in the academic literature focuses upon single agent problems even though the nature of SCM almost always involves multiple parties. Such focus is often necessary to formulate tractable problems but it may raise concerns about credibility in the minds of some managers who instinctively argue that there is no such thing as a single-agent SCM problem. Chang and Grimm (2006) reports that there are still a relatively small number of empirical studies using dyadic or triadic methodologies. SCM scholars have urged researchers to broaden the context of SCM research from a focal firm to the dyads or the network of firms. However, most strategy research with an inter-organizational context has used data only from a single firm perspective. Of course, on the modeling side there has been an explosion of work addressing the competitive interactions at all levels of the supply chain (suppliers, retailers, etc.). We will avoid replicating what can be found in the superb survey paper by Cachon and Netessine (2003).

Dischinger et al. (2006) argues that the ideal SCM professional must have skills and capabilities in at least 5 major areas including: (1) functional skills in areas such as procurement, demand/supply planning, manufacturing, global logistics, and customer fulfillment; (2) technical skills, particularly in information technology selection, implementation, and application as it relates to SCM issues; (3) leadership skills including communication, negotiation, problem solving, team leadership and project management; (4) global management experience including work outside the home country, and (5) high levels of experience and credibility because virtually all SCM initiatives involve multiple parties and often parties that are not intimately familiar with the qualifications and history of the manager leading the efforts. On one hand, it seems safe to say that we have made great strides in providing tools, insights, and materials which help to convey technical knowledge. On the other hand, it also seems that for these professionals, research findings that downplay the significance of inter-firm relationships and management across functional, national, and corporate boundaries miss the truly "hard part" of SCM.

Arguing that managers are increasingly facing a new supply chain competitive landscape, Christopher (1998) stated that successful SCM must model future—not past—relationships. With this in mind, it seems that managers have a distinct need for research that gives them clues about where SCM is going, rather then lessons about fine-tuning an existing system. Managers want to know how the economic, technological, social, and political forces will serve to shape business and SC practices in the future. Managers also seem to be searching for insights which tell them what types of SC related capabilities can be leveraged for a sustainable advantage, rather then passed along to customers through lower margins. SCM researchers may need to collaborate with researchers in the fields of economics, and strategy to explore the relationships between SCM practices and scale economies. For example, as the approaches to SCM become more sophisticated do they become a barrier to entry, and which practices protect the firm from competition even if they add inefficiencies to the chain. In a related vein, it is important to consider how government regulation or market interactions can lead to the adoption of supply chain behavior that is in the public good, even if it does not benefit any particular firm.

Additionally, there is a clear need to package and interpret lessons from the SCM research to benefit customers and providers in service industries, including health care, and education. It appears that opportunities to apply lessons from SCM research abound. For example the linkages between the huge marketing forces and product delivery efforts in the Pharmaceutical industry involve billions of dollars and related expenditures which seem to grow faster then inflation. Recent years have seen a sharp growth in efforts to model and consider disruptions in supply chains for physical goods, but this problem may be much more acute in service chains because of the inability to store the product at any level of the chain.

Several researchers have argued that practitioners will benefit from more research at the interface of other traditional OM topics. We may be missing glaring research opportunities which are right under our noses if we are not willing to view "old" topics in "new" ways related to supply chain dynamics. For example, Robinson and Malhotra (2005) finds that even though the philosophies of quality management and SCM have been researched extensively in the literature, few studies examine these agendas jointly, and that research about quality management in the supply chain is highly disjointed and lacks treatment as a significant dimension of SCM. They offer a definition of a rarely used term "Supply Chain Quality Management" as "the formal coordination and integration of business processes involving all partner organizations in the supply channel to measure analyze, and continuously improve products, services, and processes in order to create value and achieve satisfaction of intermediate and final customers." They conclude that the establishment of programs and tactics to manage and monitor supply chain quality is a fundamental step towards maximizing the competitiveness and market leadership of supply chains, yet the extant literature does not provide a comprehensive examination of this topic. This work goes on to point out that managers focused on quality need to move away from a product focus to a process focus, and in particular, need help in understanding how to improve processes that cross firm boundaries to improve the performance of the supply chain. They also note that few firms even have measurements and standards which relate to quality from a chain-wide perspective. Basic questions remain unanswered in this area. For example, what performance measures can a supply chain utilize to monitor supply chain processes and their alignment with customer desires?

Finally, a recent stream of literature examines the benefits of RFID technologies in managing supply chains (and it will be featured in a soon to be published Special Issue in POM, which will include: Heese 2007, Ngai et al. 2007, Delen et al. 2007, Barratt and Choi 2007, Karaer and Lee 2007, Amini et al. 2007, and Whitaker et al. 2007). Some research focuses on the application of RFID to retail environments (Gaukler et al. 2004; Karaer and Lee 2007; Lee and Ozer 2005), while other research focuses on the application of RFID to logistics processes (Gaukler et al. 2005) and to manufacturing and assembly operations (Gaukler et al. 2005). Some recent research work in Kouvelis and Li (2006) is pioneering in its study of the value of RFID technologies in obtaining more accurate lead-time information and then using it for smart response strategies in uncertain supply systems. While most of the current research on RFID implications for supply chain management practices has focused on the use of updated demand and inventory information, it is important that research also focuses on understanding how updated lead-time information can be exploited via dynamic response strategies in an effort to better match supply and demand. We believe that a greater focus on lead-time information will have a profound impact on the global supply chain literature and will lead to a better understanding of the sources and value of new information and tracking technologies which allow the dynamic and accurate updating of lead-time information.

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