Quantitative Analysis for Internet-Enabled Supply Chains

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A supply chain, from an operations perspective, has three components: sourcing or procurement, manufacturing and distribution, and inventory disposal. In each component, the Internet is significantly affecting how supply chains are being managed, leading to new challenges while ultimately promising to provide value. The likely future is collaborative supply-chain management that promises to make, for the first time, the dream of virtual integration a reality. Quantitative modeling provides companies decision support as well as insights for better management of supply chains. But there are still a number of challenges that require further OR/MS analysis.
or three months inventory would be at a disadvantage to one keeping only two or three days inventory. Now companies increasingly move toward outsourcing, contract manufacturing, and third-party logistics as short product life cycles and tight profit margins demand minimal inventories. Supply chains today are dynamic, flexible, and responsive webs whether they support standard (for example, catalog or commodity) products, modified-standard (or configurable) products or custom manufactured products [Veeramani, Joshi, and Sharma 1999]. If there is a major change in demand, the chain can respond quickly. The Internet offers high-speed communication and tight connectivity, opens new venues for trade, such as electronic marketplaces, and makes channels, such as auctions and spot markets for capacity, more accessible. By using these channels, firms can dispose of excess inventory or procure needed inventory and build flexible supply chains (or supply webs). The Internet also facilitates collaboration among parts of a supply chain and promises to make the dream of virtual integration a reality by providing a centralized optimal solution in a decentralized world. In fact, the future is most likely to be one of collaborative supply-chain management.

To exploit these new avenues to improve their profitability, companies need both decision-support tools, which provide evaluation of alternatives using OR/MS models, and managerial insights based on models from economics that allow practitioners to think strategically. The urgently needed niche that combines OR/MS tools with economic insights is a substantial value-added service that our community can bring to business practice. The urgency stems from the fact that the fast-paced nature of the Internet economy is hurrying companies to interact with each other in auctions and e-marketplaces. The inefficiencies due to strategic gaming may outweigh the possible benefits of combined optimization, unless the structures of the interactions are designed in a sophisticated manner. We find that even stylized models—simple abstractions that seem like toy exercises—can predict the directions of change and sensitivities to various parameters, provide insights to-
wards possible surprises, and prevent costly mistakes. These models also provide insights into predicting the new supply-chain structures that are forming in different industries due to differences in the rate at which transaction costs are dropping.

In our community, we are ideally situated to use our skills of decision support (where we judiciously model many interactions to resemble reality closely and have sophisticated solution methods for solving the realistic problems quickly) to enhance simple economic models, perhaps by using computational algebra packages, such as Mathematica. By incorporating insights from stylized models in designing decision-support systems and in guiding the structure of interactions in supply chains, we can reduce the inefficiencies inherent in double-marginalization, information asymmetry, variability propagation, and strategic gaming among members of the chains. (When independently managed firms operate the supply chain, conflicts in the interests of these firms may lead to inefficiencies known as double marginalization. Further inefficiencies may arise because firms hold private information which they may not reveal in equilibrium.) Academic economists have already moved forward in the area of business-to-business auction design by partnering with consulting firms (for example, Market Design Inc.).

**New Channels of Distribution**

To achieve supply-chain flexibility, companies increasingly use new Internet-enabled channels in selling both first-run items and excess inventory. In addition to traditional channels, such as selling through distributors, two of the most prominent sales channels on the Internet are direct sales via company Web sites and sales via electronic marketplaces.

**Direct sales.** In the direct sales model, companies usually sell their own products through their own Web sites. Such sites are managed by the supplier, are limited primarily to the supplier's products, and differentiate the supplier's products from others. Multiple competing sites may sell similar products. Among the leaders in direct sales are Dell Computers and Cisco Systems [Magretta 1998]. In 1999, Dell sold $30 million worth of computer gear a day and Cisco handled over 70 percent of its orders through the Web. Companies following the direct sales model execute online various functions, such as order configuration, pricing, order placement, order tracking, and customer service.

**E-marketplaces.** Electronic marketplaces (also called exchanges or e-hubs) aggregate buyers and sellers, creating marketplace liquidity (a critical mass of buyers and sellers) and reducing transaction costs. These marketplaces can focus on specific industries or markets (vertical hubs) or on specific functions or business processes (functional hubs) [Sawhney and Kaplan 1999]. Examples of vertical hubs include Altra Energy for energy, e-Steel for steel, PlasticsNet for plastics, and Sci-Quest.com for life sciences. Examples of functional hubs include BidCom for project management, CarrierPoint for global logistics, and The Return Exchange for reverse logistics.

Electronic marketplaces facilitate any-to-any transactions and distribute market information efficiently. Forrester Research
estimates that online business-to-business transactions in the US will reach $2.7 trillion and transactions via electronic exchanges will account for 53 percent of all online business trade by 2004 [Kafka et al. 2000]. E-marketplaces pool products from different suppliers in one place and buyers can search this integrated catalog more easily than multiple paper catalogs or Web sites. Suppliers gain access to new customers who post requests online (e-orders) and to other companies’ inventory and capacity posted on the Web (e-inventory and e-capacity). The availability of e-orders, e-inventory, and e-capacity, added to a company’s existing customers, inventory, and capacity, provides it with opportunities for improving its efficiency. For example, to supply large or difficult orders that do not fit into their production schedules, manufacturers can buy inventory or capacity from other suppliers through these exchanges. Some suppliers may want to sell directly to their primary customers and use e-marketplaces to sell excess inventory or capacity.

**Decision support needs for e-marketplaces.** Based on their internal information about demand, inventory levels, and so forth, and the information they gather from an e-marketplace, companies will make decisions about what to sell, what to buy, and what to promote [Keskinocak et al. 1999]. These decisions require a firm to match supply and demand to meet its objectives. Demand includes orders, forecasts, requests for quotes (RFQs), and requests posted on the Internet. Internet demand may be posted via e-marketplaces or be sent directly via e-mail or electronic data interchange (EDI) documents. Supply includes a company’s own inventory and capacity as well as e-inventory and e-capacity. While making these decisions, companies will need decision support in at least two areas: identifying potential matches and deciding on which subset of the potential matches to execute.

As an example, consider an e-marketplace for paper products and the manufacturers participating in this marketplace who make paper with various characteristics. One manufacturer is looking for potential orders to match its available capacity to produce seven 2,300 mm-wide paper rolls. One customer posted an order for four 400 mm rolls and another posted an order for 15 600 mm rolls. If these orders match the manufacturer’s capacity in all attributes other than width, then a 2,300 mm roll can be cut to produce one 400 mm roll and three 600 mm rolls with 100 mm wasted. In this match, four of the supplier’s 2,300 mm rolls are simultaneously matched to two orders, filling the first order (for four 400 mm rolls) and partially filling the second order (12 out of 15 600 mm rolls). If a supply is converted to satisfy multiple demands simultaneously, as in this example, the corresponding match carries information about the conversion equipment and the conversion ratio (the fraction of the matched supply quantity used by the demand items). In this example, the conversion equipment is a rewinder and the conversion ratio is
When creating matches with product transformations, one needs to consider numerous alternatives to maximize efficiencies and thereby to minimize conversion costs and waste.

Another possibility is to assign the supplier's capacity to multiple orders by allocating partial quantities. The supplier with available capacity (or inventory) for seven 2,300 mm rolls can consider an order for three 2,300 mm rolls and another for 11 2,300 mm rolls. If the supplier's capacity matches these orders in all attributes, then the supplier could use three rolls to fill the first order and partially fill the second order with the remaining four rolls. In this case, one supplier's capacity is matched to two different orders. Similarly, it is possible to have matches with two or more suppliers and a single order, if no one supplier can fill the order on time.

Identifying such advanced matches, which include more than one buyer and more than one supplier and possibly conversion, requires more than the simple catalog-search mechanisms available in most marketplaces today. IBM has developed a decision-support system that recommends good matches to buyers and sellers who expand their supply chains by participating in e-marketplaces or by connecting to other buyer and seller sites via the Internet. Currently, the decision-support system is under testing within an e-marketplace for paper products [Keskinozak et al. 1999].

Once potential one-to-one and multiway matches are identified, companies need to decide which subset of these matches to execute. The resulting matches will suggest which orders a company should satisfy from its own inventory and capacity, which orders to outsource using e-inventory and e-capacity, and which orders to satisfy using a combination of inventory, e-inventory, capacity, and e-capacity, what inventory and capacity to sell, and what promotions to send to which customers. Buying inventory or capacity to supply orders and forecasted orders may be advantageous because of current production constraints and may increase the manufacturer's profits. In deciding to sell capacity, the firm makes a complex trade-off between maintaining flexibility so that it can use capacity for the most profitable types of production and making sure capacity does not go unused. This problem is similar to the yield-management problem in which airlines sell seats on planes with various restrictions at various times for different prices.

Manufacturers have the added complication that they can outsource orders or partial orders. A decision-support system for deciding what to sell could recommend what types of inventory and capacity to offer, to whom, for what price, with what restrictions, and when. In addition to offering inventory or raw capacity for sale, a manufacturer can push sales of profitable products via promotions. Since it can use capacity to make different items, it should limit each promotion to items of interest to a customer. A decision-support system that matches supply with hypothesized demand can assist a firm in deciding what products to promote simultaneously (since there may be substitutes or complements) and how to price them.

E-marketplaces as central coordinators.

By combining its internal information
about its own demand, inventory, and capacity with the partial information it gathers from the e-marketplace on other companies’ demand and capacity, a buyer or a supplier can play matchmaker in finding good matches to satisfy its needs. For example, a decision-support system hosted on a manufacturer’s Web site can help the manufacturer to develop an order-fulfillment plan taking into account the manufacturer’s internal production capabilities, costs, internal demand, and orders posted on an e-marketplace. However, good-quality one-to-one matches may not exist, and it might be necessary to combine multiple supplies to match one demand or to split a supply to match multiple demands. To help companies achieve

It remains to be seen how much internal information companies will share.

production economies of scale and scope, the e-marketplace could play the coordinator or matchmaker and suggest matches by taking orders from buyers and assigning them to producers to satisfy the buyer’s preferences and minimize the related costs (such as production and distribution costs). In creating these matches, the coordinator could split and combine buyer orders into intermediary orders to reduce producers’ setup efforts and increase their efficiency by narrowing the range of characteristics in the orders assigned to each producer.

For example, consider two neighboring manufacturers S1 and S2 that both produce two products P1 and P2 and supply them to two customers A and B. If each of these manufacturers has a single production line and the setups are costly and time consuming, it might be advantageous for them to partially exchange the orders of these customers. Assuming that the order values of the customers for the two products are the same, in an alternative matching of suppliers to orders, S1 would produce only P1 and S2 would produce only P2, each satisfying the demands of both customers for one product. Although S1 and S2 might not want to share production and customer information with each other, they might be willing to do so with an independent intermediary, such as an e-marketplace, which would function as coordinator.

In addition to helping companies achieve manufacturing efficiencies, e-marketplaces can also act as independent intermediaries in helping companies to coordinate their shipments and to save on transportation cost. As manufacturers move towards just-in-time production to reduce inventory costs and risks, they expect smaller and more frequent shipments from their suppliers. Since some shipping costs are fixed (for example, fuel and driver costs are essentially the same whether the truck is only half full or completely full), geographically close companies may find it profitable to consolidate their shipments, possibly via e-marketplaces that provide consolidation services. Some intermediaries already provide consolidation and capacity-trading opportunities for shippers and carriers, and at least 20 companies have announced plans to offer domestic transportation-exchange services [McCullough, Temkin, and Howard 1999].

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To help companies make globally optimal decisions, the coordinator would need information about production capabilities, production schedules, costs, and orders from both buyers and sellers who participated in the marketplace, information they might not want to share with their competitors. Hence, the coordinator would need to be an independent, trustworthy entity who would keep information confidential and would use it to benefit all parties and not use it to give some parties an advantage over others. More realistically, decisions would be based on posted prices (which could be dynamically updated by the various entities) or prices revealed by auctions as proxies for costs as is done now, leaving the strategic choice of pricing to each supplier. The coordinator should also ensure the parties involved share the gains from such a coordination fairly. Although companies increasingly move towards sharing information through such initiatives as CPFR (collaborative planning, forecasting, and replenishment), it remains to be seen how much internal information companies will share with their supply-chain partners or third-party independent intermediaries. For example, GM, Ford, and DaimlerChrysler announced the development of a joint exchange called Covisint for procurement, supply-chain management, and collaborative product development, but to achieve these goals, they must overcome the cultural factors inhibiting collaboration.

We provide a linear-programming model that takes into account potential synergies from combining and splitting orders, assuming that an independent intermediary knows the production costs and capacities of the suppliers, demands of the buyers, and the transportation costs (online appendix). Such a model could help a coordinator to create efficient matches between demands and supplies.

Although the number of e-marketplaces and participating companies is increasing rapidly, decision-support technology to help buyers and sellers use these new channels effectively is still in its infancy. We present these issues as challenges to practitioners and analysts.

Auctions

In addition to selling items based on posted prices, a mechanism that is being used by many companies, both on company Web sites and electronic marketplaces, is auctions. Auctions have explicit rules determining resource allocation and prices based on bids from the market participants [McAfee and McMillan 1987]. The use of auctions for exchanging goods, such as artwork, antiques, agricultural produce, mineral rights, US treasury bills, corporations, and gold, has a long history. With the advance of Internet technology, the use of auctions for exchanging goods among and between individuals and companies has increased significantly in recent years. For example, AuctionNet and BidFind list hundreds of sites with auctions.

Internet auctions have several benefits compared to traditional auctions, including lower information, transaction, and participation costs; increased convenience; ability for asynchronous bidding; and access to larger markets [Lucking-Reiley 2000]. Hence, companies increasingly use Internet auctions to buy and sell excess inventory, first-run goods and commodities, to test prices for new consumer goods, to
market one to one, to fine-tune inventory levels, to bypass existing links in the supply chain, and to gain access to new markets.

Currently, there are two types of online business-to-business auctions: third-party auction services, which allow companies to sell in e-marketplaces, and private auctions, which companies build on their own extranets to serve their dealers or customers. Examples of private auctions include the auction-block site of Ingram Micro and Grainger Auction. Grainger Auction lists about $5 million in inventory, including daily specials, discontinued products, and other items Grainger no longer carries in its catalog. Ingram Micro’s auction-block site enables a real-time auction for more than 10,000 authorized bidders to place bids on excess inventory (including discontinued and refurbished products). Ingram Micro formerly used phone calls and faxes to collect sales leads on excess inventory that could not be returned to manufacturers and then sold its final surplus to liquidation firms in large inexpensive blocks. Using auctions, Ingram significantly increased its revenue from excess inventory sales [Murphy 1998]. Independent trading sites that hold auctions include ChemicalBid, FastParts, MetalSite, and TradeOut. Although current auction sites focus mainly on selling excess inventory, industry analysts estimate that online business auctions will routinely carry first-run products in the future and that their volume will exceed half a trillion dollars by 2004.

Commonly used auction formats on the Internet include first-price (English) auctions (with variations on minimum bids, reserve prices, and buyout prices), first- or second-price sealed-bid auctions, Dutch auctions (FairMarket, Reverse-Auction.com), and continuous-trading double auctions (FastParts, LabX). Multiunit auction mechanisms include different auction rules, such as the discriminatory pay-your-bid rule (Onsale, uBid) and the uniform-price rule (OpenIPO auctions of WR Hambrecht + Co). Klemperer [1999] and McAfee and McMillan [1987] provide an introduction and comprehensive review of auctions.

**Modeling bidding behavior.** Several issues need to be considered while designing or participating in an auction. The rich literature on auctions covers some but not all aspects of Internet auctions. For example, before the Internet, it was practically impossible to sell airline tickets to individuals via auctions. Moreover, since the Internet allows simultaneous access to multiple auctions, questions concerning the duration of auctions or bidding strategies in competing auctions are more pertinent.

Most business-to-business Internet auctions handle excess inventory and hence use multiunit auction mechanisms. (Most of the existing auction literature concerns single-unit auctions or multiple-unit auctions in which each bidder wants at most one unit.) Examples of auction sites that host multiunit auctions include FairMarket and OpenIPO.

FairMarket’s AutoMarkdown mechanism is essentially a multiunit Dutch (or decreasing price) auction, in which a seller posts a group of items for an opening price, say, $80 per item, and buyers bid the quantities they want at that price. Af-
ter some time, say two days, the price drops to, say, $60 per item. After more time, the price drops again. The markdowns continue until all items are sold or the price hits the floor set by the seller. This is an example of a discriminatory pay-your-bid rule with buyers paying different prices depending on when they bid. In contrast, OpenIPO, which conducts initial public offerings of corporate stock through sealed bid multiunit auctions, applies the uniform-price rule and charges the amount of the lowest accepted per-share bid to all winning bidders. To choose the winning bidders and the price they will pay, the auctioneer orders all bids in decreasing order of price and assigns each bidder the minimum amount available or the bid quantity. (The winning bidder with the lowest bid price may receive less than his or her bid quantity.) All the winning bidders pay the price of the lowest accepted bid. In the special case in which each bidder wants only one unit, the seller’s expected revenues in uniform- and discriminatory-price auctions are equal. (This is an extension of the revenue equivalence theorem for single-unit auctions, which states that the ascending, the descending, the first-price sealed-bid, and the second-price sealed-bid auctions yield the same expected revenue under certain conditions [Myerson 1981; Vickrey 1961].) However, if bidders demand multiple units, Ausubel and Cramton [1998] show that the ranking of these two auction types in terms of revenue maximization and allocative efficiency is ambiguous and critically depends on the underlying demand structure.

The auction mechanism used by Fair-
as his marginal surplus in the second step, then that bidder should bid all his demand in the first step. In an alternative model, the price in the first step of the auction could be higher than the valuation of one of the buyers. By setting prices in this way the seller can obtain high revenue from one buyer but leave the other buyer out of the competition in the first step. In this case, the optimal bidding strategy for the buyer with the higher valuation, say bidder 1, is the following: If the marginal surplus of bidder 1 in the first step is too small, bidder 1 will wait for step 2, risking the total amount he can purchase. Otherwise, bidder 1 will bid his total demand in step 1. How should the seller set prices in the different steps to maximize revenue? In a two-step auction, the optimal price in the second step is slightly less than the valuation of bidder 2. Using the optimal bid quantity for bidder 1 in step 1, Elmaghraby, Gülçü, and Keskinocak [2000] found a closed-form solution for the optimal price in the first step of the auction.

The design of auctions and bidders’ behavior in real life can be a lot more complex than what stylized models capture. However, stylized OR/MS models can still be very useful for their insights about how the interaction of auction parameters affects bidding behavior and the revenues of the buyers and the seller. As e-commerce grows, so will the need for such models. Soon individuals and companies may use software agents not only to search for best prices but also to place bids in online auctions and to negotiate. For example, the proxy bidding mechanism of eBay acts as a bidder agent, although not an intelligent one, by automatically increasing the bidder’s bid in small amounts as soon as the bidder is outbid, until the maximum amount set by the bidder is reached. The objective of this agent is to reduce the transaction cost of monitoring the status of the auction. Kasbah [Chavez and Maes 1996] is an agent-mediated marketplace developed by researchers at MIT’s Media Lab, in which human users delegate the responsibility for buying or selling physical goods to agents that engage in one-on-one negotiations with other agents. Park, Durfee, and Birmingham [1998] have studied the use of Markov modeling to create successful bidding strategies for agents participating in a continuous double auction. We are not aware of any intelligent agents currently used in practice that employ complex bidding strategies autonomously, but today’s simple agents are a first step towards the implementation of more sophisticated bidding agents.

**Multiunit auctions.** As in OpenIPO auctions, most multiunit auctions on the Internet assume that a buyer who bids for $x$ units is willing to accept any number of units less than $x$. However, this may not be true for business-to-business sales. A buyer who needs $x$ units may want to buy all of them from one source for various reasons, for example, to obtain uniform quality, to save on transportation cost, or to simplify order tracking.

To understand how a standard ascending-price multiunit auction may inconvenience buyers (or sellers), consider the following example with three bidders and four units of product P for sale. Bidders A and B submit the following de-
mand curve: two units for $8 or less, one unit between $9 and $10. Bidder C is a manufacturer who wants to buy multiple units of product P to make product Q. Bidder C’s setup cost for production is $22, unit cost of production is $30, and selling price is $45. Bidder C’s profit on x units bought at the auction would be $15x – 22 – p(x), where p(x) is the price paid for x units.

To make a profit, C wants to buy at least two units or none, paying a maximum unit price of $3 for two units, $7 for three units, and $9 for four units.

Suppose the auction proceeds as follows:

<table>
<thead>
<tr>
<th>Units demanded at the current price</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
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<tbody>
<tr>
<td>Price</td>
<td>4</td>
<td>2</td>
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<td>7</td>
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<td>?</td>
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Having clinched two units at $9, C will lose money for any bid in the last stage (when price equals $10). C bid $9 assuming she could get four units, not two. If C knew the private values of A and B, then C would bid differently and drop out earlier. If C dropped out earlier (after $4), then A and B would each get two units at $7. The seller’s revenue would then be only $28 instead of the $36 C would have paid for four units.

A similar situation could occur in a procurement auction with a bidder, for example, a manufacturer, offering a price that depended on selling some quantity, considering economies of scale. If the auctioneer accepted only part of that quantity at the seller’s bid price per unit, providing the partial quantity might not be profitable for the seller.

To remedy the problems with partially accepted bids, the auctioneer could use an alternative mechanism and ask each bidder to submit a demand schedule of quantity and price pairs (q_i, p_i). The auctioneer could then choose a subset of these bids to maximize the seller’s profits and assign winning bidders their total desired quantities without exceeding the available quantity. More formally, if S is the set of bidders who each submitted a bid, we would like to choose a subset of the bidders S’ ⊆ S such that ∑_{i ∈ S’} p_i q_i is maximized and ∑_{i ∈ S’} q_i does not exceed the total available quantity. Unfortunately, the seller’s resulting revenue might be considerably lower than what could be obtained by splitting the quantity of a bid. (The auctioneer could also add incentive compatibility constraints to ensure truth telling at optimality. In an incentive-compatible mechanism, an agent has an incentive to reveal its true type, for example, how much it values an item, and not to misrepresent itself as another type.)

An alternative approach for multunit auctions is to use sequential auctions with a single winner in each auction. FreeMarkets uses this approach for procurement auctions. In this format, a buyer announces that he or she wants to procure K units of an item in a sequence of auctions. During each auction j, the bidders bid only a price, and the bidder with the lowest price wins the auction and provides the buyer a quantity Q ≤ K_j, where K_j is...
the amount left to be procured at the \( j \)th auction. \( Q \) might be limited by the capacity of the bidder and might be smaller than \( K_j \). A winning bidder cannot participate in the remaining auctions. In this format, bidders know the exact amount they can sell at the \( j \)th auction (if they win), so they can choose their bid prices considering potential economies of scale. Bidders also see other bidders' offers. One drawback of this mechanism is that it might not result in the lowest cost procurement alternative for the buyer. For example, suppose at step \( j \) of the auction seller \( A \) could provide \( K_j = 100 \) units for as low as \$10 per unit, whereas the lowest bid placed by bidders other than \( A \) is \$15 per unit. If no other seller can go below \$15 per unit, then seller \( A \) can win the auction at, say \$14.99 per unit, costing the buyer an extra \$499. Other strategic behaviors need to be explored, and it is not clear whether this mechanism leads to efficient allocation.

There is an urgent need to determine whether such standard auction formats work in business-to-business situations.

Designing and bidding in multiunit auctions can also be quite complex if multiple nonidentical items are auctioned off and if there are potential complementarities between the items. Two items are called complements (have superadditive value or exhibit synergies) when their combined value is larger than the sum of their independent values. More formally, if a bidder has values \( v(x) \) and \( v(y) \) for two items \( x \) and \( y \) and value \( v(x + y) \) for the two items combined, then \( v(x + y) > v(x) + v(y) \) if \( x \) and \( y \) are complements. For example, in FCC auctions for distributing spectrum licenses, some bidders may have superadditive values for certain combinations of licenses because of the synergies arising from owning licenses in adjoining geographical areas [Krishna and Rosenthal 1996; Ledyard et al. 1999; Milgrom 2000]. Similarly, in transportation bidding it may be beneficial for a carrier to win bids on a group of continuous lanes, which don't require empty travel between them.

One approach for auctioning off multiple nonidentical units with complementarities is to allow combinational or package bids, where a bidder may submit a bid for a group of items and wins either all or none of them. Such combinatorial auctions allow bidders to incorporate their synergies into their bids. While this benefits the bidders, the auctioneer's problem of finding the best set of winning bids is computationally very difficult. Rothkopf, Pekec, and Harstad [1998] discuss some of these difficulties and identify several different structures of combinational bids that result in a computationally tractable problem for the auctioneer. Kelly and Steinberg [2000] describe a combinatorial auction mechanism that presents the auctioneer with a tractable bid-evaluation problem.

A successful application of combinatorial bidding comes from The Home Depot, Inc., which has recently used this mechanism for contracting carrier capacity [Elmaghraby and Keskinocak 2000]. Before the bidding process begins, Home Depot provides potential bidders with information on origin and destination locations (for example, retail stores, supplier locations, or distribution centers), lane details, and demand forecasts. A lane is a unique origin-destination pair requiring a specific
type of service and equipment. Lanes can be point-to-point (for example, vendor to DC), point-to-zone (for example, DC to cluster of stores), zone-to-point (for example, cluster of vendors to DC), or zone-to-zone (for example, cluster of vendors to cluster of stores). For each lane, Home Depot specifies the origin and destination, average route distance, average number of stops, demand forecast, equipment requirements, and service requirements.

Given this information, carriers prepare bids, which may include combinations of lanes as well as individual lanes. In addition, carriers may specify constraints on available capacity (for example, maximum amount of business awarded in a geographic area), or submit conditional bids (for example, a carrier may submit two combinations C1 and C2 and request that at most one of C1 and C2 be awarded). Home Depot can also impose restrictions on winning bids, such as the maximum number of carriers that are awarded freight across the entire network. After collecting the bids, Home Depot uses linear integer programming to select a subset of these bids that best satisfies its needs.

Home Depot currently uses combinatorial bidding for truckload shipments and is expanding it to less-than-truckload shipments.

Creating bundles is another approach for auctioning off multiple nonidentical units with complementarities. In this case, the auctioneer has to decide on how to group multiple units into bundles and on the right combination of different size bundles. These decisions will affect what type of bidders will submit bids. For example, if the bundles are too large (in quantity or value), small businesses may not bid and if the bundles are too small, large companies may not be interested. This is in essence the key problem that FreeMarkets solves as a buyer-centric auctioneer attracting suppliers to bid. Consider a situation in which a buyer wants to source $M$ items across $T$ periods in one auction. One way of bundling is across items within one period (period-wise bundling); thus, there are $T$ bundles being auctioned. Another extreme is to bundle by item, that is, to create $M$ bundles, with each bundle covering all periods (duration bundling). Numerous bundling strategies exist; FreeMarkets chooses one and the suppliers then place bids.

Stylized examples given by Elmaghraby [2000] illustrate the importance of bundling decisions by showing that certain auction formats, such as period-wise bundling, cannot guarantee efficient allocation; that is, as the auction is run, the equilibrium strategy does not guarantee that the lowest-cost producer will post the lowest price. Period-wise bundling may create severe inefficiencies because some suppliers may choose not to participate and the strategic behavior of participating suppliers may distort the prices so that the contract goes to a costly producer. However, duration bundling guarantees efficient allocation. This is an example of how stylized economic models can guide auctioneers in bundling decisions by reducing the number of alternatives that need to be considered; however, the actual choice also requires the consideration of capacity and quality and so requires the use of decision support. FreeMarkets currently uses data from its large supply base to deter-
mine the bundling structure, using OR/MS algorithms.

**Simultaneous auctions and negotiations.** The Internet allows buyers and sellers to conduct or participate in multiple simultaneous auctions for identical or similar products. The implications of buying or selling simultaneously at multiple auction sites are not clear. If a seller has multiple units for sale, should she auction off all of them in one place, or should she run simultaneous auctions for fractions of the total quantity? If a seller is running multiple auctions, should she inform the bidders about these auctions, or is she better off if some bidders know about only one or very few of the auctions? For a buyer, what is the best bidding strategy on items being auctioned at multiple auctions simultaneously?

In addition to posted prices and auctions, a growing number of e-marketplaces also support negotiations. For example, at ChemConnect, a seller starts with an initial price, and a buyer places a bid. If the buyer’s bid is lower than the seller’s initial price, the seller can place a counterbid that is between the original price and the buyer’s bid. How should a seller or a buyer enter counterbids in a negotiation environment? The answers to such questions are not known beyond simple models dealing with a small number of units and a small number of players [Tirole 1988].

**Channel conflicts.** Auctions impact supply chains by allowing anonymous buyers to sidestep established channels and end users to compete directly with dealers. This might cause the suppliers to reroute their products to private auctions to protect their channels. OpenWebs is one company that operates private auctions in the tire industry, connecting buyers and manufacturers, such as Michelin and Dunlop. Tire distributors also participate in these auctions as they try to protect their position in the supply chain and avoid the inevitable supply chain compression that could lead to their obsolescence. Quantitative modeling and analysis can shed light on these problems, and strategic management firms are working out some likely scenarios.

**Spot Markets for Capacity**

Increasingly, manufacturing firms are moving to quick-response production, rather than relying on forecasts for production and then worrying about stockouts and excess inventory. Such firms usually design their products for late customization, and once they have orders, they purchase finishing capacity, which they sometimes reserve in advance. The emerging practice of purchasing capacity in diverse areas of manufacturing is a reaction to shrinking margins, the near-commoditization of products allowing easy substitution, increased uncertainty in demand (as the market base becomes more fragmented), and the shortening of product life cycles.

The Internet opens new venues for companies to access capacity spot markets easily, for example, via electronic marketplaces and private extranets. After most of the uncertainty about the state of the market is resolved, manufacturers can turn to these spot markets if necessary. For example, CarrierPoint provides a spot market for truck capacity; in the natural gas industry, Streamline.com provides a spot
market for pipeline capacity; in the pulp and paper industry, buyers, manufacturers or converters of paper products participate in electronic marketplaces to buy and sell inventory or capacity through an integrated catalog or through auctions. Manufacturers often compete in the same end-consumer market (for example, manufacturers in the injection-molding industry compete for plastic parts), making the supply-side competition even more critical. A manufacturer of customized products is especially likely to use different options for capacity purchasing, because the demand is possibly unexpected over a vast array of choices and owning the capacity for satisfying different types of demand might be too costly. The practice of purchasing capacity is most prevalent in the semiconductor industry where foundries—as the manufacturing fabs (fabricants) are called—supply capacity to fabless manufacturers that are basically chip-design companies [Brown and Lee 1997]. While any set of five engineers can set up a fabless manufacturing company (and there are hundreds of these firms in Silicon Valley alone), a manufacturing fab typically costs over $500 million.

Although participation in Internet-enabled spot markets is growing rapidly, the implications of capacity availability in the spot market are not well understood. Several questions on the benefits of spot markets for capacity and their effects on competition, on supplier or manufacturer profitability, and on the prices to the end consumer still have to be answered. Also, firms need to trade off the benefits of spot markets for managing uncertainties in demand and the additional uncertainties spot markets may cause, such as incomplete knowledge about the products or participants in the market and pending bids.

When does a spot market help improve channel efficiency? Erhun, Keskinocak, and Tayur [2000] studied buyer and supplier behavior in capacity reservation and spot bidding to examine the benefits of spot markets. They considered a simple stylized model with one supplier who sells to one manufacturer. The manufacturer uses the supplies to make final products whose price decreases as their availability in the market increases. The manufacturer can reserve supplies (or supplier’s capacity) in advance, or buy later in the spot market. Consider the following two models: (1) the supplier announces the wholesale prices for reservation and for the spot market in advance; and (2) the supplier announces the reservation price first, and after the manufacturer makes a decision regarding reservation, announces the spot-market price. In the first model, the supplier commits to wholesale prices in advance, and adding the spot market does not increase the profits of either the supplier or the manufacturer. However, the spot market positively affects the supply chain in the second model (when the capacity is not binding), where the supplier’s profit increases by 12.5 percent and the manufacturer’s profit increases by 18.75 percent. Moreover, the market price of the product decreases by 8.33 percent. Hence, in the second scenario the spot market increases the overall efficiency of the supply chain, and all parties benefit. (In the online appendix, we provide further details of these models, present opti-
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Figure 2: As the number of periods increases, the total quantity increases and the market price of the product decreases.

Figure 3: The top point on the vertical line corresponds to the reservation price, and the bottom one corresponds to the last spot-market price. As the number of periods for spot markets increases, the last spot market’s price decreases.

ormal strategies for the supplier and the manufacturer, provide a partial proof of some of the results, and present a simple numerical example.)

An interesting question is the impact of spot markets on supply-chain efficiency as the number of periods for potential spot markets increases (Figures 2 and 3). As the number of periods for spot markets increases, the reservation price increases, the last spot market’s price decreases and the manufacturer buys more capacity towards the end of the game. The decrease in the last spot market’s price dominated the in-
crease in reservation price, and hence the marginal cost of the manufacturer decreases and the manufacturer is not affected by the increase in the reservation price. Each additional period increases the total quantity produced and the efficiency of the supply chain.

When can spot markets help buyers hedge against uncertainty? If the demand is stochastic, uncertainty creates an option value as the manufacturer retains flexibility by delaying investment or output decisions until after uncertainty is resolved. The manufacturer must trade off the value of flexibility against the strategic value of early commitment. Spencer and Brander [1992] considered several strategic duopoly settings and showed that high levels of uncertainty lead firms to delay deciding on output until after uncertainty is resolved, and low levels of uncertainty lead firms to commit output before uncertainty is resolved. If the uncertainty is low but positive, firms are trapped in a prisoner’s dilemma (online appendix).

Collaborative Supply-Chain Management

With the goals of reducing inefficiencies in supply chains (which result in excess inventories and unproductive activities and assets) and increasing responsiveness to consumer demand, companies increasingly consider collaborating with trading partners. The first step in collaboration is information sharing or data exchange. For example, through its RetailLink system, Wal-Mart allows its suppliers access to sales data. In the next step, information is not only exchanged, but it is also jointly developed through the collaboration of supply-chain partners. Generally this in-
formation deals with future product plans and needs. For example, in the case of working collaboratively on consumer requirements, trading partners might work jointly on new product designs and consumer demand forecasts. Working collaboratively to match supply and demand might involve trading partners jointly deciding how many and when products will be produced to meet expected consumer demand [Lapide 1998].

Enterprise resource planning (ERP) systems (from Oracle and SAP, for example) provide a backbone for data storage and transaction tracking, and help to standardize data formats and to create a discipline for collecting and updating data. The current software offerings in execution software (termed supply-chain execution, SCE) from i2 Technologies, Manugistics, and SAP are a layer on top of the ERP systems. Combining these existing technologies with new Internet technologies, companies will now be able to collaborate in managing their supply chains (Figure 4).

While the companies selling the execution systems market their products and services as optimization, their software usually does not provide optimal solutions. First, within their narrow scope of implementation, inside a factory, for example, neither SAP-APO from SAP nor Factory Planner from i2 Technologies considers lot-sizing decisions (which are complex nonlinear optimization problems) in a sophisticated manner, and both provide only heuristic solutions to capacity management and scheduling problems. The latter part is perhaps unavoidable given the computational difficulty of scheduling problems; however, the heuristics are not very sophisticated and these products could be called feasibility studies rather than optimization. Ignoring the lot sizing—which the software leaves to the client to work out—or suggesting economic-order-quantity (EOQ) lot sizes can lead to solutions so far from optimality as to compromise the entire value of the scheduling. As competition in this space intensifies and customers become better educated, we can hope that the demand for more sophistication will lead to better products (using OR/MS tools already in place). In fact, i2 Technologies' purchase of IBM's Franz-Edelman-Prize-winning Asset Management Tool (AMT) is a good start [Lin et al. 2000].

Optimality is also lost when each piece of execution software works nearly in ignorance of other data and execution decisions in the supply chain. The Internet can close this gap and is rapidly doing so. Companies are creating visibility across the supply chain by using, for example, Ariba software, and the alliance of i2 Technologies, IBM, and Ariba is a wonderful step towards closing the gap. Aware of these developments and others, boutique start-ups are providing focused solutions (with rapid deployment over the Web) as

![Figure 4: New Internet technologies enable supply-chain collaboration.](image-url)
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application service providers (ASPs) and thus are closing additional gaps in functionality that exist today.

The dream of virtual integration—the ability to obtain the equivalent of centralized optimal solutions in a decentralized world—is becoming a reality as supply-chain collaboration matures. The ASPs allow rapid deployment of solutions, and the standardization, due to XML extensible markup language and other technologies, allows simple plug and play between ERP and tactical-planning ASPs, and between tactical-planning ASPs and execution software. Thus, several companies with internal ERP and execution software can collaborate through the ASPs and through Ariba-enabled portals in electronic marketplaces. The future will perhaps not be focused on the competition between companies (yesterday), nor on the competition between supply chains (today), but on the competition between dynamic supply webs based on collaboration [Lapide 1998].

**Conclusion**

Newly available channels for building electronic supply chains promise benefits and pose new challenges for businesses. The increase in connectivity and in access to numerous information sources tremendously increases the number of alternatives firms need to consider in making decisions. To take full advantage of the opportunities the Internet offers, companies must respond quickly to opportunities as they arise and make smart decisions based on the vast amount of data now available. By developing new decision-support tools using operations-research techniques and obtaining insights from new stylized models in economics, the OR/MS community can add great value to industry and be part of the Internet revolution.

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**Online References**

Underlined terms in the paper indicate online references.

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AuctionNet (www.auction.net)
BidCom (www.bidcom.com)
BidFind (www.vsn.net/af/af-list.html)
CarrierPoint (www.carrierpoint.com)
ChemConnect (www.chemconnect.com)
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