Ratcheting Up: Linked Technology Adoption in Supply Chains

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It is generally assumed that a firm will adopt complementary technologies simultaneously. Apparel industry data indicate that, because of the close links between suppliers and retailers, there was a ratchet-up adoption of complementary information technologies. The consequence was that a rapid regime shift occurred without explicit coordination or planning. One implication is that the study of technology adoption may need to be more widely conceptualized to incorporate the relationships between upstream manufacturers and downstream retailers.

> Manufacturing is undergoing a revolution. The mass production model is being replaced by a vision of a flexible multiproduct firm that emphasizes quality and speedy response to market conditions, while utilizing technologically advanced equipment and new forms of organization.—Milgrom and Roberts (1990)

"Modern manufacturing" has received considerable attention in recent years. Technological advances in manufacturing enable firms to produce a wide range of products more rapidly and efficiently. Less widely discussed, particularly in the academic literature, are developments in the retail industry that have substantially altered the distribution of products. Information technologies that enable retailers to track products efficiently (via bar codes) have diffused widely and rapidly from first-movers like Wal-Mart to other retail channels, including specialty retailers, and even automobile dealerships (Gill and Abend 1996).

Information technologies that provide real-time information on specific products at the store, region, and company level help retailers reduce inventory levels by substituting information for inventories. (Brown 1997; Aguirregabaria 1999). This infusion of information has also changed the manner in which retailers relate to their suppliers. Retailers that have accurate and

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timely information on product sales order more frequently and in smaller quantities, and demand faster order fulfillment (Fisher and Raman 1996).

The apparel industry provides a striking example of how information technologies that link suppliers and retailers revolutionized a traditional order-processing method—characterized by large and infrequent orders—that had been in place for decades. Coordinating changes in technology practices and standards is typically difficult. The economic incentives must be large enough to induce adoption, and firms must agree on the new standards, or a lead firm must function as an implicit coordinator. Yet, a regime shift from traditional to modern information systems in the apparel industry occurred in a surprisingly short period of time without explicit industry coordination or planning. The empirical evidence presented in this paper indicates that these technologies were adopted in a ratchet-up fashion, as retailers spurred supplier innovation and vice versa.

Specifically, we investigate how changes in retailing and manufacturing together affected the diffusion of technology in the apparel industry via a feedback loop between demand-side changes by retailers, and the adoption of modern manufacturing practices by suppliers. The process occurred in a stepwise fashion because the payoffs to complete, instantaneous adoption were not sufficient. Retailers typically adopted the new information technology systems first. Increased demand for rapid replenishment by retailers then stimulated suppliers to adopt new manufacturing practices, and make greater investments in complementary information technologies. This caused a ratchet-up process as the payoffs to adopting increased when more customers and suppliers, respectively, adopted. This evidence suggests that the nature of supplier–retailer relations plays an important role in shaping technological innovation and should be incorporated into studies of technology adoption.

Section one discusses the emergence of new methods of manufacturing and retailing apparel. Section two describes the data set and key variables used in the analysis. Section three describes the hypotheses of the study. Section four presents empirical evidence on patterns of adoption of advanced manufacturing practices in the apparel industry. Implications and concluding remarks are in section five.

A Revolution in the Apparel Industry

Despite its reputation as a low-skill, sunset industry, U.S. apparel manufacturing firms have adopted a wide variety of information, distribution, and manufacturing practices usually associated with more advanced firms and industries. These practices involve technologies that increase the speed and accuracy of information flow between and within firms, and increase the ability of firms to manufacture a more diverse set of products in a flexible manner—practices often associated with modern manufacturing (Milgrom and Roberts 1990; Black and Lynch 2001). For a comprehensive discussion of the empirical literature on modern manufacturing and performance outcomes, see Ichniowski and Shaw (2003).

The adoption of advanced manufacturing practices by apparel business units has occurred in the context of a fundamental change in the relationship between apparel suppliers and their retail customers Chen (2003). Because retailers are the link between manufacturers and consumers, retail practices critically affect the payoffs for suppliers who adopt modern manufacturing practices.

A stock-keeping unit (SKU) is the most detailed level of product specification. For the apparel industry, an SKU is a unique product with a specified manufacturer, color, fabric, style, and size; for example, a white, pinpoint oxford cloth, men's button-down dress shirt, 16″ collar, 35″ sleeve, manufactured by a specific company. The typical number of SKUs provided by retailers over the course of a year can range from a price club offering large quantities of a few thousand SKUs to an upscale department store that may stock over one million different items. Retailers face an ongoing problem of managing this profusion of products. At an operational level, this means deciding the types and quantities of goods to stock in order to maximize profits, allocating space efficiently, responding to shifts in consumer tastes, setting prices to deal with both the direct cost of goods and the uncertain nature of consumer demand, and controlling inventory costs.

Retail practice is being transformed by investments in information processing technologies and automated distribution centers, and the creation of pricing, inventory, and logistic strategies that draw on these investments. Innovative retailers aim to reduce their exposure to demand risk by adjusting the supply of products at retail sites to match consumer demand on the basis of daily, point-of-sale information flowing from bar code scanners within individual stores. These retailers consolidate their data, and send orders to suppliers based on actual sales. As a result, retailers demand that suppliers compete not only on the basis of price, but also on their ability to meet rapid-replenishment requirements that reduce the amount of time between the receipt of a retailer's order and the delivery of goods to the retail distribution center. They also require that suppliers provide associated services to help move shipments more rapidly through retail distribution centers and to individual stores for stocking. For a complete discussion of these changes in retailing, see Abernathy et al. (1999).

Traditional Retailing. Traditional retailers provided diverse goods at competitive prices by ordering desired products far in advance of the selling season. Retail buyers, assigned to a specific product line area, would procure products based on their assessment of what would sell and using past experience of rules of thumb to determine a distribution of product sizes and variety. These transactions might occur 18 to 24 months before the goods ultimately appeared on the retailers' selling floor. The buyer's success hinged on his or her ability to make accurate predictions of what people would want to buy, and the buyer's ability to procure those products at the lowest cost possible.

Once an agreement between the buyer and the apparel manufacturer had been made, the order remained unchanged until delivery to the retailer's distribution center or individual stores. The typical shipment was large and of low frequency (e.g., once per season). Once delivered, the retailer held the products in central warehouses or in inventory at the store site. At the desired time, the product was stocked on the selling floor, and replenished from store and warehouse inventories as the selling period progressed. Inventory control consisted of biannual counts relying on sales receipts and manual counts of floor, store, and central inventory. Overstocks at the close of a season were marked down for clearance, warehoused in inventory for future sales, or sold to discount retailers.

Traditional retailers lowered their direct costs of procurement, and in the process usurped the role of suppliers in the apparel distribution channel (Chandler 1977). The purchase of large quantities, however, subjected retailers to the risk attendant with selling perishable products like apparel (Pashigian 1988). In terms of the retail bottom line, this risk manifested itself in the indirect costs associated with holding inventories of unwanted products or running out of highly successful products.

Modern Retailing. Access to information became critical to retail success in the 1990s. The ability to gather, transmit, and use information on sales at the cash register created a new retailing model. The modern retailer provides customers with a variety of products, while reducing exposure to demand risk by constantly adjusting the supply of products offered to consumers to match actual market demand. Modern retailers attempt to incorporate into their total cost functions both the direct product costs charged by suppliers and the indirect costs associated with demand uncertainty, including the costs of stock-outs, markdowns, write-offs, and inventory management.

Because of the large number of SKUs carried by retailers, and the enormity of daily transactions, it is very expensive to capture this information manually on a timely basis. The key technological innovations include (1) bar codes, bar code scanning equipment, and related technologies that allow rapid, automatic identification of products and packages, (2) electronic information transfers, and (3) automated distribution operations drawing on scanners for automated identification and computer-controlled conveyance and sorting systems.

Modern retailing combines these technologies to track sales on an individual style, color, fabric, and size basis at the store level on a real-time basis, and to manage inventories at both the store and firm level. Based on daily sales information, products are replenished at the store level relatively quickly, and order flows to suppliers become more continuous and of lower volume, but often of greater diversity.

A Ratchet-Up Process. The technological revolution in the apparel industry has been very expensive, and it is remarkable that it occurred so quickly and smoothly. It is very risky for a supplier to make all of its investments at once, with no assurance that retailers will adopt complementary technologies. And it is very risky for a retailer to make all of its investments at once, with no assurance that suppliers will adopt complementary technologies. Instead, they adopted in stages, with each side providing incentives for the other side to adopt.

Some retailers initiated the process by installing bar code scanners in order to speed up the recording of sales, and to improve the efficiency of check-outs; a tangible payoff would be a reduction in the number of clerks required to process purchases. The initial adopters (who had sufficient incentives even if their suppliers have not yet adopted matching technologies) were large retailers who developed systems to move a lot of products quickly through their checkout lines.

These retailers could either affix bar codes to products or persuade suppliers to do so by paying slightly higher prices or by refusing to purchase products without bar codes. Some suppliers applied the bar codes in order to receive higher prices, maintain their sales, or obtain new accounts with these retailers. In addition, suppliers can reduce their delivery costs by affixing bar codes because retailers with bar code technology can process the received goods more quickly and accurately.

Once a large number of suppliers are using bar codes, smaller retailers find that it is economical to install scanners too. The large retailers, in turn, find that, with so many bar coded products, it is economical to purchase computer systems to monitor inventory instead of using hand counts. Large suppliers find the same to be true.

Once retailers and suppliers have computer systems in place that process data based on common bar codes, it becomes economical to use electronic data interchange to place orders, and automate the distribution system. Once again, small retailers and suppliers find it profitable to take advantage of this installed technology.

With timely inventory data and a computerized ordering system, retailers now find it economical to reduce their inventories by rapidly replenishing products. To do so, retailers invest in technologies that can identify and sort incoming shipments, and offer incentives to suppliers that put bar codes on shipping containers. The retailers' demand for rapid replenishment also encourages suppliers to use leaner production processes that can produce small batches quickly.

The traditional analysis of complementarities focuses on a single firm, and is not well-suited to explain the regime shift described here. For example, Milgrom and Roberts (1990, 1995) provide a comparative-statics analysis of manufacturing complementarities. Their model implies that complementarities "make it relatively unprofitable to adopt only one part of the modern manufacturing strategy. The theory suggests that we should not see an extended period of time during which one component of the strategy is in place, and the other components have barely begun to be put into place" (1990, p. 524). Their argument suggests that within-firm and cross-firm complementarities will lead to simultaneous all-or-nothing technology adoption: revolutionary change in a revolutionary step. What occurred in the apparel industry was a dynamic, asynchronous adoption of a sequence of complementary technologies: revolutionary change in evolutionary steps.

Data

A business unit is defined as the lowest level of a firm with responsibilities for the formulation of annual policies dealing with merchandising, planning, manufacturing, distribution, and related activities for a product line or lines, and which collects financial data for those activities. For some organizations, the business unit may be the overall corporation. For others, a number of business units might operate within a single corporate umbrella. This paper uses a database of 103 business units in the U.S. apparel industry compiled from two comprehensive surveys of apparel suppliers on their 1988 and 1992 practices in the area of information system, logistics, sourcing, design, manufacturing, supplier relations, as well as information about throughput, lead time, and profitability, and other performance outcomes. The sample of apparel manufacturers in the data set represents approximately one-fifth of all shipments of apparel products in the United States in 1992.

The detailed and confidential information requested in the survey meant that a random, stratified sample of the whole apparel industry was not feasible. Instead, in order to secure such detailed responses, the survey effort required sponsorship and support from industry participants. Sponsorship included one major U.S. department store; one major mass merchandiser; and both of the major clothing unions. The two retail sponsors provided listings of their major suppliers and a cross-section of their smaller suppliers. The clothing unions provided lists of employers under contract with the union in targeted product markets. While the contents of the questionnaire were restricted to the investigators, all survey sponsors provided extensive follow-up support to ensure responses from the targeted industry segments. This survey research design was particularly successful in assuring response by major manufacturers in the targeted product segments. As a result, the sample is biased toward larger firms and business units.

Table 1 shows that 1988 retailing practices were mainly characterized by the traditional model described previously, with a large share of products shipped on an infrequent basis. For example, 69 percent of shipments to mass merchants (e.g., Kmart and Wal-Mart) were purchased on a single order basis, as were 56 percent for national chains (e.g., Sears and JC Penney) and 61 percent for department stores (e.g., Dillards, Federated, Nordstrom). In contrast, less than 10 percent of sales were replenished on a daily or weekly basis for any of these categories. Replenishment patterns changed markedly in the next four years. Mass merchants, which typically provide apparel at low price points, increased the percent of sales replenished on a daily or weekly basis sixfold from 7 to 42 percent. National chains, which provide apparel at medium price points, increased the percent of sales replenished on a daily or weekly basis by more than fivefold from 8 to 42 percent. Department stores, which typically provide the widest variety of apparel, and sell at the highest price points, increased the percent of sales replenished on a daily or weekly basis from 2 to 27 percent. The percent of total sales replenished on a daily or weekly basis grew from 9 to 34 percent, while the percent of sales never replenished fell by two-thirds from 62 to 23 percent.

Dependent Variables. Apparel suppliers' ability to provide products under the modern retailing system depends on a combination of four technological innovations and business practices that affect how apparel suppliers acquire and use information concerning demand at the product level. Three of these practices are generic to a wide variety of consumer product industries, while the fourth has parallels in manufacturing settings that draw on various methods of team production.

TABLE 1

AVERAGE PERCENTAGE OF SALES REPLENISHED AT DIFFERENT FREQUENCIES, 1988 AND 1992

	1988	1992	Difference	*p* value
Mass merchants (26% of market in 1988, 27% in 1992)				
Daily	1.49	8.38	6.89	0.007
Weekly	5.40	34.06	28.65	0.000
Biweekly	3.56	11.07	7.52	0.000
Monthly	17.31	23.82	6.51	0.159
Never	68.96	22.90	−46.06	0.000
National chains (18% of market in 1988, 14% in 1992)				
Daily	0.72	8.90	8.17	0.001
Weekly	7.46	33.61	26.15	0.000
Biweekly	5.70	8.81	3.11	0.209
Monthly	26.19	23.59	−2.60	0.596
Never	56.04	25.10	−30.94	0.000
Department stores (28% of market in 1988, 32% in 1992)				
Daily	0.00	0.05	0.05	0.290
Weekly	1.92	26.70	24.78	0.000
Biweekly	3.41	11.95	8.54	0.001
Monthly	31.74	38.83	7.10	0.187
Never	60.51	22.22	−38.29	0.000
All channels				
Daily	1.56	3.74	2.18	0.138
Weekly	7.17	30.14	22.98	0.000
Biweekly	3.56	11.07	7.52	0.000
Monthly	26.03	30.71	4.67	0.253
Never	61.69	22.52	−39.17	0.000

Bar-coded Sales. The percentage of sales utilizing Uniform Product Code (UPC) bar codes. The first practice involves the adoption of standardized product identification systems that provide unique, electronically scannable, bar codes for identifying products at the detailed stock-keeping unit level. The availability of a standardized system of classification and the means to input, store, transmit, and access information on demand inexpensively opens up a wide variety of opportunities. Use of the UPC bar code system confers to adopters a potential capability of significantly decreasing transaction costs. While bar coding is measured as a specific practice, it implies the adoption of a number of technological investments (bar code readers and writers, hand scanners, computer hardware and software) and conventions (the bar codes promulgated by the Uniform Product Council).

Electronic Data Interchange. The percentage of purchase orders received via electronic data interchange (EDI). The second practice involves the use of EDI as a means of transmitting UPC data between apparel suppliers and retailers. Like bar codes, EDI requires a set of investments (computer hardware and software capable of sending and receiving data rapidly) and conventions (a standardized system of data interchange).

Bar-coded Shipping. The percentage of shipments sent by business units with a bar-coded marker on the shipping container is called bar-coded shipping. This third practice involves changes in the way business units prepare products for shipment. The modern distribution centers of major retailers are capable of rapidly identifying and sorting incoming shipments from suppliers through the use of scanning systems, automated sortation and conveyers, and computer controls. At the same time, these systems use this information to process and reconcile invoice information on incoming and outgoing shipments. This requires that incoming shipments adhere to a set of technological and process standards regarding the use of bar code systems for labeling boxes, and the parallel adoption of standards for packing, placing, and shipping products.

Modular Assembly. This is the percentage of domestic sewing output produced using modular or related team assembly systems. Rather than breaking up assembly (sewing) into a long series of small steps, modular production entails grouping tasks, and assigning those tasks to a module, thereby reducing the elapsed throughput time required to assemble a given product. Adoption of this assembly technique entails altering the physical layout of sewing machines and changing human training requirements, compensations systems, and methods of supervision (Dunlop and Weil 1996).

Suppliers responding to frequent purchase-order requests from retailers benefit from the combination of these practices. The access to timely, accurate, and low-cost information via bar-coded sales and EDI transmission reinforces the benefits conferred by providing retailers with shipments marked with bar codes adhering to common shipping standards. Business units that adopt both bar codes and EDI are able to reduce the cost of processing shipments, as this combination enables retailers to scan incoming shipments, check them against purchase orders, authorize payments to suppliers, and identify discrepancies between invoices and actual shipments.

Furthermore, when bar-coded sales and EDI practices are adopted in the presence of bar-coded shipping containers and related shipping conventions (e.g., hand scanning individual products as they are loaded into a box in order to generate a bar-coded shipping container marker), the individual benefit of each practice is further enhanced as order processing occurs more rapidly, accurately, and with less paper. The returns from using a uniform system of product identification thus grow with the presence of systems for transmitting information on a more frequent basis at lower cost per transmission. In turn, the returns from a uniform platform of electronic transmission systems rise with a uniform system of product classification that enables information to be transmitted more efficiently.

Modular production enables firms to reduce the time required for a given product to move through the assembly process from 9 days to 2 for the sample's business units. The benefits of throughput reduction cannot be fully realized, however, if firms are not rewarded for their ability to replenish rapidly. Rapid replenishment, in turn, is premised on the availability of detailed demand data and its frequent and accurate transmission. In this way, modular assembly systems are expected to be complementary with advanced information practices. Advanced practices in distribution and team production may also be complementary because of their mutually reinforcing reduction of throughput time. Similarly, distribution operations that efficiently process finished products (i.e., do not hold them in warehouses or inventories) reinforce the benefits of a modular assembly system. Thus we also look at these three dummy variables:

Advanced Information. A 0–1 dummy variable that takes the value of 1 if the business unit has advanced information technology practices, as evidenced by the product of the fractions of sales utilizing bar codes, EDI, and advanced distribution techniques exceeding 0.05.

Advanced Manufacturing. A 0–1 dummy variable that takes the value of 1 if the business unit is using advanced manufacturing techniques, as evidenced by the business unit using point-of-sales data for production planning and either employing modular assembly techniques or employing advanced cutting, marking, and spreading techniques for more than 30 percent of its sales. The business unit is also considered advanced if the manufacturer uses point-of-sales data for production planning, and employs modular assembly techniques.

Initiative. A 0–1 dummy variable that takes the value of 1 if firm demonstrates high initiative in determining replenishment quantities and initiating quick-response programs with retailers.

It is important to note that adoption decisions regarding the four core practices are typically made by managers in different departments of apparel business units. Bar code decisions primarily reside in the marketing/merchandising area because of their relation to both product specification and pricing. Decisions regarding EDI and related systems reside with management information system departments. Shipping systems are the domain of logistic or distribution departments. Finally, decisions regarding apparel assembly typically reside with manufacturing managers as well as human resource personnel because of the compensation and training implications.

Explanatory Variables. Sales. Business unit sales in millions of dollars. Larger firms are able to spread high fixed costs across more output, and thus enhance cost savings from technology adoption. Other studies of technology adoption (e.g., Rose and Joskow 1990) have typically found evidence of such economies of scale.

SKUs. The total number of stock-keeping units that a business unit produces. SKUs measure the amount of product variety, which should increase the benefits from adopting information technologies.

Basic Products. The percentage of basic products (such as T-shirts, underwear, and socks) in a business unit's collection is called the basic products. The type of products provided by a business unit should provide an incentive to adopt each of the technologies, as most replenishment programs focus on basic products.

Rapid Replenishment. The percentage of sales provided by apparel suppliers to mass merchants and national chain stores on a daily or weekly basis. Rapid replenishment serves as a reasonable proxy for retailer adoption of information technologies, and also reflects the requirements placed on apparel business units by retailers as they demand faster order fulfillment cycles and more rapid replenishment by apparel manufacturers. Case evidence on specific retailers (Gill and Abend 1996) and on the diffusion of bar code technologies (Brown 1997) demonstrates a clear pattern of retailers acting as the first movers in establishing rapid replenishment requirements. Over time, manufacturers and retailers modified their partnerships as manufacturers with more advanced information technology practices matched up with retailers who were also using more information technologies, and thus demanding more rapid replenishment of their orders.

Advanced Channels. A dummy variable that takes the value of 1 if the business unit sells to an advanced retailer, as evidenced by the retailer initiating quick-response and/or rapid-replenishment programs, sharing point-of-sales data with manufacturers, and receiving daily or weekly shipments from their manufacturers. Out of 103 business units in our data set, 33 sold to advanced retailers in 1992.

The historical stock of technologies already adopted will also be unique to business units. For example, some business units adopted bar codes in 1988, while others did not adopt it until several years later. The current stock of technology already employed certainly affects the firm's incentive to adopt further technologies.

Propositions

The first proposition is that the first movers had a unilateral incentive to adopt that did not depend on the adoption of technology by retailers. The second proposition is the ratchet-up hypothesis that technology adoption occurred in steps via a feedback mechanism in which manufacturers adopted more technology as retailers adopted more technology. The third proposition is diffusion hypothesis that the new technologies were adopted by an increasing number of manufacturing firms over time, because the increasing number of downstream firms that adopted affects the incentives of upstream firms.

Empirical Analysis

Smith's (2004) model of the adoption of complementary technologies provides a theoretical explanation for the rapid adoption of linked technologies via a ratchet-up effect. This paper explores three empirical propositions. The first is whether supplier first movers have a unilateral incentive to adopt that does not depend on the number of retail firms that have adopted the matching technology. Bar-coded sales are a necessary precursor to EDI and bar-coded shipping technologies. Table 2 shows that the first movers who adopted bar-coded sales technology by 1988 tended to be larger firms with more product variety and basic items who sold more to mass merchants and on a more frequent replenishment basis. However, only 11 percent of their sales were on a daily or weekly basis, our proxy for the retailer adoption of information technologies. The first movers adopted bar codes before retailers demanded them.

TABLE 2

MEAN VALUES OF CHARACTERISTICS OF BUSINESSES THAT DID AND DID NOT ADOPT BAR-CODED SALES TECHNOLOGY BY 1988

	Some bar-coded sales (n = 49)	No bar-coded sales (n = 51)	Difference	p value
Sales ($ millions)	196.04	116.32	79.72	0.060
Number of SKUs	12,466	6973	5493	0.020
Basic products	49.04%	33.67%	15.36%	0.008
% of sales to mass merchants	33.89%	18.06%	15.83%	0.009
Rapid replenishment	10.97%	2.95%	8.02%	0.021

TABLE 3

REGRESSION MODELS OF TECHNOLOGY ADOPTION BY 1988, *p* VALUES IN PARENTHESES

	Bar-coded sales	EDI	Bar-coded shipping	Modular assembly
Bar-coded sales		0.194* (0.007)	0.750* (0.000)	0.007 (0.634)
EDI			1.994* (0.000)	0.082 (0.461)
Bar-coded shipping				−0.006 (0.872)
Sales	8.016 (0.152)	2.042 (0.228)	4.056 (0.329)	−0.071 (0.823)
SKUs	6.929 (0.078)	2.297 (0.064)	−0.686 (0.816)	−0.271 (0.157)
Basic products	0.633* (0.013)	0.063 (0.419)	−0.117 (0.551)	0.016 (0.199)
Rapid replenishment	0.441 (0.265)	−0.017 (0.877)	−0.731 (0.055)	0.013 (0.491)
Constant	−119.065 (0.004)	−41.891 (0.001)	−62.034 (0.042)	−1.203 (0.516)
Regression *p* value	0.002	0.000	0.000	0.471

*Significant at 5 percent level.

Table 3 shows Tobit estimates of regression models of technology adoption by 1988. The omission of EDI and bar-coded shipping from the bar-coded sales equation, and bar-coded shipping from the EDI equation reflects the reality that bar-coded sales, EDI, and bar-coded shipping are adopted sequentially. At the 5 percent significance level, bar-coded sales is related to product type; EDI adoption is related to bar-coded sales; and bar-coded shipping is related to bar-coded sales and EDI. None of these supplier practices are affected by rapid replenishment, which measures the number of retail firms adopting the matching technology. These results confirm that the first movers were not motivated by retailer demands.

The second proposition is the ratchet-up hypothesis that technology adoption occurs in steps via a feedback mechanism between suppliers and retailers. We investigate whether apparel manufacturers are more likely to adopt information technologies if retailers have adopted matching technologies. Table 4 shows that manufacturers selling to advanced retailers by 1992 were more likely to have adopted the new technologies. Specifically, manufacturers selling to advanced retailers have 50 percent more sales using bar codes (76.61 percent versus 51.45 percent), double the sales using EDI technology (50.57 percent versus 25.64 percent), 50 percent more sales using automated distribution systems (43.75 percent versus 27.91 percent), and 50 percent more sales using modular team assembly techniques (14.12 percent versus 9.08 percent). Firms selling to advanced retailers are also three times more likely to have adopted advanced information technology systems (66.67 percent versus 21.43 percent), and twice as likely to have adopted advanced manufacturing techniques (48.48 percent versus 25.71 percent). These firms also have significantly shorter lead times, and half as many stockouts and

TABLE 4

MEAN VALUES OF CHARACTERISTICS OF BUSINESSES SELLING TO ADVANCED AND NONADVANCED RETAILERS, 1992

	Advanced Channels = 1 (*n* = 33)	Advanced Channels = 0 (*n* = 70)	Difference	*p* value
Sales ($ millions)	265.4	127.8	137.6	0.029
Number of SKUs	11,693	8410	3283	0.147
Basic products	52.95%	32.35%	20.60%	0.001
Rapid replenishment	52.82%	18.16%	34.66%	0.000
Bar-coded sales	76.61%	51.45%	25.16%	0.002
EDI	50.57%	25.64%	24.93%	0.000
Bar-coded shipping	43.75%	27.91%	15.84%	0.025
Modular assembly	14.12%	9.08%	5.04%	0.106
Advanced information	66.67%	21.43%	45.24%	0.000
Advanced manufacturing	48.48%	25.71%	22.77%	0.022
Profit margin	8.52%	8.54%	−0.025%	0.507
% goods delivered on time	89.59%	85.95%	3.64%	0.077
Lead time in days	73	105	−32	0.011
% stockouts	7.90%	15.22%	−7.32%	0.013
% substitutions	7.11%	10.41%	−3.30%	0.166

substitutions. These data indicate that a feedback loop encourages advances on the manufacturing side when retailers adopt new technologies. If retailers were not adopting better technologies, manufacturers would have little or no incentive to adopt better manufacturing techniques.

The Tobit estimates in Table 5 show that, at the 5 percent significance level, the adoption of bar-coded sales, EDI, and bar-coded shipping technology in 1992 are related positively to the past adoption of the same technology. In addition, bar-coded sales and EDI are positively related to whether the firm sells to technologically advanced retailers. EDI is also related positively to product type, and bar-coded shipping is related positively to bar-coded sales and SKUs. These results indicate that, by 1992, retailer technologies were affecting supplier technologies.

Table 6 indicates that the technology adoption decisions of manufacturers and retailers are positively related. The correlations between selling to an advanced retailer and using advanced information systems and advanced manufacturing systems are 0.44 and 0.23, respectively. The logit estimates in Table 7 show that controlling for size, product variety, and basic product mixes, manufacturing firms are more likely to adopt advanced information systems, and to show more initiative in initiating quick response programs and in determining their own replenishment quantities if they sell to advanced retailers who have adopted matching technologies. The coefficients in the table

TABLE 5

REGRESSION MODELS OF TECHNOLOGY ADOPTION BY 1992, p VALUES IN PARENTHESES

	Bar-coded sales	EDI	Bar-coded shipping	Modular assembly
Bar-coded sales 1988	0.696* (0.002)	0.137 (0.077)	0.233 (0.365)	0.095 (0.414)
EDI 1988		0.686* (0.005)	0.728 (0.352)	0.692* (0.050)
Bar-coded shipping 1988			1.766* (0.006)	0.013 (0.943)
Modular assembly 1988				−4.010 (0.751)
Sales	4.213 (0.415)	2.758 (0.150)	18.470* (0.005)	3.993 (0.134)
SKUs	0.751 (0.813)	−0.020 (0.987)	−7.367* (0.049)	0.160 (0.927)
Basic products	0.358 (0.084)	0.290* (0.000)	0.038 (0.877)	−0.177 (0.120)
Rapid replenishment	0.547* (0.018)	0.327* (0.000)	0.352 (0.176)	−0.001 (0.992)
Constant	−0.759 (0.979)	−7.785 (0.483)	−35.127 (0.311)	−18.581 (0.225)
Regression p value	0.000	0.000	0.000	0.145

*Significant at 5 percent level.

TABLE 6

RELATIONSHIP BETWEEN TECHNOLOGY ADOPTION OF MANUFACTURERS AND RETAILERS IN 1992, p VALUES IN PARENTHESES

	Advanced channels	Advanced information	Advanced manufacturing
Advanced channels	1		
Advanced information	0.440 (0.000)	1	
Advanced manufacturing	0.226 (0.022)	0.206 (0.037)	1

TABLE 7

REGRESSION MODELS OF FEEDBACK EFFECT: IMPACT OF BEING IN ADVANCED CHANNEL IN 1992, p VALUES IN PARENTHESES

	Advanced information	Advanced manufacturing	Initiative
Sales	0.103* (0.021)	0.133* (0.002)	0.051 (0.099)
SKUs	−0.010 (0.724)	0.024 (0.357)	0.026 (0.230)
Basic products	0.003 (0.067)	0.004* (0.010)	0.001 (0.700)
Advanced channels	0.362* (0.001)	0.061 (0.557)	0.224* (0.005)
Constant	−0.759 (0.004)	−1.123 (0.000)	−0.730 (0.001)
Regression p value	0.000	0.000	0.001

*Significant at 5 percent level.

are dP/dX, the estimated effect on the adoption probability of a change in the explanatory variable, at the mean values of the explanatory variables. For example, it is estimated that selling to an advanced retailer increases the probability of adopting advanced information systems by 0.362, and

TABLE 8

CORRELATION EVIDENCE OF MATCHING PROCESSES, *p* VALUES IN PARENTHESES

1988

	Rapid replenishment	Bar-coded sales	EDI	Bar-coded shipping	Modular assembly
Rapid replenishment	1				
Bar-coded sales	0.205	1			
	(0.041)				
EDI	0.184	0.261	1		
	(0.067)	(0.008)			
Bar-coded shipping	−0.024	0.451	0.449	1	
	(0.810)	(0.000)	(0.000)		
Modular assembly	0.080	0.081	−0.083	−0.054	1
	(0.428)	(0.855)	(0.407)	(0.588)	

1992

	Rapid replenishment	Advanced channels	Bar-coded sales	EDI	Bar-coded shipping	Modular assembly
Rapid replenishment	1					
Advanced channels	0.525	1				
	(0.000)					
Bar-coded sales	0.437	0.288	1			
	(0.000)	(0.003)				
EDI	0.553	0.414	0.433	1		
	(0.000)	(0.000)	(0.000)			
Bar-coded shipping	0.262	0.194	0.263	0.406	1	
	(0.007)	(0.050)	(0.007)	(0.000)		
Modular assembly	0.087	0.124	0.016	0.132	0.244	1
	(0.385)	(0.212)	(0.875)	(0.185)	(0.013)	

increases the probability of showing initiative by 0.224. The level of technological sophistication of the customers should only matter in a situation where ratcheting-up is occurring.

Table 8 presents additional evidence consistent with a matching process. The correlations between rapid replenishment, the percentage of sales to mass merchants and national chains on a daily or weekly basis, and bar-coded sales, EDI, and bar-coded shipping rose between 1988 to 1992 from 0.21 to 0.44, 0.18 to 0.55, and –0.02 to 0.26, respectively. Table 8 also shows substantial and statistically persuasive correlations between selling to an advanced retailer and adopting bar-coded sales and EDI technologies. This suggests that these technologies are more important for providing rapid replenishment than under traditional retailing. This evidence is also consistent with the idea that firms are sorting partners over time as manufacturing firms with more information technologies match up with retailers who are using more information technologies, and thus demanding more rapid replenishment of their orders.

TABLE 9

Evidence of Diffusion of Technologies

	1988	1992	Difference	*p* value
Average percentage sales				
Bar-coded sales	24.75	59.51	34.76	0.000
EDI	5.11	33.63	28.52	0.000
Bar-coded shipping	8.24	32.99	24.75	0.000
Rapid replenishment	6.88	29.33	22.45	0.000
Percent of firms that adopted any positive amount				
Barcoded sales	50.49	85.44	34.95	0.000
EDI	39.81	84.47	44.66	0.000
Bar-coded shipping	30.10	60.19	30.09	0.000
Modular assembly	7.77	50.49	42.72	0.000

The third proposition is that, over time, an increasing number of firms adopt the new technology as the network effect increases. Table 9 demonstrates that both the adoption intensity and breadth of adoption rose over time. Evidence of increased intensity of adoption can be seen from the fact that the average percentage of sales using bar codes more than doubled (from 25 to 60 percent), using EDI more than quintupled (from 5 to 34 percent), and using bar-coded shipping more than quadrupled (from 8 to 33 percent) in 4 years between 1988 and 1992. We also see evidence of greater breadth of adoption over time. The fraction of firms adopting bar-coded sales increased more than 50 percent. The fraction of firms adopting EDI and bar-coded shipping more than doubled, and the fraction of firms adopting modular team systems more than quintupled between 1988 and 1992.

Conclusion

This paper presents evidence of a ratchet-up process of technology adoption where linked technologies induce a rapid regime shift without explicit coordination or planning. We find that the level of technological sophistication of the retail customers matters for technology adoption by suppliers, which would only be expected if ratcheting-up were occurring. If retailers were not adopting better technologies, manufacturers would have little or no incentive to adopt better manufacturing techniques. The ratchet-up effect also implies that firms sort partners over time as manufacturing firms with more information technologies match up with retailers who are also using more information technologies, and thus demanding more rapid replenishment of their orders.

Controlling for size, product variety, basic product mixes, and the firm's past stock of technology, manufacturing firms selling to advanced retailers who have adopted the matching technology were found to be more likely to adopt bar codes, EDI, advanced information systems, and to show more initiative in initiating quick response programs, and in determining their own replenishment quantities. Moreover, firms that sell to advanced retailers have lower inventories, higher profits, higher on-time deliveries, much shorter lead times, stockouts, and substitutions than firms that are not selling to advanced retailers.

The methods of retailing described here are becoming widespread. Modern retailing practices have now diffused in the retail distribution of food and groceries, toys, consumer electronics, office products, home building supplies, and automobiles. The firms that supply these retailers face many of the same incentives described here. Economists studying technology adoption in these industries should therefore look at the complete supply chain. When information technologies link upstream manufacturers and downstream retailers, the interaction adoption decisions of each affect each other's decisions.

References

Abernathy, Frederick, John T. Dunlop, Janice H. Hammond, and David Weil. 1999. *A Stitch in Time*. Oxford: Oxford University Press.

Aguirregabaria, Victor. 1999. "The Dynamics of Mark-ups and Inventories in Retailing Firms." *Review of Economic Studies* 66(2):275–308.

Black, Sandra E. and Lisa M. Lynch. 2001. "How to Compete: The Impact of Workplace Practices and Information Technology on Productivity," *Review of Economics and Statistics* 83(August):434–445.

Brown, Stephen. 1997. *Revolution at the Checkout Counter: The Explosion of the Bar Code*. Cambridge, MA: Harvard University Press.

Chandler, Alfred D., Jr. 1977. *The Visible Hand: The Managerial Revolution in American Business*. Cambridge, MA: Harvard University Press.

Chen, Zhiq. 2003. "Dominant Retailers and the Countervailing-Power Hypothesis," *RAND Journal of Economics* 34(Winter):612–625.

Dunlop, John T. and David Weil. 1996. "Diffusion and Performance of Modular Production in the U.S. Apparel Industry," *Industrial Relations* 35(July):334–355.

Fisher, Marshall, and Ananth Raman. 1996. "Reducing the Cost of Demand Uncertainty Through Accurate Response to Early Sales," *Operations Research* 44(Jan–Feb):87–99.

Gill, Penny and Jules Abend. 1996. "Wal-Mart: The Supply Chain Heavyweight Champion," *Supply Chain Management Review* (Summer):8–16.

Ichniowski, Casey and Kathryn Shaw. 2003. "Beyond Incentive Pay: Insiders' Estimates of the Value of Complementary Human Resource Management Policies," *Journal of Economic Perspectives* 17(Winter):155–180.

Milgrom, Paul and John Roberts. 1990. "The Economics of Modern Manufacturing," *American Economic Review* 80(June):511–528.

———. 1995. "Complementarities and Fit: Strategy, Structure, and Organizational Change in Manufacturing," *Journal of Accounting and Economics* 19(March–May):179–208.

Pashigian, Peter B. 1988. "Demand Uncertainty and Sales: A Study of Fashion and Markdown Pricing," *American Economic Review* 78(December):936–953.

Rose, Nancy L. and Paul L. Joskow. 1990. "The Diffusion of New Technologies: Evidence from the Electric Utility Industry," *Rand Journal of Economics* 21(Autumn):354–373.

Smith, Margaret Hwang. 2004. "A Model of the Linked Adoption of Complementary Technologies," *Economics of Innovation and New Technology* 13(January):91–99.