Applications of flexible pricing in business-to-business electronic commerce

by M. Bichler
J. Kalagnanam
K. Katircioglu
A. J. King
R. D. Lawrence
H. S. Lee
G. Y. Lin
Y. Lu

The increasingly dynamic nature of business-to-business electronic commerce has produced a recent shift away from fixed pricing and toward flexible pricing. Flexible pricing, as defined here, includes both differential pricing, in which different buyers may receive different prices based on expected valuations, and dynamic-pricing mechanisms, such as auctions, where prices and conditions are based on bids by market participants. In this paper we survey ongoing work in flexible pricing in the context of the supply chain, including revenue management, procurement, and supply-chain coordination. We review negotiation mechanisms for procurement, including optimization approaches to the evaluation of complex, multidimensional bids. We also discuss several applications of flexible pricing on the sell side, including pricing strategies for response to requests for quotes, dynamic pricing in a reverse logistics application, and pricing in the emerging area of hosted applications services. We conclude with a discussion of future research directions in this rapidly growing area.

For centuries, businesses used negotiations and bartering as a matter of routine. The industrial age saw the emergence of mass production and extended distribution chains, which made face-to-face negotiations with each customer impractical. Fixed prices became necessary to manage the enormous growth in both the volume and the variety of products, distributed over larger geographic regions.[1] The advent of the Internet and electronic commerce has greatly impacted the way businesses price their goods and services, and has allowed for more flexible pricing based on customer characteristics or dynamically determined based on supply and demand.

Two trends in electronic commerce are causing this shift from fixed to dynamic pricing. First, the Internet has reduced the transaction costs associated with dynamic pricing by eliminating the need for people to be physically present in time and space to participate in a market. The menu costs are also considerably reduced. Whereas in the physical world changing a price incurs huge costs, the same task in electronic commerce is reduced to a database update. Second, price uncertainty and demand volatility have risen and the Internet has increased the number of customers, competitors, and the amount and timeliness of information. In addition, the increased use of flexible pricing itself leads to increased price uncertainty. Businesses are finding that using a single fixed price in these volatile Internet markets is often ineffective and inefficient.

Differential pricing. Electronic markets can reduce customers' costs for obtaining information about prices and product offerings from alternative suppliers. They can also reduce these suppliers' costs for communicating information about prices and product characteristics to customers. This has implications for the efficiency of an economy in terms of the search costs experienced by buyers and their ability to locate appropriate sellers.[2] Electronic catalogs were the first step in this direction. Over the past few years, companies have put their product catalogs on the Web, in order to make them widely available. Most electronic catalogs are comprised of fixed offers in the form of fixed list prices. Search engines and shopping bots (robots) make it easy for customers to compare these offers. In particular, standardized goods are subject to price wars and strong brands often become commoditized. Researchers in agent-based computational economics have analyzed these developments using computer simulations.[3] MySimon (http://www.mysimon.com) or DealTime (http://www.dealtime.com) provide real-world examples for this new kind of competition.

Many economists see product and price differentiation as a solution to this "over-commoditization." *Product differentiation* can be accomplished by adding additional attributes (e.g., service agreements) or by generalizing existing attributes (e.g., flexibility in terms and conditions). By differentiating products, suppliers can decrease the substitutability of their products and services and customize offers to the requirements of specific consumers or market segments. The more successful a company is at differentiating its products from those of others, the more monopoly power it has—that is, the less elastic the demand curve for the product is. In such markets (often referred to as monopolistic competition), it is possible for providers to extract consumer surplus even from consumers who have perfect price information. Often, suppliers use mechanisms such as personalization, targeted promotions, and loyalty programs in order to distinguish their products from those of their competitors and establish customer relationships.

Impeding price comparison basically means reintroducing search costs.[4,5] This can also be achieved by charging different prices to different consumers for the same product. *Price differentiation*[6] is achieved by exploiting differences in consumer valuations, such as volume discounts and group pricing (e.g., senior citizen discounts). This discrimination strategy requires detailed consumer information and independent billing and is also described as third-degree price differentiation. Second-degree price differentiation (or "nonlinear pricing") means that the producer sells different units of output for different prices, but every individual who buys the same amount of the product pays the same price (i.e., quantity discounts and premiums). Finally, first-degree or "perfect" price differentiation means a producer sells different units of output for different prices and the prices may differ from person to person.

Airlines are often cited as pioneers in differential pricing. Airline pricing can actually be seen as an example of both price discrimination (e.g., frequent fliers) and product differentiation (e.g., refund policies, weekend stays, etc.). Currently, it is easy to search for convenient flights, but finding the least expensive rate is cumbersome, because the number of different tariffs is huge. Complicated pricing schemes for airline tickets defy comparison shopping. Airlines introduced this discriminated price structure (frequent flyer programs, early reservation discounts, weekend tariffs, etc.) to deliberately reduce market transparency after a phase of open price competition.[7] This field has matured, and by the mid-1970s most airlines had already deployed sophisticated revenue (or "yield") management systems, which use optimization and forecasting techniques to calculate the prices that are to be offered to customers now in order to maximize overall profitability.[8]

Dynamic pricing. Although product and price differentiation have successfully been deployed in many industries, they have had less penetration in markets where there is uncertainty about the price of goods or services and there is little knowledge about market participants. This uncertainty may stem from unknown or volatile supply and demand (e.g., bandwidth, electricity), or from the fact that the item being traded is unique. Auctions and competitive bidding (often referred to as *dynamic pricing* mechanisms) help to find a price in cases where no one person knows the true value, and each individual's estimate may be highly imperfect. In an auction, a bid-taker offers an object to two or more potential bidders whose bids indicate how much they are willing to pay for the object.[9] That is, any well-defined set of rules for determining the terms of an exchange of something for money can reasonably be characterized as an auction.[10] An auction clears when it commands an allocation based on the bids it has received. The competitive process serves to consolidate the scattered information about bidders' valuations.

By ensuring that prices match current market conditions, these mechanisms create an optimal outcome for both the buyer and the seller that is otherwise unobtainable. In traditional markets, the high transaction costs associated with dynamic pricing mechanisms have limited their application to specific sectors such as finance, commodities, and art. On the

Internet, companies such as Onsale or eBay successfully run live auctions where people outbid one another for computer gear, electronics components, and sports equipment.[11,12] However, the shift from fixed pricing to dynamic pricing is expected to be most evident in the business-to-business electronic commerce. Although the future penetration of dynamic pricing is unknown, predictions by some industry analysts are very optimistic. Forrester Research predicts that sales involving dynamic pricing models will reach $746 billion by 2004 across all industries in the United States, compared to $30 billion in 2000.[13] The conclusion is that bidding, and other forms of electronic negotiation, can be expected to be more competitive in electronic markets than in traditional markets.[14] Certainly, fixed pricing will never disappear, but the Internet is changing the balance in favor of dynamic pricing. This opens a wealth of new research issues ranging from revenue management in the context of dynamic pricing to the design of new pricing mechanisms.[8]

In this paper we survey new applications of flexible pricing in electronic commerce and describe how new pricing strategies have become possible through the Internet. We use the term *flexible pricing* to refer to both differential pricing and dynamic pricing. Through a variety of relevant IBM projects, we illustrate how flexible pricing impacts the way business is being conducted and the challenges companies face in dealing with this new phenomenon throughout their supply chain. We focus on the challenges of business-to-business electronic commerce—for dynamic pricing in business-to-consumer electronic commerce we refer the reader to Kannan and Kopalle.[15]

In the section "Flexible pricing and the supply chain," we analyze the impact of flexible pricing from a supply chain management point of view. Then, in "Price negotiation for procurement," we describe a number of multidimensional auction formats for procurement and sourcing. In the section "Sell-side pricing strategies," we analyze new applications of flexible pricing on the sell side. We conclude with a brief summary and final comments.

Flexible pricing and the supply chain

Flexible pricing for an enterprise in a business-to-business (B2B) context presents independent challenges on both the buy side (procurement) and the sell side of a typical enterprise supply chain.[16] Flexible pricing requires tight integration between the buy and sell sides, with the capability of real-time updates to key operational data flows.

Figure 1 illustrates some of the mechanisms for flexible pricing on the buy and sell sides. Auctions are probably the most common realization of dynamic pricing on the sell side. Assuming demand exceeds supply, the price of the auctioned entity rises to a level where there is no excess demand. Computer manufacturers, such as Sun Microsystems and IBM, are now selling increasing numbers of servers via auctions. Another sales channel common in the computer industry is the request for quote (RFQ), in which a buyer posts an RFQ for a specific product meeting certain minimal requirements, and sellers respond with a single closed bid, with possible subsequent negotiation. This problem is discussed in more detail in the section, "Sell-side pricing strategies." Sellers may also sell through indirect channels, such as intermediaries, and this presents the challenge of establishing optimal pricing and allocations across all available channels. The final sell-side channel shown in Figure 1, direct Web-site sales, is basic to business-to-consumer (B2C) models. Many such sites have implemented personalization capabilities designed to target content to individual consumers based on knowledge of their individual preferences. In some cases, this has led to controversial price differentiation in the prices to consumers.[17]

Turning to the buy side, channels for procurement include reverse auctions, RFQs, and direct contract negotiations. Reverse auctions[18] are emerging as a standard buy-side dynamic pricing technique in which a single buyer accepts bids from multiple sellers, with the lowest bid ultimately determining the winning bid. Business transactions are complex, and auction infrastructures must increasingly support multidimensional auction in which the offering consists of multiple products and/or services, and bidders are allowed to bid on a subset of the products. These negotiation mechanisms for procurement are discussed in detail in the section "Price negotiation for procurement."

As shown in Figure 1, sell-side demand generates requirements that eventually impact procurement policies, whereas procurement management must be able to generate accurate real-time available-to-promise information in order to satisfy instantaneous demand on the sell side. These issues are addressed later in this section.

Figure 1 Flexible pricing and the supply chain

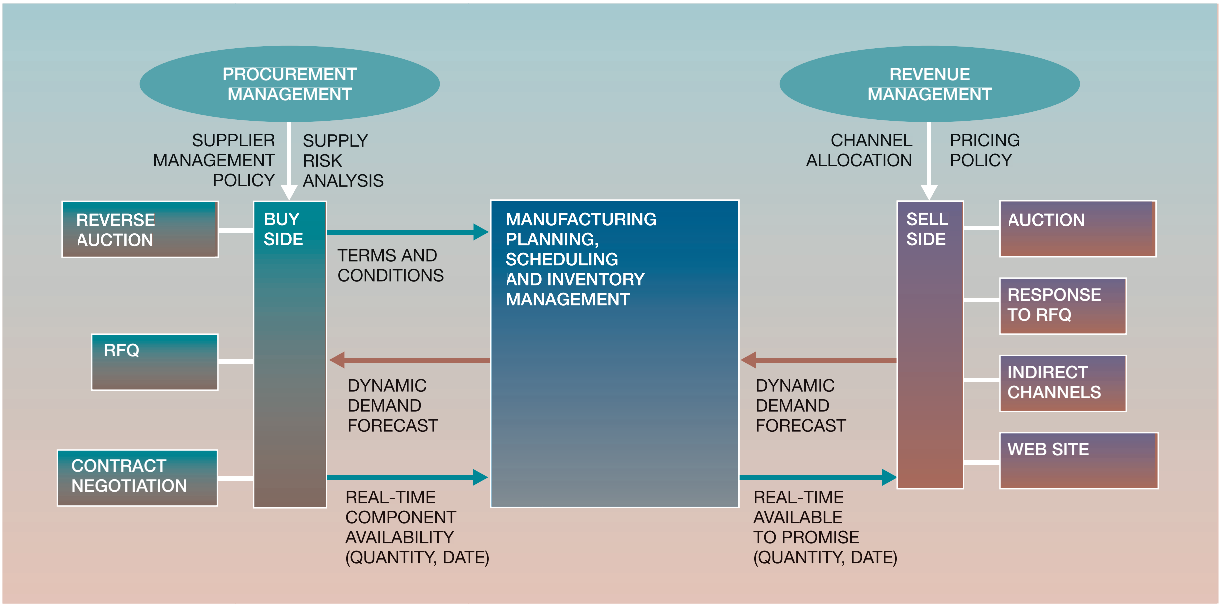
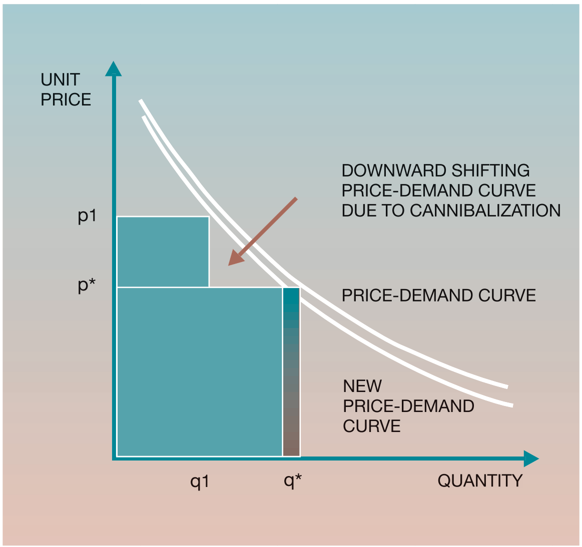


Figure 2 Seller-based price discrimination



Revenue management. Revenue management originated in the airline industry as the practice of controlling the availability and/or pricing of travel seats in different booking classes, with the objective of maximizing revenue and/or profits.[19] Other recent applications of revenue management are discussed in References 20–23. As shown in Figure 1, we generalize these concepts to include pricing policy (e.g., price discrimination) on the sell side as well as the question of how to allocate fixed product resources optimally across the multiple sales channels mentioned above. Price discrimination is illustrated in Figure 2, where we consider a simple seller-based price-demand curve. Customer segmentation can be used to assign customers to price classes. Using a single price class p*, demand for quantity q* will generate total revenue of q* times p* (p* is selected to maximize this revenue). By adding an additional price class, p1, with associated demand q1, additional revenue of q1 times (p1 − p*) can be generated. As noted in Figure 2, it is possible for this additional revenue class to promote "cannibalization," or customers switching between fare classes. The downward shifting of the price-demand curve in Figure 2 is due to cannibalization. In general, it is possible to increase revenue by optimal allocation of the total quantity across multiple price classes.[4] Significant additional complications arise when bills of materials are present, because we need to do a similar analysis across multiple resources.

Pricing policy, including product-portfolio decisions, can include product differentiation (mentioned earlier in the section "Differential pricing") and product/service bundling as a means of capturing consumer surplus (i.e., the portion of the market that is willing to pay more than the average price). At any point in time, different sell-side channels will have potentially different market conditions (e.g., demands and price elasticities), and thus channel allocation, driven by current market conditions, is becoming an increasingly important technology for businesses with multiple sales channels. To some extent, this is driven by the observation that the Internet not only provides buyers the ability to make price comparisons but can also make sellers' costs transparent to buyers.[24]

Product differentiation imposes specific requirements across the supply chain. Bundling price and delivery commitments in a business-to-consumer environment and providing enhanced inventory management offerings such as JIT (just in time) and VMI (vendor-managed inventory) in a business-to-business environment can be a means to create differentiation. It is a widespread practice among the suppliers in assembly manufacturing and high-tech industries to offer price and service bundles. A manufacturer, for instance, can bundle price with a number of delivery options and thus generate differentiation.[25] In order for this practice to be effective, a manufacturer needs to be able to generate an accurate ATP (available to promise) profile. Companies also need to be able to make real-time projections of the cost of providing these bundles. This may require advanced ABC (activity-based costing), particularly in cases where bundles are massively customized.

Procurement management. Improving procurement cost efficiency and availability of components requires proper demand planning, component inventory management, and supply contract management. For instance, a manufacturer that needs to procure components in a procurement auction first needs to determine what components should be procured through this channel and at what quantities. Then, in order to maximize procurement cost effectiveness within the manufacturing availability requirements, it needs to balance the management of its supply contracts simultaneously with its procurement-auction policies. In commodity spot markets, supply shortages are known to cause wild price fluctuations. Therefore, many companies may have to implement a hybrid procurement strategy in which they maintain long-term contracts for some portion of the anticipated demand, and use reverse auctions or participate in spot markets or trading exchanges to satisfy more speculative demand. This issue is discussed further in the subsection "Business process for direct procurement."

In high-tech industries, purchasers desire flexible supply contracts because of frequent technology changes, sudden changes in demand characteristics, and rapid price decline. Using buy auctions for contract portfolio management could be promising for efficient procurement management. In an environment where this is practiced, design of contracts that can address manufacturing planning and execution requirements is essential for efficient supply-chain management. Furthermore, buyers will have to be able to evaluate and compare multiple bids. Price, flexibility in delivered quantity, on-time delivery, and reliability are all desired performance measures that will typically have to be traded off against each other. This requires advanced contract evaluation tools that are designed for multiobjective decision making, as well as minimizing risk associated with reliance on too few suppliers. Suppliers will also have to use such tools to understand cost and profit implications of their bids and improve their chances of making a winning bid. A supply-chain management framework that encompasses such decision-making processes will be needed.

Buyers, as well as suppliers, will require advanced contract evaluation tools for decision support.

Supply-chain coordination. Supply-chain coordination is essential for companies that seek to implement dynamic pricing strategies. It is critical for all parties involved in a supply-chain relationship to understand the kinds of collaboration capabilities needed for successful implementation. This coordination is needed at both the planning and execution levels.

Coordination of supply and demand is a key issue in planning. In particular, propagating timely signals (of market reaction to changes in price) and updated forecasts to all parties in the supply chain is crucial. In typical supply-chain management, demand is assumed to be an external variable that needs to be forecasted. The use of dynamic pricing, however, adds price as a control variable, and makes demand forecasting a much more complex process that needs to be coupled with the pricing process. For companies that participate in auctions, for instance, parameters of demand forecasting are very rich and change constantly. Supply-chain partners that share such information may be able to develop a better understanding of their collective demand structure. As a result, a more efficient demand and supply planning can be achieved throughout the supply chain.

Supply-chain partners can also use dynamic pricing to reduce excess inventory in the supply chain. Excess supply created as a result of over-prediction of demand can be reduced via coordinated actions (e.g., discounted prices and the use of special auctions with low reservation prices) across the supply-chain partners. Because demand and supply planning have inventory implications for all parties in the chain, pricing policies to eliminate unwanted inventories will have to be coordinated across all parties as well.

Similarly, during supply-chain execution, companies that can coordinate information with their supply chain partners will have significant advantages over the competitors that lack such coordination, particularly in advanced e-marketplace environments. As an example, consider a marketplace for computers that gives advanced configuration possibility to buyers. In such a marketplace, a manufacturer disconnected from its suppliers may lack competitive power, even if it is able to generate real-time ATP to quickly respond to buyer bids. If there is demand in excess of planned supply, companies that do not have real-time connectivity with their suppliers will not be able to respond to such revenue opportunities. On the other hand, a manufacturer that has real-time coordination capability with its suppliers can check its suppliers' ATP (price, quantity, delivery date), plan the desired configuration, project when it can deliver, calculate the total cost of all components and the cost of assembly, and finally generate an asking price "on the fly."

The following two sections contain examples of the methodologies discussed here. The next section describes an example of multidimensional procurement auctions, and the following section discusses several examples of flexible pricing on the sell side.

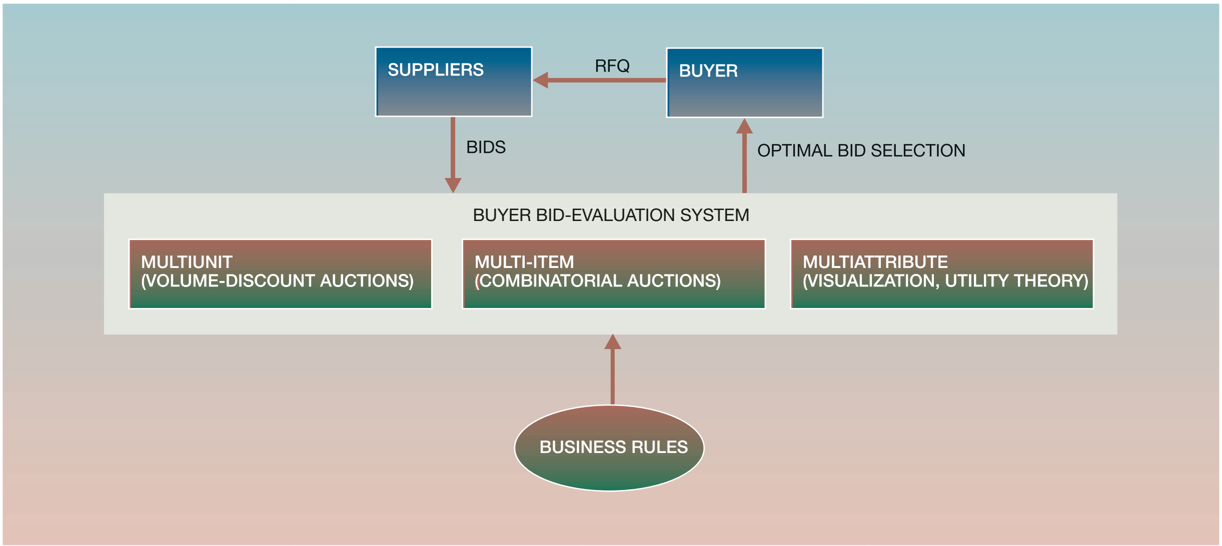
Price negotiations for procurement

Although there exist several alternatives for price negotiations, auctions have emerged as the most popular mechanism for implementing negotiations in the context of electronic commerce and are the focus of this section. Auctions achieve high rates of Pareto efficiency,[26] and exhibit rapid convergence to equilibrium, which is important in a business context. These features are very attractive in a procurement context where large companies are buying, both directly and indirectly, materials from suppliers that are dependent on them for a significant portion of their revenue. In such settings, the buyers institute private auctions as the price negotiation mechanism for procurement and require suppliers to participate in the process as part of the business relationship. Procurement auctions take the form of reverse auctions with a single buyer and a set of precertified suppliers negotiating within the context of a private exchange.

Decision support for procurement. The business process and essential functional requirements for auction-based price negotiations are illustrated in Figure 3. The procurement manager (buyer) initiates an auction by sending a request for quote (RFQ) to various select suppliers. The RFQ specifies the item(s) that the buyer intends to purchase, and the responses (or bids) to the RFQ provide an indication of the supplier's ability to satisfy this demand and at what cost. As discussed below, evaluation of these bids can require sophisticated analysis in order to determine the optimal bid, subject to certain business rules as constraints.

The typical use of electronic auctions has been in a business-to-consumer context, where the negotiations are restricted to price, since the product attributes are fixed *a priori*. In a business-to-business context, items being purchased often need to be specified along several attributes and are themselves subject to negotiations. As a result, bids should allow the specification of multiple attributes. In addition, the negotiation is conducted for a large number of units of an item, and the bids often include volume discounts. Buyers also tend to bundle their demand for multiple items in a single auction, and thus increase the size of the transactions, and to exploit cost complementarities in an effort to minimize procurement cost. Such a setting requires that the suppliers be allowed to provide all-or-nothing bids for bundles of items. Auctions designed to capture these complexities are sometimes called "multidimension-

Figure 3 Decision support for procurement

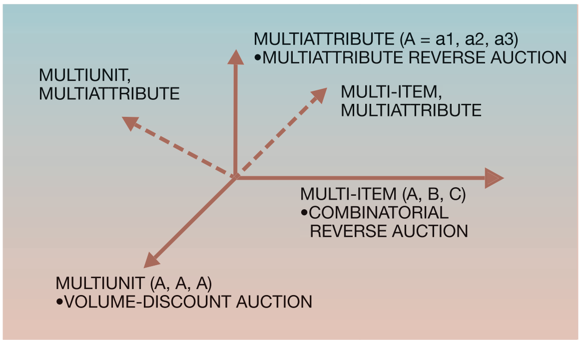


al auctions," where the dimensions refer to (1) the multiple attributes, (2) the multiple units, and (3) the multiple items over which the negotiation is being conducted.[8,27] Figure 4 illustrates these dimensions. The need for multidimensional auctions, and hence sophisticated bid-evaluation systems, is growing.

Another consideration in the bid-evaluation process is the use of business rules to constrain the selection of winning suppliers. Typical rules are motivated by risk hedging considerations. For example, the number of winning suppliers may be constrained to have a minimum, because dependence on too few suppliers might expose the firm to the misfortunes or supply fluctuations of the chosen suppliers. Conversely, too many suppliers would lead to high administrative costs, and hence the number of winning suppliers is also constrained from above. Other constraints might be related to regulations such as requirements of choosing at least a minority supplier.

The focus of this section is on the decision support tools required for different bid types (in terms of the dimensions defined in Figure 4). The next subsection describes a bid evaluation engine for multi-item and multiunit bids, whereas the following subsection briefly discusses evaluation and visualization techniques appropriate for multiattribute bids.

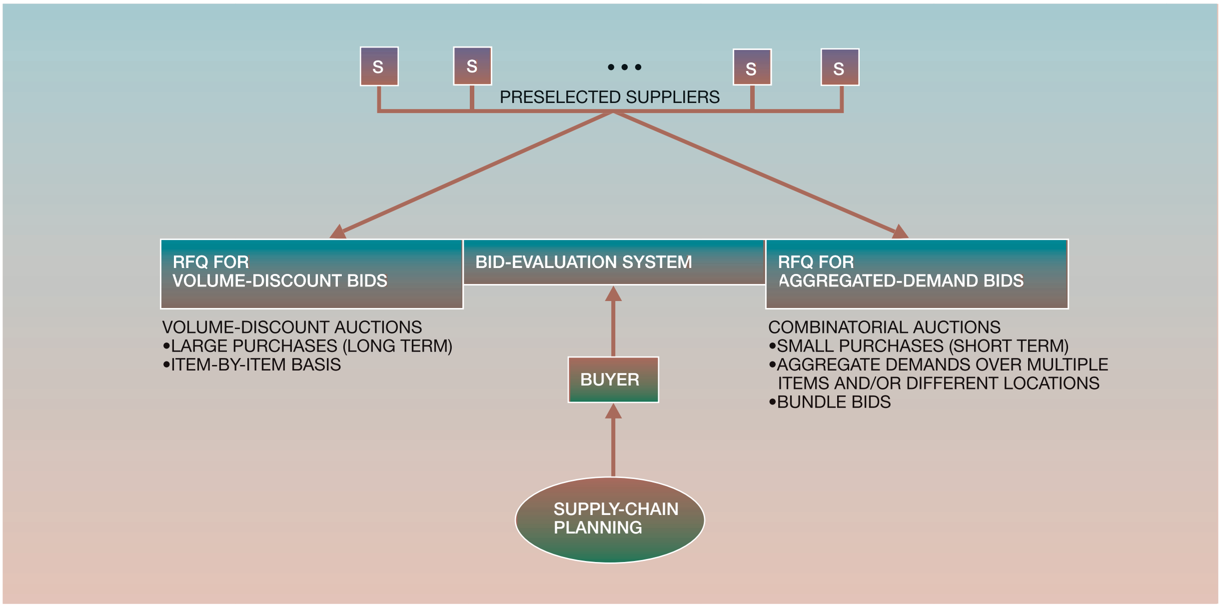
Figure 4 Multidimensional procurement auctions



Evaluation of multi-item and multiunit bids. Transactions arising in the procurement of direct inputs used in the manufacturing of a company's primary outputs are usually very large (in total quantity and in dollar value) and require the use of special price negotiation schemes that incorporate appropriate business practices. Typically, bids in response to an RFQ in these settings have the following properties:

1. The transaction volume is large and the suppliers provide volume discounts that are specified as a curve with a quantity range associated with

Figure 5 Business process for direct procurement



each price level (e.g., $1000/unit up to 100 units, $750/unit over 100 units).

2. Often the suppliers provide all-or-nothing bids on a set of items where a special discounted price is offered on a bundle (e.g., $150 for 30 units of item 1 and 20 units of item 2, and will not sell the items partially or separately).

After receiving such bids, the buyer needs to identify the set of bids that minimizes total procurement cost subject to business rules such as:

- The total number of winning suppliers should be at least a minimum number to avoid depending too heavily on just a few suppliers.
- The total number of winning suppliers should be at most a maximum number to avoid the administrative overhead of managing a large number of suppliers.
- The maximum amount procured from each supplier is bounded to limit exposure to a single supplier.
- At least one (or some fixed number of) supplier(s) from a target group (e.g., a minority) needs to be chosen.
- If there are multiple winning bid sets, then the set that arrived first is taken as the winning set.

Identifying the cost minimizing bid set subject to these business rules is a hard optimization problem and difficult to do by inspection, as is common practice today. We are developing a bid evaluation engine that provides the decision support required in this setting. Additionally, the engine can be coupled with an existing auction platform to conduct complex auctions that allow for the above-mentioned real-world business practices. It is estimated that the use of this decision support tool to identify optimal bids can reduce procurement costs by a few percent, resulting in very significant savings for organizations with large procurement budgets.

Business process for direct procurement. The quantity of items to be purchased is usually based on the forecast demand for a planning horizon—typically a quarter of a year. However, since there is considerable uncertainty in the forecast, a common strategy is to do an initial procurement up front in order to satisfy a significant fraction of the demand forecast, followed by a series of more frequent (e.g., weekly) procurements in order to satisfy short-term fluctuations in demand. Since the initial, up-front procurement is potentially large, suppliers typically provide volume discounts in their bids. However, the short-term demand is usually much smaller and there is less room for price negotiation. In addition, indirect items are also procured in small quantities. An approach adopted to induce more competition is to aggregate demand over several commodities and over different locations, and negotiate price for the entire bundle. Also, in order to exploit the cost complementarities that suppliers might have for different commodities or locations, it becomes necessary to allow all-or-nothing bids over bundles. Figure 5 provides an overview of the business process for direct procurement. Note that the long-term demand is procured using volume-discount bids, and the weekly demand is procured by aggregating across different locations and plants and soliciting all-or-nothing bids to exploit complementarities in supplier's cost structure.

Volume-discount auctions. Volume-discount bids allow the seller to specify the price charged for an item as a function of quantity that is being purchased. For instance, a computer manufacturer may charge \$1000 per computer for up to 100 computers, but for more than 100 computers would charge \$750 per computer. Bids take the form of *supply curves*, which specify the price per unit of an item as a function of the quantity of items being purchased. In general, when there are multiple suppliers providing volume discount bids, the choice of the winning bids and the amount to be procured from each supplier is a difficult optimization problem that is modeled as an integer program and solved using a commercial solver like IBM's Optimization Solutions Library (OSL).[28] In addition, the various business rules are captured as side constraints within the mathematical formulation. The solution approach is based on modeling the problem as a variation of the multiple choice knapsack problem.[29]

The volume discount auctions lead to a mixed integer linear program with continuous variables. These problems are quite difficult to solve. The use of customized knapsack covers is effective in improving the performance of these problems for up to 40 suppliers and 30 items. For larger problems, we have developed column-generation-based heuristics that provide approximate solutions to within 1 percent of optimal.[30]

Combinatorial auctions. As mentioned previously, for procuring weekly demand it is advantageous to aggregate demand over several locations and plants, since this leads to a larger transaction. An additional advantage is that suppliers can provide a discounted bid on a bundle (e.g., demand for sugar in New York and in New Jersey), since they might have excess inventory in a local warehouse or spare capacity in the carrier and hence can reduce transportation costs. However, the discounted bid price is valid only if the entire bid is accepted. Figure 6 provides a simple illustrative example in the context of a food manufacturer.

Figure 6 An example of a combinatorial auction with bundled bids

PROCUREMENT ITEM: SUGAR UNITS	SUPPLIERS			
	S1	S2	S3	S4
100 TO NEW YORK	30	80	100	30
5 TO CHICAGO	0	5	5	0
20 TO BOSTON	20	10	20	10
SELLER BID PRICE	\$150	\$125	\$300	\$125
DECISION VARIABLE	x1	x2	x3	x4

$$
\begin{array}{llllll}
\text{MINIMIZE} & 150\,x1 + & 125\,x2 + & 300\,x3 + & 125\,x4 & \\
\text{SUCH THAT} & 30\,x1 + & 80\,x2 + & 100\,x3 + & 30\,x4 & >= 100 \\
 & & 5\,x2 + & 5\,x3 & & >= 5 \\
 & 20\,x1 + & 10\,x2 + & 20\,x3 + & 10\,x4 & >= 20
\end{array}
$$

SOLUTION: x2 = 1 AND x4 = 1 → PRICE = \$125 + \$125 = \$250

In this example, a food manufacturer has posted an RFQ for sugar in three locations (locations of manufacturing plants) and solicits bids from four suppliers. Each supplier has provided a bundled "all-or-nothing" bid and a price for the bundle represented by the seller (first) column in Figure 6. By introducing a simple decision variable (x1, x2, x3, and x4) for each bid, we can formulate an optimization problem that can be solved optimally using the formulation shown in the figure. The formulation attempts to minimize total procurement cost while ensuring that the demand for each item is satisfied. Notice that the optimal supply may over-satisfy demand, as is the case here for sugar in New York (the minimum cost solution generates a supply of 110 tons). If there are no holding costs, this might be acceptable or even desirable.

The complexity of finding the cost minimizing bid set in general can be a very hard problem as the number of bids begins to get large. Notice that each supplier is usually allowed more than one bid and, as the number of items increases, the number of bids can get quite large. The combinatorial auction can be formulated as a set covering problem with side constraints (arising from the business rules). A significant departure from the conventional formulation is that the side constraints make the feasibility problem hard. However, we introduce (expensive) dummy bids to effectively deal with the feasibility problem. Integer programming techniques are effective in solving problems with 500 items and up to 5000 bids. We rely on combinatorial optimization to solve this problem by modeling it as an integer program and using OSL.

Future directions include the development of multiattribute auction formats as well as the combination of multiattribute and volume discount auctions in order to enable negotiations on multiple units of complex goods. Decision support for buyers and suppliers plays an important role in these complex auction formats. A key requirement is the buyer's trade-off for various attributes. Assuming that this is available, the utility for each unit (based on a bid) can be computed and used in the bid evaluation procedure by replacing cost minimization by utility maximization.

Evaluation of multiattribute bids. A crucial issue for multiattribute auctions is the bid evaluation and scoring process, which also influences how suppliers try to improve their bids. If the bid process is repeated frequently, and the number of bids for each RFQ is high, then determination of the winning bid by conventional evaluation methods can be tedious and time-consuming. This problem can be addressed by a combination of analytical bid evaluation techniques and visualization. One straightforward approach is to assume that the bid score is a linear weighted sum of the contributions due to each attribute, with the weights specified by the bid evaluator. A more sophisticated analytical approach[31] is to determine these weights via an iterative process whereby the evaluator is asked to rank-order selected pairs of bids determined by the algorithm. This analytical approach has been integrated with the ABSolute system[32] to form an effective bid-evaluation tool.

In the ABSolute system developed at the IBM Thomas J. Watson Research Center, we provide a capability for bid evaluators to explore visually multiattribute bids using parallel coordinates.[33] It provides a tree-view for RFQ specification and revision, and a table-view and a visualization for displaying submitted offers. Providing a comprehensive overview of all bids by visualization helps users make purchase decisions with confidence. Furthermore, the visual interface is an effective multiattribute decision analysis tool that allows buyers to view, explore, navigate, search, compare, and classify submitted bid offers. For interactive analysis, the interface provides a set of useful visual facilities including dynamic filtering and querying, dynamic scoring and ranking, comparison, tagging, color-coding, Pareto optimality analysis, and zooming.

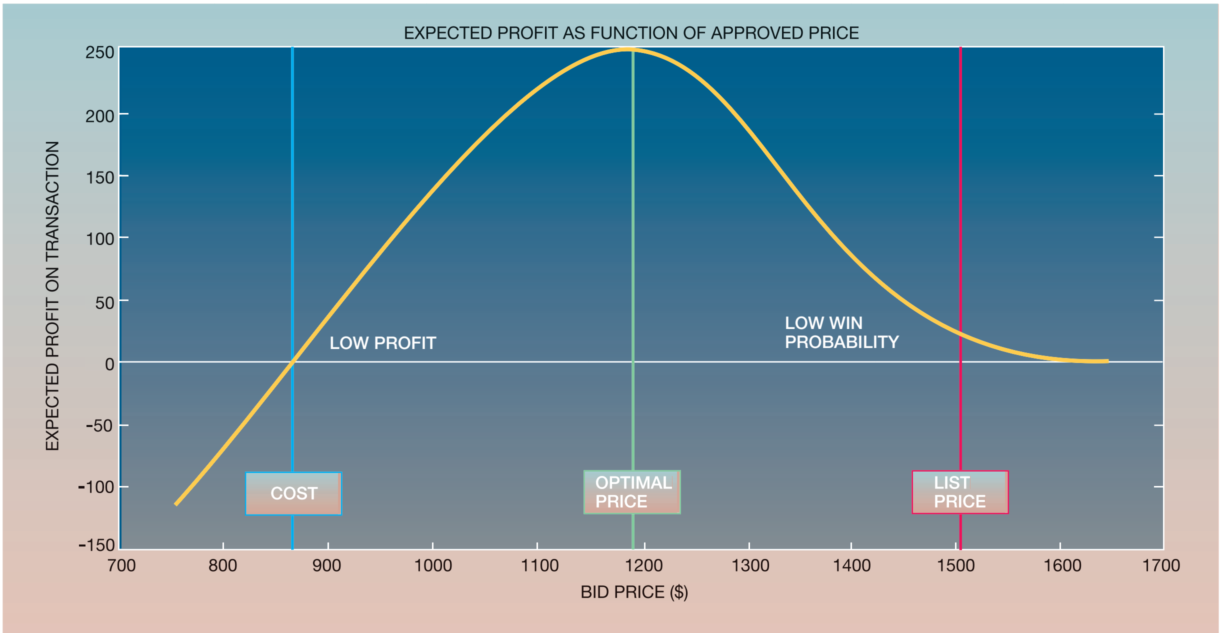
Sell-side pricing strategies

In this section, we present two examples of decision support systems for pricing strategies developed at IBM Research, and then consider some interesting flexible-pricing issues that arise in the emerging area of e-utilities.

Flexible pricing for response to RFQ. One form of flexible pricing that arises on the sell side is the capability to apply price differentiation in responding to an RFQ received from a prospective customer. An example is a computer vendor deciding how to price a request for a bid on a large number of specific computers. Typically, a pricing specialist will take into account a number of factors in arriving at a final offering price for the overall configuration to a specific customer. These factors can include inventory, profit at approved price, quantity, degree of competition for this bid, and anticipated future revenue and profit from this customer. If inventory is taken into account, then this problem can be viewed as a yield-management problem in which the objective is to allocate a constrained resource across the current demand so that revenue or profit is optimized.

Bid pricing is typically performed in the absence of inventory information, and seeks a price that maximizes expected profit based on the probability of winning the bid as a function of offered price. Reference 34 provides an overview of various bid-pricing models. Figure 7 shows a specific example of the determination of an optimal price given the computed expected profit as a function of the bid-response price. This price clearly reflects a trade-off between enhanced likelihood of winning a bid at a low price (e.g., cost) versus increased profit at a higher price (e.g., list price). Computation of the winning probability is a difficult problem, given its dependence on a number of factors including the specifics of the bid and the number and identity of the

Figure 7 Price optimization in bid response



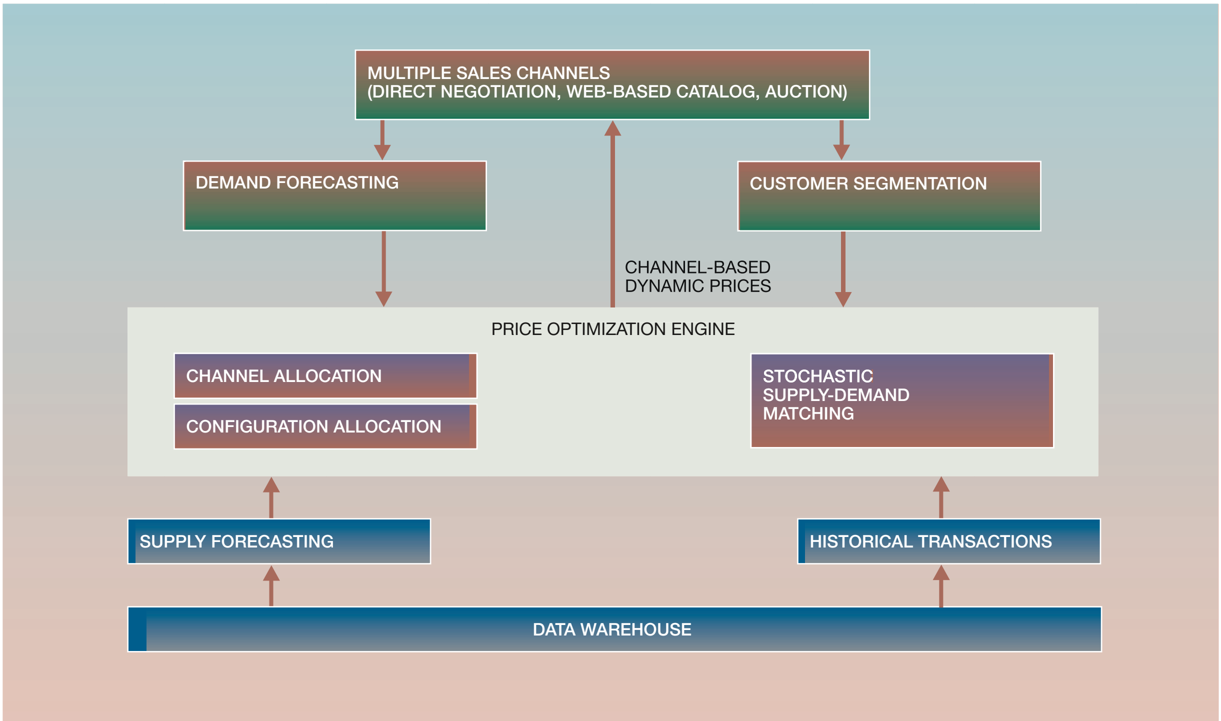
competing bidders. One approach is to use historical bid data to build a predictive model[35] to estimate the winning probability for a new bid. Such a model requires a large number of historical bids, each tagged with a win/loss label as well as a set of attributes characterizing the conditions at the time of the bids. Separate models can be built within each customer segment and each product group, reflecting different behaviors across both customers and purchased products. For losing bids, it is likely that neither the winning price nor the identity of the winning bidder will be known, thus complicating the development of robust models. Unlike price-based auctions, it is also possible that the winning bid will not necessarily reflect the lowest offered price, but indeed may reflect other factors (discussed earlier in the subsection "Evaluation of multi-item and multiunit bids") taken into account by the buyer's bid evaluation system.

An alternative approach[34] to the strict use of historical data is to rely on input from human pricing experts to evaluate parameters in a simplified predictive model. These parameters can include the customer's price sensitivity, as well as key attributes of each known competitor such as discounts off list price as a function of demand. Extensions to these models can use estimates of potential future revenue, analogous to the use of "lifetime value" in consumer-based customer-relationship-management models. Using this information, flexible pricing ultimately can be used to offer lower prices to customers based on the enhanced likelihood that a winning bid will generate proportionately greater revenue in the future.

Flexible pricing for reverse logistics. In this section, we discuss reverse logistics, a form of flexible pricing on the sell side, integrated with a special kind of supply-chain environment. The reverse logistics process includes the management and the sale of surplus and returned equipment and machines from the hardware leasing business. To maximize the profit, manufacturers can sell the machines at market values, or dismantle (de-manufacture) the machines to sell parts, or use a combination of the two, directed across various sales channels.

The typical sales channels for reverse logistics include traditional direct negotiation (e.g., via telephone) with a set of preferred brokers/business partners, Web-based catalog sales, and auctions. In practice, the preferred channels for commodity products such as PCs are direct Web catalog sale, negotiated medium volume contract sale, or market clearance sale

Figure 8 Decision support system for reverse logistics with flexible pricing



for all lots. Larger servers are normally sold to the business partners and brokers, with smaller remaining quantities sold through auctions.

The trading process is complex since it involves multiple products ranging from parts (e.g., memory cards) to machines (e.g., PCs, servers, and supercomputers), sold across multiple channels characterized by different demands across the different products. Furthermore, each channel has its unique operation mechanism, and a group of products might go through several of them before completing the sale. An additional complication is that the supply of products is driven by external factors such as lease expiration dates, whereas the demand potentially varies on a much different (and less predictable) timescale.

Figure 8 shows the structure of a decision support system performing channel allocation and flexible pricing for the reverse logistics application discussed above. Inputs to the price optimization engine include supply forecasts (e.g., the number of machines expected to be returned from leasing), historical transactions to establish current bounds on market prices and price elasticities, demand forecasts across the multiple channels, and possibly customer-segmentation information. The optimization engine determines optimal strategies, including the division between whole systems and systems disassembled for parts, the allocation of components and systems across the multiple sales channels, pricing strategies within each channel, and transitions between sales channels. For example, given a supply of machines, the output of the optimization engine is a set of allocations and recommended prices (or reserve prices for auctions) for each channel, as well as terms or conditions for the switch to different channels. Some of the optimization tools, such as the optimal disassembling decision support tool, have been successfully employed in a reverse logistics application. Others, e.g., catalog pricing strategy, can be borrowed from the practice of various other industries, and some are developed anew, such as the channel transition scheme. More importantly, all these modules are integrated in order to provide a set of strategies that can achieve a global optimum.

Flexible pricing for e-utilities. In an accelerating trend, corporations of all sizes out-source their informational and commercial Web sites to professionally managed hosting companies, such as IBM. The basic services offered by hosting companies are shelf-space rental, electricity, air conditioning, and bandwidth. In many cases, hosting companies provide or maintain servers and storage as well. These are the first steps toward an "e-utility."

Pricing models for hosting are becoming standardized, with a combination of flat rate and variable charges. A "best-effort" treatment of all user requests leads to outsourcing customers over-subscribing to hosting services in order to protect premium users, thereby substantially increasing costs. A simple remedy is to provide differentiated services to classes of user requests, which may be grouped by profile, by past history, or by the Web page requested. Ideally, premium users should always be able to access the site even at peak usage. Differentiated services, if properly priced, would be universally beneficial. It would lower the cost to nonpremium users, increase the probability that services are available for premium users, and yield the proper incentives to the service provider. This model follows the revenue management strategies developed within the airline industry (see the "Differential pricing" subsection early in this paper).

An application scenario generic to most Web hosting configurations is the following. When a user HTTP (HyperText Transfer Protocol) request arrives, it is handled by a request dispatcher, which serves the role of gatekeeper, and by a load balancer directing traffic to the server clusters in the back end. Depending on the implementation of the dispatcher, a request may be forwarded for immediate service, buffered in a best-effort queue, or dropped. The dispatcher can access the cookie information stored in a request message in order to look up user-specific information, thereby establishing the user profile and the class membership. Accepted requests are forwarded to the server clusters. The dispatcher receives constant information about system resource usage, and applies control policies to prevent over-loading and consequent violation of contracted service level agreements.

Paschalidis and Tsitsiklis[36] study resource allocation using a revenue management formulation, with the motivation to find a fair allocation of network resources viewed as a common good. Their basic assumption is that there is a relationship between demand and price, and the price is set based on network congestion and allocation of resources to the highest bidder. This is similar to the ways that airline seats have been sold (at least until reverse auctions became possible). In the case of the e-utility, however, the users of the service are not necessarily the ones who pay for the service. While conceptually one may wish to think of premium users paying a higher price for assured access, the actual payment may be made on their behalf by the Web site owner who in return will require evidence that premium users are being well treated. This evidence will necessarily be statistical in nature, and will probably be averaged over fairly long time intervals in order to develop a reasonable quality-of-service (QOS) estimate for different service classes. Liu et al.[37] develop a quite realistic model whereby a Web-hosting service provider can optimally allocate resources to meet differential QOS measurements, for forecasted arrival and service rates.

Flexible pricing has become a mechanism used by businesses to balance supply and demand in real time to manage risks and improve profitability.

In the e-utility, dynamic pricing will probably apply when the estimated loads are much higher than predicted. In this case, the Web site owner is in the same position as the business traveler who requires an airline seat on short notice. The owner may wish to contract for a short-term "assured" burst to cover the requirements of the premium users. Of course, since this burst is over and above the contracted levels, the service provider can and should charge a high premium for it. It may be possible for the service provider to estimate the frequency of such bursts, since from the point of view of the service provider one premium user is the same as another, just as a late-booking IBM business traveler is the same to the airline as one from General Electric. It is the total population of premium users that determines the arrival process and the consequent requirement to allocate excess capacity. But in contrast to the airlines, it does matter which Web site is bursting, because the actual loads generated will vary from Web site to Web site.

This suggests that in addition to specifying differentiated quality of service, e-utility contracts should also specify peak load forecasts broken out by service classes. When these peak load forecasts are violated, then the service provider can charge appropriately high prices for those bursts. By standardizing the service classes (and possibly also the applications used by the premium service classes), the service provider may be able to develop robust statistical models for the bursting and thereby manage the capacity needed to meet the assured service levels.

Summary and conclusions

The increasingly dynamic nature of business-to-business commerce and value-chain relationships has accelerated the shift from fixed pricing to flexible pricing. Flexible pricing has increasingly become a necessary mechanism for companies to stay competitive, balance supply and demand in real time, manage risks, and improve profitability. However, the short cycle time for real-time decision making and the requirement to analyze the huge volume of data has created new challenges for enterprises. New flexible pricing and more intelligent decision support tools are needed to help companies manage real-time information from complex market environments and value-chain relationships, as well as to optimize their operations. The requirement for flexible pricing opens a wealth of new research issues, ranging from revenue management in the context of dynamic pricing to the design of new pricing mechanisms based on real-time supply-chain and market information.

This paper is intended to lay a foundation for the design of intelligent decision support systems for flexible pricing and to explore ways to maximize their impact on business objectives. We have focused our discussion of flexible pricing from the supply-chain management perspective. We first summarized the concept of differential pricing and dynamic pricing and called it flexible pricing. We then discussed flexible pricing in the context of supply chain, including revenue management, procurement, and supply-chain coordination. Key issues, challenges, and research areas were identified. Several new scenarios and applications involving flexible pricing in business-to-business electronic commerce were presented. Finally, the opportunities, issues, and strategy for applying flexible pricing techniques to the emerging application hosting services (e-utilities) were discussed.

We argue that flexible pricing must be integrated with the end-to-end supply-chain management: real-time market information and company supply-chain velocity need to be considered in pricing strategies. Successful utilization of flexible pricing can significantly enhance a company's competitive advantage and help manage changing market demands, improve customer relationships, and manage supplier relationships. Although flexible pricing has demonstrated promising results, current research is still in its early stage. Additional work is needed in defining flexible pricing strategies based on different business objectives, and on the development of new algorithms for analyzing real-time information. With the advances in research and the tight integration of pricing and supply-chain management, flexible pricing will become a common business practice in the next few years.

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Accepted for publication November 13, 2001.

Martin Bichler *IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598 (electronic mail: bichler@us.ibm.com).* Dr. Bichler is an associate professor in the Department of Information Systems at the Vienna University of Economics and Business Administration. He received his M.Sc. degree in information systems from the University of Vienna and his Ph.D. degree from the Vienna University of Economics and Business Administration. Dr. Bichler was research Fellow at the University of California at Berkeley and is currently a visiting scientist at the IBM Thomas J. Watson Research Center, where he is working on multidimensional market mechanisms and multiattribute negotiation support.

Jayant Kalagnanam *IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598 (electronic mail: jayant@us.ibm.com).* Dr. Kalagnanam received his Ph.D. degree from Carnegie Mellon University in 1991. His research goal is developing decision support capabilities for electronic commerce. His recent work has focused on computational issues in the design and deployment of dynamic pricing mechanisms such as auctions.

Kaan Katircioglu *IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598 (electronic mail: kaan@us.ibm.com).* Dr. Katircioglu is a research staff member in the Department of Enterprise Solutions Research at the IBM Research Center. He received his Ph.D. degree in management science/transportation & logistics from the University of British Columbia, Canada, in 1996. His research interests include theory of inventory control, supply-chain management, e-business, stochastic models, and risk management.

Alan J. King *IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598 (electronic mail: kingaj@us.ibm.com).* Dr. King is a research staff member with the Mathematical Sciences Department at the IBM Research Center. He received his Ph.D. degree in 1986 at the University of Washington in Seattle, working with R. T. Rockafellar and Roger J-B Wets on properties of empirical estimators of solutions to stochastic programming problems. His research interests include algorithms and estimation in stochastic programming, asset-liability management, options pricing, dynamic resource allocation, and managing risk in the supply chain.

Richard D. Lawrence *IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598 (electronic mail: ricklawr@us.ibm.com).* Dr. Lawrence is a research staff member and manager, eMarketplace and Supply Chain Analytics, at the IBM Research Center. He received his B.S. degree from Stanford University and his Ph.D. degree from the University of Illinois. Since joining IBM Research in 1990, he has received IBM Outstanding Innovation Awards for his work in parallel-processing communication libraries and scalable data-mining applications. His research interests include the development of data-mining algorithms and applications in the areas of product recommendation systems, stock-market analysis, and dynamic-pricing applications.

Ho Soo Lee *IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598 (electronic mail: leehs@us.ibm.com).* Dr. Lee is a manager in the Deep e-Commerce Department at the IBM Research Center. He received his Ph.D. degree in computer science from Northwestern University in 1985, and subsequently joined the Research Center as a research staff member. His research interests include electronic commerce, with emphasis on advanced B2B auctions and intelligent bid evaluation, supply-chain optimization, and rule-based programming languages.

Grace Y. Lin *IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598 (electronic mail: gracelin@us.ibm.com).* Dr. Lin is a senior manager at the IBM Research Center. Her department conducts research in the areas of supply-chain optimization, adaptive business model, and advanced decision support, including dynamic pricing and risk management for e-commerce. She received her M.S. and Ph.D. degrees in industrial engineering from Purdue University. She received the IIE Doctoral Dissertation Award, several major IBM Research and Corporate Outstanding Technical Achievement Awards, and the INFORMS Edelman Award. She is an associate editor of *Operations Research*, a member of the INFORMS Academic/Practitioner Interface Committee, and a council member of CPMS. She serves on the 2001 Edelman judge panel and is a member of INFORMS and IIE.

Yingdong Lu *IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598 (electronic mail: yingdong@us.ibm.com).* Dr. Lu joined IBM Research in 2000 after receiving his Ph.D. degree in operations research from Columbia University. His research interests include stochastic modeling and discrete control.