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The Impact of E-Replenishment Strategy on Make-to-Order Supply Chain Performance

E. Powell Robinson Jr.†
Department of Information and Operations Management, Mays Business School, Texas A&M University, College Station, TX 77843-4217, e-mail: probinson@cgsb.tamu.edu

Funda Sahin
Department of Marketing and Logistics, College of Business Administration, The University of Tennessee, Knoxville, TN 37996-0530, e-mail: fsahin@utk.edu

Li-Lian Gao
Department of Management, Entrepreneurship & General Business, Frank G. Zarb School of Business, Hofstra University, Hempstead, NY 11549, e-mail: li-lian.gao@hofstra.edu

ABSTRACT

This research investigates the impact of electronic replenishment strategy on the operational activities and performance of a two-stage make-to-order supply chain. We develop simulation-based rolling schedule procedures that link the replenishment processes of the channel members and apply them in an experimental analysis to study manual, semi-automated, and fully automated e-replenishment strategies in decentralized and coordinated decision-making supply chain structures. The average operational cost reductions for moving from a manual-based system to a fully automated system are 19.6, 29.5, and 12.5%, respectively, for traditional decentralized, decentralized with information sharing, and coordinated supply chain structures. The savings are neither equally distributed among participants, nor consistent across supply chain structures. As expected, for the fully coordinated system, total costs monotonically decrease with higher levels of automation. However, for the two decentralized structures, under which most firms operate today, counter-intuitive findings reveal that the unilateral application of e-procurement technology by the buyer may lower his purchasing costs, but increase the seller's and system's costs. The exact nature of the relationship is determined by the channel's operational flexibility. Broader results indicate that while the potential economic benefit of e-replenishment in a decentralized system is substantial, greater operational improvements maybe possible through supply chain coordination.

Subject Areas: E-Business, MIS/OM Interface, Purchasing, and Supply Chain Management.

INTRODUCTION

Recent developments in electronic replenishment (e-replenishment) technology are enabling firms to rethink their business processes and explore new avenues for

†Corresponding author.

cost reduction. This is occurring at an opportune time, as higher levels of product variety, shorter product life cycles, and greater reliance on outsourcing of manufacturing processes are increasing supply chain complexity and cost. However, an incomplete understanding of the operational impact of e-replenishment on supply chain operations and costs often hinders efforts to move forward with system improvement. This is particularly true when the technology decisions of one channel member influence the actions and performance of its partners.

E-replenishment is the seamless automation of the buyer's procurement and vendor's fulfillment processes (PricewaterhouseCoopers, 2002). Procurement is a multipart process, which includes vendor certification and selection, requisition preparation and approval, order placement, goods receipt, reconciliation and payment of the invoice, and order archiving. Fulfillment activities include responding to requests for information and quotes, acknowledging order receipt, order processing, order preparation for shipment, shipment, invoice preparation, and accounts receivable management. E-replenishment saves time and money by replacing paper catalogs/drawings and manual activities with electronic catalogs/drawings, computer-assisted requisitioning, electronic workflow management, a data transmission mechanism to route orders to the appropriate vendors in the correct format, an archive system for recording transactions, and electronic payment.

E-replenishment systems are evolving for both make-to-stock and make-to-order systems. Make-to-stock items, such as those purchased for resale, office supplies, maintenance, repair, and operations (MRO) supplier, and generic components, are typically managed with statistical inventory planning and control procedures. Owing to numerous customers drawing on the same inventory pool, an individual customer's purchase order (PO) has a negligible direct impact on upstream replenishment activities other than processing and shipping the order from stock. Make-to-order items can be either end items or direct inputs into the production process, where all manufacturing and order fulfillment processes are initiated after receiving the customer's order. In this environment, the procurement activities of one-partner directly impact the operations of upstream channel members, such as when an order triggers a dedicated production run and shipment by the vendor. Material requirements planning (MRP) software is the standard approach for determining replenishment quantities and timing in make-to-order systems.

To enhance supply chain performance, many firms are exploring e-replenishment systems for make-to-order systems and the software is available from a variety of sources including enterprise resource planning and supply chain software vendors. In addition, third party service providers and industry consortium electronic marketplace exchanges provide access to e-replenishment systems for a fee. Most systems permit transactions over the firms' existing electronic data interchange (EDI) connections or the Internet and can link with the automated, semi-automated, and manual-based procurement systems of the trading partners. Therefore, channel partners may choose from an array of alternative replenishment strategies and cost structures for supply chain integration. Traditional manual-based systems are heavily labor-based with relatively high variable cost structures, but require low technology investment. Fully automated systems, which replace labor with information systems technology, have low variable costs, but require substantial technology investment. In between, semi-automated systems have moderate operational and investment costs. Third party service providers and industry consortia exchanges provide moderate cost alternatives, often including a combination of a fixed annual fee and a per transaction charge.

Although there is a growing stream of literature examining the impact of information technology on supply chain performance within a make-to-stock environment (for literature surveys, see: Sahin and Robinson, (2002) and Tayur, Ganeshan, and Magazine (1999)), we failed to identify any research investigating e-replenishment within a make-to-order setting. Furthermore, e-replenishment research at the operational level focuses primarily on the transaction costs of the individual channel members. We found only a single article investigating the impact of e-replenishment on supply chain cost, and the focus was on a make-to-stock retail environment.

This research fills some of the gaps in the literature by documenting the procurement activities associated with the traditional make-to-order supply chain of two Fortune 500 companies providing custom made drilling equipment. Next, on the basis of the collected data, we conduct an experimental analysis of the alternative replenishment strategies. The level of automation, including manual, semi-automated, and fully automated, in the procurement and fulfillment processes differentiates the replenishment strategies. Our objective is to identify how e-replenishment strategy drives channel activities and performance under traditional decentralized, decentralized with information sharing, and coordinated supply chain structures. These organizational structures represent commonly applied and theoretically accepted approaches to supply chain management in today's business environments. For each organizational structure, we propose simulation-based rolling schedule planning procedures, which link the channel members and mathematically characterize procurement, transportation, and fulfillment activities under alternative replenishment strategies. These modeling features generalize the single-enterprise rolling schedule frameworks in the literature to consider two-stage supply relationships. In addition, we employ a more general modeling representation of the coordinated replenishment problem that considers the cost structures of the buyer, seller, and transportation provider in determining an optimal solution. Prior coordinated replenishment models only address the problem from a single-firm perspective (see Robinson and Lawrence (2004), for a recent literature survey of the problem). The experimental frameworks provide a new approach for modeling and understanding the impact of e-replenishment on supply chain performance and operational activity.

Utilizing data derived from the equipment supply chain, we investigate the impact of e-replenishment strategy on supply chain operations and costs at the system, channel member, and cost component level. The findings indicate that the cost reduction for moving from a traditional manual-based system to a fully automated system is 19.6%, 29.5%, and 12.5%, respectively, for traditional decentralized, decentralized with information sharing, and coordinated decision-making supply chain structures. However, the savings are unequally distributed among channel participants, and the allocation of savings varies significantly across decision-making structures. As expected, for the coordinated system, total costs decrease monotonically with higher levels of automation. However, for the decentralized systems, under which most firms operate today, unexpected findings reveal that the implementation of higher levels of e-procurement technology by the manufacturer may lower his costs, but increase total system costs. Further analysis indicates that the flexibility ratio of the supply chain's procurement processes to fulfillment processes is a major determinant of the channel's effectiveness in handling the larger number of orders associated with enhanced e-replenishment technologies in a decentralized decision-making supply chain environment.

Although channel flexibility emerged as a prime factor influencing system performance in this research, it is largely overlooked in the literature, and merits consideration when evaluating operational-based supply chain relationships. The findings also isolate environmental factors that favor the application of increased automation and compare the impact of e-replenishment across decision-making structures. Broader findings associated with the research suggest that while the potential economic benefit of e-replenishment in a decentralized system is substantial, greater economic opportunities may be available through improved supply chain coordination. This research provides basic theoretical and managerial insights into the relationships among e-replenishment, operational activity and cost performance, and decision-making structures in make-to-order supply chains.

LITERATURE REVIEW

The literature investigating the application of e-business technologies to replenishment processes is rapidly emerging. Chopra, Dougan, and Taylor (2001) identify several distinct areas, where business-to-business e-commerce is applied to extract value. These include improved market efficiencies, reduced transaction costs, and supply chain integration.

E-marketplaces improve market efficiencies by facilitating the search for trading partners and products. A full discussion of e-marketplaces is outside the scope of this research owing to their primary application to catalog and spot market purchases. Timmers (1999), Turban, Lee, King, and Chung (2000), Eisenmann (2002), Kalakota (2000), and Kaplan and Sawhney (2000) provide comprehensive treatment of e-marketplace business models, value propositions, and taxonomies.

The impact of electronic procurement processes on transaction costs has received considerable research attention. Moving from traditional procedures with heavy reliance on telephone, paper, e-mail, and fax to electronic processes eliminates human involvement, thereby reducing labor costs, error rates, and order cycle lead-time. Woodall (2000) reports 90% savings in transaction costs at British Telecom by going online. Ruzicka (2000) finds that traditional ERP based transactions cost $75 per order and automated electronic transactions cost $3 per order. Eisenmann (2002) indicates that the cost to manually administer a PO ranges from $40 to $200, whereas the cost to process an electronic PO ranges from $1 to $20. Other researchers report similar transaction costs for traditional and electronic order processing systems (Kalakota, 2000; Tan & Dajalos, 2001). The above studies document the impact of e-procurement on transaction processing costs. However, the impact of these reduced costs on channel activities and costs at the firm and system level are not addressed.

Research addressing the impact of information technology on supply chain integration and performance accelerated in the mid-1990s. Sahin and Robinson (2002) provide an in depth survey of this research classifying it into three categories on the basis of the alternative levels of information sharing and decision-making structure. The first category is based on Forrester's (1958) seminal study of "traditional" supply chains, which are characterized by a decentralized decision-making (i.e., local optimization) structure with no information sharing among channel members. Major findings, termed "industrial dynamics" or the "bullwhip effect," reveal that minor changes in demand at the customer level can amplify moving upstream in the supply chain causing operational inefficiencies. Numerous researchers investigate the causes of the bullwhip effect and quantify its impact on channel performance (Lee, Padhamanabhan, & Whang, 1997a, b; Metters, 1997; Baganha & Cohen, 1998; Cachon, 1999; Taylor, 1999).

The next research category also examines decentralized decision-making but with information sharing (demand forecasts, inventory data, advance orders, ordering policy, etc.) among channel members. Noteworthy research includes Bourland, Powell, and Pyke (1996), Iyer and Bergen (1997), Gilbert and Ballou (1999), and Gavirneni, Kapuscinski, and Tayur (1999), among others. Although this research finds that information sharing yields significant benefits, it does not eliminate the bullwhip effect in decentralized systems.

The final category considers coordinated supply chains, which are characterized by full information sharing and system optimization. Significant work in the area includes Whang (1995), Anand and Mendelson (1997), Hariharan and Zipkin (1995), Cachon and Fisher (2000), and Krajewski and Wei (2001). In closely related work, Aviv and Federguen (1998), Waller, Johnson, and Davis (1999), and Fry, Kapusincski, and Olsen (2001) study coordination in VMI environments. Comparing the research findings across the studies indicates that information sharing and coordinated decision-making may reduce supply chain costs anywhere from 0% to 35% depending on the specific supply chain structure and problem assumptions. Consequently, Cachon and Fischer (2000) caution against transferring the findings associated with one problem environment onto another one with dissimilar operating characteristics.

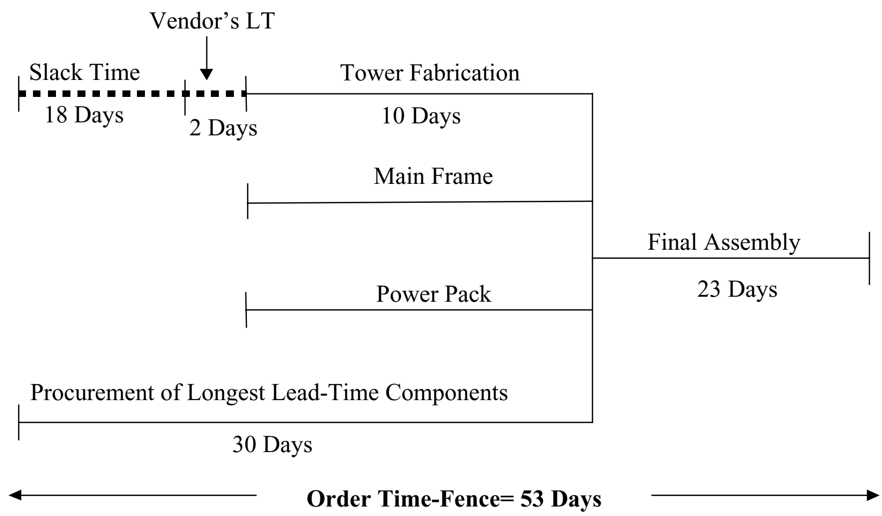
All of the cited research concentrates on make-to-stock systems and employs statistical inventory control procedures, which assume an independent demand environment, a single-item with a stationary stochastic demand pattern, an infinite planning horizon, and that inventory is stocked in anticipation of demand. These operational features are in direct contrast with those of make-to-order supply chains, which are characterized by dependent demand relationships, multiple items, highly erratic and often discontinuous demand at the end item level, lumpy and deterministic dynamic-demand at the component level, short finite planning horizons, and an inability to maintain inventory in anticipation of demand. These demand and supply characteristics are more accurately modeled by simulation-based rolling schedule procedures. Furthermore, only a single paper (Cachon & Fisher, 2000) considers the potential impact of e-replenishment technologies on supply chain operations. Their findings, assuming a decentralized decision-making structure with a single vendor serving multiple retailers facing identical independently distributed stochastic demand, suggest that the impact of e-procurement in reducing batch sizes and replenishment lead times may exceed the benefits associated with improved forecast accuracy due to the sharing of point-of-sales data among channel members.

This research on e-replenishment systems in a make-to-order supply chain fills an important gap in the literature. We propose that different information technologies have unique cost and operational characteristics that determine which application is best suited to a particular supply chain and decision-making structure. In contrast to Cachon and Fisher's (2000) results for make-to-stock systems, we find that moving to an e-procurement system can potentially increase system costs in a make-to-order environment. These unexpected results, when coupled with the distinct demand and operational characteristics of make-to-stock and make-to-order supply chains, justify studying the replenishment systems of each system type independently. In addition, although e-procurement promises to lower the manufacturer's transaction costs, past research on system dynamics indicates that it is myopic to focus on optimizing an individual channel member's performance since it might yield a sub-optimal system solution. Specifically, an investment in e-procurement technology by the manufacturer can reduce his transaction costs and the associated economic purchase quantities, which can influence replenishment activities and costs of upstream channel members. Given the interdependencies among channel members, it is not clear whether lowering the buyer's transaction costs results in system benefits, and if it does, how these benefits are distributed among trading partners. We attempt to shed light on these issues in traditional decentralized, decentralized with information sharing, and coordinated supply chain structures. Our results lay the foundation for understanding the potential impact of e-replenishment technology on channel activities and performance both within and across these organizational structures. Of particular interest is the finding that channel flexibility is a prime factor in determining the potential impact of increased procurement automation on system performance. Finally, the simulation-based rolling schedule framework proposed in this research provides an effective decision support tool for analyzing and understanding the economic trade-offs inherent in alternative e-replenishment strategies.

MAKE-TO-ORDER PROBLEM ENVIRONMENT

This research is based on our observations of a vendor-manufacturer relationship involving two Fortune 500 firms in the construction equipment industry. The environment is representative of traditional supply chain processes throughout this industry, and others. The product line includes custom drilling applications ranging from truck-based water well drilling equipment to heavy-duty platforms for drilling mining blast holes. Unit prices range from $200,000 to $2 million. We focus on the truck-based product line and a vendor of steel components for mainframe platform and drilling tower fabrication. Owing to the custom nature of the applications and the inability to accurately forecast module options, both channel members

Figure 1: Cumulative manufacturing and procurement lead times.



employ a make-to-order production strategy. We briefly describe the production, procurement, and order fulfillment processes of this system.

The manufacturer's processes include engineering design, component production, fabrication, final assembly, testing, and coordination of a diverse vendor base. Examples of purchased components include truck chassis, valves, power packs, and metal components for drilling towers. The manufacturer quotes its customers a minimum 53-day delivery lead-time, which equals the longest cumulative lead-time path in the bill-of-materials (BOM). Once an order's delivery date passes a 53-day order time fence, its configuration and order quantity are frozen in the final assembly schedule. This provides sufficient lead-time for all procurement and production operations along each path of the BOM. The cumulative lead times associated with the product line are illustrated in Figure 1.

Viewing the BOM from a critical path management perspective with the project start time at zero and the finish time at day 53, the slack time, ST_j, associated with item (component) j's path is $ST_j = l_{\mathrm{CP}} - l_j$, where l_{CP} is the lead-time of the critical BOM path and l_j, is the length of an item j's BOM path. The slack time indicates how long the manufacturer can delay launching a PO for item j once the end item crosses the order time fence. This establishes the maximum planning horizon for component replenishment. The slack time for the metal components used in tower fabrication is $ST_j = 53 - (23 + 10 + 2) = 18$ days. By delaying the order placement until day 18, the manufacturer can potentially accumulate additional requirements during the slack time interval and conduct economic lot-size scheduling.

A MRP system coordinates the manufacturer's production and procurement schedules. Since replenishment lot-sizes may change from one MRP processing cycle to the next as new end items cross the order time fence, the firm uses a 12-period frozen time fence to control schedule nervousness. All orders within the first 12 planning periods are frozen in quantity and timing, whereas orders in period 13 to the end of the planning horizon are considered slushy and frozen in time but their order quantities may change. Blackburn, Kropp, and Millen (1986), Orlicky (1975), Sridharan, Berry, and Udayabhanu (1987), Vollmann, Berry, and Whybark (1997), and Zipkin (2000) discuss the application of time fences in MRP systems.

The steel components are strategic purchases whose timely delivery is critical for efficient production operations. Hence, the manufacturer maintains close relationships with a limited number of high quality and reliable vendors for these items. Each vendor provides 10–80 different components with each component being single sourced. A separate PO is submitted to the vendor for each item triggered for replenishment by the MRP system. Local "hot shot" truck service provides same-day across town point-to-point delivery for a fixed charge plus a variable cost per unit weight. All items scheduled for delivery on the same day share the fixed shipment charge.

The supply chain's current replenishment processes are labor-based relying on paper, mail, fax, phone, and e-mail. The procurement process begins when MRP triggers an order release at the manufacturer. The purchasing agent reviews the suggested order, identifies the appropriate vendor, fills out a paper PO, obtains approval as necessary, prints multiple hard copies of the PO, faxes the PO to the vendor, mails a hard copy as a backup, and files a copy for his records. Depending upon the criticality of the order, he may follow up with the vendor to verify the progress of the order. After receiving the inbound shipment, the PO is pulled and matched with the bill-of-lading (BOL) to insure order fulfillment accuracy. After the invoice is received from the vendor and any variances are resolved, three-way matching of the paperwork (PO, BOL, and invoice) occurs and the documents are submitted to accounts payable for processing.

Upon receiving the PO, the vendor manually enters it into his system, verifies its accuracy, creates a production work order assigning it a start and completion date, and then confirms receipt of the PO and its anticipated shipment date by faxing or e-mailing the manufacturer. Multiple paper copies of the work order are made. One is held in the office, and two are sent to the production scheduler who files one and releases the second as a traveler with the work-in-process. Upon completion of production, the parts are palletized, and positioned in the yard until their shipping date. On each day requiring a shipment to the manufacturer, the vendor notifies the trucking firm and prepares a separate BOL for each order. The BOL contains the part number, quantity, description, PO number, etc. and is filled out in quadruplicate for distribution to the vendor, transportation provider, and manufacturer. After shipment, the vendor pulls the PO, matches it with the BOL, prepares an invoice, mails it to the manufacturer's accounts payable department, and files the paperwork. When payment is received, the paperwork is once again pulled for processing.

MATHEMATICAL MODELS AND SOLUTION PROCEDURE

We propose simulation-based rolling schedule planning procedures for linking the operational processes of the manufacturer, vendor, and transportation provider under traditional decentralized decision-making, decentralized decision-making with information sharing, and coordinated decision-making supply chain structures. These organizational structures are well documented in the literature (Sahin & Robinson, 2002) and range from the most rudimentary to the most highly integrated systems. We propose a unique rolling schedule framework and solution procedure for each system type. The procedures extend the single-enterprise rolling schedule frameworks reported in the literature to a two-stage environment.

Owing to their frequent application and importance in industry, rolling schedule procedures are widely studied (see Yeung, Wong, and Ma (1998) for a literature survey). The general approach is to solve a static replenishment problem on the basis of the available data over a limited planning horizon. However, only the earliest orders are implemented before the static model is resolved utilizing newly available demand data. In this manner, the replenishment plan is continually being updated using the latest information. Our research methodology replicates this rolling schedule process with computer simulation, where the static replenishment problems are solved to optimality.

An important aspect of the mathematical model development is determining the level of model detail for the static replenishment problem. The model must be robust enough to capture the main economic tradeoffs and structural constraints driving the problem solution, without over burdening it with unnecessary detail. The proposed models consider the economic impact of all relevant resources consumed by the channel members, but do not explicitly consider resource capacity constraints. This is in accordance with strategic planning models, where capacity is considered variable in the intermediate term and the objective of the model is to identify strategic capacity levels. In addition, the replenishment strategy does not impact the annual demand facing the channel members, but impact only the quantity and timing of orders. Recognizing that the vendor and transportation provider serve a variety of customers, it is reasonable to assume that each maintains adequate capacity to accommodate adjustments in order patterns.

As the intent of the research is to study the impact of e-replenishment strategy on operational activities and costs, the models do not include the sunk costs associated with implementing the various information technologies. However, it should be clear that the frameworks provide insight into the potential operational savings associated with a specific technology investment, thereby providing valuable economic input into the technology investment decision.

Traditional Decentralized Supply Chain: Mathematical Model

The operational features of the traditional supply chain model mirror the systems studied in Forrester (1958), Bourland et al. (1996), and Fry et al. (2001) and our observations of the drilling equipment industry. Key features are decentralized decision-making with no information sharing among channel members.

On the basis of gross requirements derived from the assembly schedule, the manufacturer optimizes his procurement schedules for each item $j = 1, 2, \ldots, N$ over a T-period planning horizon and releases orders one at a time according to the vendor's delivery lead time, L_j, for item j. In the absence of any visibility into future orders, the vendor responds on a lot-for-lot basis and schedules transportation shipments as specified by the manufacturer's replenishment due dates. The manufacturer employs an n-period ($n \leq T$) frozen time fence. To determine the start of the next planning cycle for each item, the scheduling system rolls through time until it encounters the first period whose demand is not covered by an order in the current frozen replenishment schedule. The system then offsets by L_j time periods and initiates the next T-period planning cycle. Owing to differences in cost and demand parameters, the items may have different starting time periods for the planning cycles. To simplify the notation, and without loss of generality, we assume $L_j = 0$ for all j and omit it from the problem formulations.

Our experimental framework considers a K-period problem, which is solved as a series of T-period rolling horizon problems. Potential replenishment periods in each rolling horizon problem are denoted $i = i_{\text{beg}}, \ldots, i_{\text{end}}$ and demand periods $t = i_{\text{beg}}, \ldots, i_{\text{end}}$. Each planning horizon is T periods long, except for the last planning horizon, which may be shorter than T periods. The beginning and ending period of each planning cycle are dynamic and determined based on the previous iteration's solution.

For each purchased item $j = 1, 2, \ldots, N$ and at each planning cycle iteration r, $r = 1, 2, \ldots, \text{IT}_j$, the manufacturer solves a Wagner-Whitin (Wagner & Whitin, 1958) type economic lot sizing problem (MLSP(j, r)) as defined in equations (1)–(5). Demand, D_{jt}, for purchased item j in time period t is obtained from the firm's MRP output and corresponds to the net requirements for component j. This demand is deterministic owing to the frozen order schedule, varies with time and must be satisfied. The manufacturer's fixed replenishment cost for item j in time i is composed of an order processing cost, S_i, and a line item cost, $P_{(m)ij}$, for order processing and material handling. Variable costs include a per-unit order processing and material handling cost, p_j, for each item j and a per unit inventory holding cost, h_{ijt}, for serving demand for product j in period t with product procured in time period i. Y_{ij} represents a PO for product j in time period i, where $Y_{ij} = 1$ if a replenishment is scheduled, and 0 otherwise. X_{ijt} is the fraction of demand in time period t for product j that is supplied from replenishment in time period i. Constraint (2) insures that demand in each time period is served. Constraint set (3) does not permit replenishment from a time period unless its replenishment fixed costs are incurred.

Equation (6) gathers the manufacturer's costs associated with the ordering decisions up to the frozen time fence where $\hat{Y}_{ij}$ and $\hat{X}_{ijt}$ are the optimal solutions to Problem MLSP(j, r) and i_z is the last period within the frozen time fence. A frozen order may cover demand in time periods extending beyond period i_z. The manufacturer's total costs over the N items and IT_j planning cycles are collected in equation (7).

Equation (8) gathers the vendor's lot-for-lot order fulfillment costs for item j in planning iteration r. Relevant costs are equipment setup cost $P_{(v)ij}$, for item j in time period i, an invoice processing cost, W_i for time period i, and a per-unit production cost, c_{ijt}, for item j replenished in time period i to meet demand in time period t. The vendor's total costs for all items and planning cycles are calculated in equation (9).

Deliveries are scheduled according to the manufacturer's due dates. Variable transportation costs are captured in equations (10) and (11), where a_{ij} is the unit transport cost based on the weight of item j shipped in time period i. Transportation fixed costs are gathered in equations (12) and (13), where V_i is a 0–1 variable indicating whether a delivery is scheduled in time i. A_i is the fixed charge for truck delivery in time i. In the model, multiple items shipped in the same time period, share the delivery fixed cost. Equation (14) tabulates total system costs.

Manufacturer's Lot Sizing Problem (MLSP)

$$\text{Problem MLSP}(j,r) \quad \text{Min} \sum_{i=i_{\text{beg}}}^{i_{\text{end}}} (S_i + P_{(m)ij})Y_{ij} + \sum_{i=i_{\text{beg}}}^{i_{\text{end}}} \sum_{t=i}^{i_{\text{end}}} (p_j + h_{ijt}) D_{jt} X_{ijt} \quad (1)$$

$$\text{subject to} \quad \sum_{i=i_{\text{beg}}}^{t} X_{ijt} = 1 \quad t = i_{\text{beg}}, \ldots, i_{\text{end}} \quad (2)$$

$$X_{ijt} \le Y_{ij} \qquad i = i_{\text{beg}}, \ldots, i_{\text{end}}, \quad t = i, \ldots, i_{\text{end}} \quad (3)$$

$$X_{ijt} \ge 0 \qquad i = i_{\text{beg}}, \ldots, i_{\text{end}}, \quad t = i, \ldots, i_{\text{end}} \quad (4)$$

$$Y_{ij} \in \{0, 1\} \quad i = i_{\text{beg}}, \ldots, i_{\text{end}} \quad (5)$$

$$C_{\text{MLSP}(j,r)} = \sum_{i=i_{\text{beg}}}^{i_z} (S_i + P_{(m)ij})\hat{Y}_{ij} + \sum_{i=i_{\text{beg}}}^{i_z} \sum_{t=i}^{i_{\text{end}}} h_{ijt} D_{jt} \hat{X}_{ijt} \quad (6)$$

$$TC_{\text{MLSP}} = \sum_{j=1}^{N} \sum_{r=1}^{IT_j} C_{\text{MLSP}(j,r)} \quad (7)$$

Vendor's Lot-for-Lot Costs (VLFL)

$$C_{\text{VLFL}(j,r)} = \sum_{i=i_{\text{beg}}}^{i_z} (P_{(v)ij} + W_i)\hat{Y}_{ij} + \sum_{i=i_{\text{beg}}}^{i_z} \sum_{t=i}^{i_{\text{end}}} c_{ijt} D_{jt} \hat{X}_{ijt} \quad (8)$$

$$TC_{\text{VLFL}} = \sum_{j=1}^{N} \sum_{r=1}^{IT_j} C_{\text{VLFL}(j,r)} \quad (9)$$

Transportation-Variable Costs (TRV)

$$C_{\text{TRV}(j,r)} = \sum_{i=i_{\text{beg}}}^{i_z} \sum_{t=i}^{i_{\text{end}}} a_{ij} D_{jt} \hat{X}_{ijt} \quad (10)$$

$$TC_{\text{TRV}} = \sum_{j=1}^{N} \sum_{r=1}^{IT_j} C_{\text{TRV}(j,r)} \quad (11)$$

Transportation-Fixed Costs (TRF)

$$TC_{\mathrm{TRF}} = \sum_{i=1}^{K} A_i V_i \tag{12}$$

where,

$$V_i = \begin{Bmatrix} 1, & \text{if } \sum_{j=1}^{N} \hat{Y}_{ij} > 0 \\ 0, & \text{otherwise} \end{Bmatrix} \quad i = 1, \ldots, K \tag{13}$$

$$\text{Total System Cost} \quad TC_{\mathrm{TRADITIONAL}} = TC_{\mathrm{MLSP}} + TC_{\mathrm{VLFL}} + TC_{\mathrm{TRV}} + TC_{\mathrm{TRF}} \tag{14}$$

Decentralized Supply Chain with Information Sharing: Mathematical Model

The operational features of the decentralized supply chain with information sharing are identical to the traditional system except that the manufacturer passes all of the orders within the planning horizon to the vendor as advance order commitments. This provides the vendor with order visibility over an n-period planning horizon permitting him to implement economic lot-sizing procedures. The mathematical models for the manufacturer and transportation provider remain unchanged as represented by equations (1)–(7) and (10)–(13).

Using the previously defined parameters, the vendor's model with information sharing follows. Each planning cycle r, the vendor solves N Wagner-Whitin type lot-sizing problems as defined in equations (15)–(19). R_{ji} is the vendor's requirements for item j that is due in time period i, where $R_{ji} = \sum_{t=i}^{i_{\mathrm{end}}} D_{jt} \hat{X}_{ijt}$. G_{fji} is the fraction of demand for item j in time period i that is produced by the vendor in time period f. F_{fj} is a binary decision variable, where $F_{fj} = 1$ if the vendor makes item j in time period f, and 0 otherwise. Per unit production and inventory holding costs are c_{fji} and h_{fji}, respectively. Equation (20) tabulates the vendor's costs for planning cycle r, whereas equation (21) gathers the vendor's total costs over K periods. As indicated, the vendor issues an invoice for each purchase order received from the manufacturer. Total system costs are collected in equation (22).

Vendor's Lot-Sizing Problem (VLSP)

$$\text{Problem VLSP}(j, r) \quad \text{Min} \sum_{f=i_{\mathrm{beg}}}^{i_{\mathrm{end}}} P_{(v)fj} F_{fj} + \sum_{f=i_{\mathrm{beg}}}^{i_{\mathrm{end}}} \sum_{i=f}^{i_{\mathrm{end}}} (c_{fji} + h_{fji}) R_{ji} G_{fji} \tag{15}$$

$$\text{subject to} \quad \sum_{f=i_{\mathrm{beg}}}^{i} G_{fji} = 1 \quad \forall i \tag{16}$$

$$G_{fji} \le F_{fj} \quad \forall f, i \tag{17}$$

$$G_{fji} \ge 0 \quad \forall f, i \tag{18}$$

$$F_{fj} \in \{0, 1\} \quad \forall f \tag{19}$$

$$C_{\mathrm{VLSP}(j,r)} = \sum_{i=i_{\mathrm{beg}}}^{i_z} (P_{(v)fj})\hat{F}_{fj} + \sum_{f=i_{\mathrm{beg}}}^{i_z} \sum_{i=f}^{i_{\mathrm{end}}} (c_{fji} + h_{fji}) R_{ji} \hat{G}_{fji} \tag{20}$$

$$TC_{\mathrm{VLSP}} = \sum_{j=1}^{N} \sum_{r=1}^{IT_j} C_{\mathrm{VLSP}(j,r)} + \sum_{i=1}^{K} W_i V_i \tag{21}$$

$$\text{Total System Cost} \quad TC_{\mathrm{INFORMATION}} = TC_{\mathrm{MLSP}} + TC_{\mathrm{VLSP}} + TC_{\mathrm{TRV}} + TC_{\mathrm{TRF}} \tag{22}$$

Coordinated Supply Chain: Mathematical Model

The coordinated supply chain structure assumes that an unbiased planning agent determines the optimal system replenishment schedules. Hence, the manufacturer does not drive supply chain replenishment activities as in the two decentralized supply chain structures. The global solution coordinates the activities of the manufacturer, vendor, and transportation provider. We formulate the static problem as a dynamic demand coordinated lot-sizing problem. Although static coordinated replenishment models have been previously applied at the single enterprise level to synchronize multiple item replenishment schedules (Silver, 1979; Robinson & Gao, 1996; Robinson & Lawrence, 2004), we generalize the modeling approach to consider the operational activities of the three channel participants and then incorporate the static model's solution procedures into a dynamic rolling schedule process.

Equations (23)–(28) provide the System Coordinated Replenishment Problem SCRP(r) that is solved each planning cycle r. The first term of the objective function models the fixed costs associated with the purchase order, truck shipment, and invoice. The binary decision variable Z_i models replenishment activity in time period i where $Z_i = 1$ if a replenishment is scheduled, and 0 otherwise. The second term in the objective function coordinates the vendor's equipment setup costs, $P_{(v)ij}$, and manufacturer's item related order processing costs, $P_{(m)ij}$, where $Y_{ij} = 1$ if item j is replenished in time i and 0 otherwise. The third component of the objective function models the per-unit processing costs at the manufacturer, production costs at the vendor, inventory holding costs and transportation costs. Constraint set (26) forces $Y_{ij} = 1$ if a replenishment for item j is scheduled in time i to meet demand in period t. Similarly, equation (25) requires that $Z_i = 1$ if any item is replenished in period i.

Equation (29) captures the costs of each planning cycle and equation (30) collects total system costs over the K-period experimental horizon.

System Coordinated Replenishment Problem (SCRP)

$$\text{Problem SCRP}(r) \quad \text{Min} \sum_{i=i_{\mathrm{beg}}}^{i_{\mathrm{end}}} (S_i + A_i + W_i) Z_i + \sum_{i=i_{\mathrm{beg}}}^{i_{\mathrm{end}}} \sum_{j=1}^{N} (P_{(v)ij} + P_{(m)ij}) Y_{ij}$$

$$+ \sum_{i=i_{\mathrm{beg}}}^{i_{\mathrm{end}}} \sum_{j=1}^{N} \sum_{t=i}^{i_{\mathrm{end}}} (p_j + c_{ijt} + h_{ijt} + a_{ij}) D_{jt} X_{ijt} \tag{23}$$

$$\text{subject to} \quad \sum_{i=i_{\text{beg}}}^{t} X_{ijt} = 1 \quad \forall j, \quad t = i_{\text{beg}}, \ldots, i_{\text{end}} \tag{24}$$

$$Y_{ij} \le Z_i \qquad i = i_{\text{beg}}, \ldots, i_{\text{end}}, \quad \forall j \tag{25}$$

$$X_{ijt} \le Y_{ij} \qquad i = i_{\text{beg}}, \ldots, i_{\text{end}}, \quad \forall j, \quad t = i, \ldots, i_{\text{end}} \tag{26}$$

$$X_{ijt} \ge 0 \qquad i = i_{\text{beg}}, \ldots, i_{\text{end}}, \quad \forall j, \quad t = i, \ldots, i_{\text{end}} \tag{27}$$

$$Y_{ij}, Z_i \in \{0, 1\} \quad i = i_{\text{beg}}, \ldots, i_{\text{end}}, \quad \forall j \tag{28}$$

$$C_{\text{SCRP}(r)} = \sum_{i=i_{\text{beg}}}^{i_z} (S_i + A_i + W_i)\hat{Z}_i + \sum_{i=i_{\text{beg}}}^{i_z} \sum_{j=1}^{N} (P_{(m)ij} + P_{(v)ij})\hat{Y}_{ij} + \sum_{i=i_{\text{beg}}}^{i_z} \sum_{j=1}^{N} \sum_{t=i}^{i_{\text{end}}} (p_j + c_{ijt} + h_{ijt} + a_{ij}) D_{jt} \hat{X}_{ijt} \tag{29}$$

$$\text{Total System Cost} \quad TC_{\text{COOR}} = \sum_{r=1}^{IT} C_{\text{SCRP}(r)} \tag{30}$$

Simulation Procedures for Rolling Schedule Planning

The computer simulation procedures for the rolling horizon frameworks are written in FORTRAN and implemented using PowerStation FORTRAN on a laptop computer. We solve each planning cycle's optimization problem using the dual-ascent based branch and bound procedures described in Robinson and Gao (1996). Specialized subroutines are developed for each organizational structure to address their unique problem features. For each planning cycle, the procedures identify the beginning time period, access the appropriate data for the planning cycle, optimize the static T-period problem, store the optimal solution and costs, and mark the last time period, whose demand is covered by the current planning cycle for each item j. The procedures begin at time zero and roll through time until all K time periods are replenished. Additional details about the procedures are available from the authors upon request.

NUMERICAL STUDY

This section summarizes the results of an experimental study that evaluates the impact of the alternative e-replenishment strategies on the three supply chain structures. The performance metrics include operational cost and activity.

E-Replenishment Strategies

We investigate nine alternative e-replenishment strategies as defined by all combinations of three levels of automation for the procurement and fulfillment processes. The three automation levels are manual (M), semi-automated (S), and automated (A). On the basis of our review of the literature and conversations with procurement managers, we set the fixed costs for procurement, S_i, and fulfillment, W_i, at \$75, \$10, and \$3, respectively, for manual, semi-automated, and automated systems.

Denoting the combined strategies by procurement/fulfillment, the systems range from completely manual M/M to fully automated A/A.

The automated strategy A/A reflects current state-of-the-art e-replenishment processes (PricewaterhouseCoopers, 2002) in which the manufacturer and supplier are electronically linked with full access to the relevant data in each other's information systems. Purchase orders are automatically generated, routed to the appropriate authority for approval, transmitted directly into the vendor's system, and archived. Fulfillment activities are also automated including order confirmation, work order and shipping document generation, advanced shipping notice delivery, invoicing, and payment receipt.

The S/S strategy reflects a range of possible processing environments including those with multiple data entry points and/or limited paper processing (e.g., manual matching of electronic and paper forms). In these instances, one of the firm's internal systems may not be fully automated or the two trading partners' systems are not fully interoperable without some manual intervention. This cost structure also models the transaction fees associated with third party service providers (see Kerrigan, Roegner, Swinford, and Zawada (2001) for a discussion of business-to-business marketplace fees).

Combinations of manual, semi-automated and automated systems are also possible. Web-based EDI provides one example of an A/M system in which a manufacturer's e-procurement system transmits orders by EDI transaction sets, which are translated into XML format before being sent over the Web. The vendors extract information from the Web site and manually enter the data into their systems and acknowledge order acceptance through the Web site. Upon order completion, the vendor manually enters shipping information and submits an invoice through the Web site. In this A/M system, the buyer maintains the efficiencies of automated e-procurement without requiring the vendor to invest in an automated fulfillment system.

Cost and Demand Parameters

This study is based on the cost and demand data drawn from the procurement and fulfillment processes associated with the metal components for drilling tower fabrication. However, in order to draw insights that are reflective of this general type of supply chain and not a specific problem scenario, we generated 12 test problems from all combinations of the following parameters: coefficient of demand variation CV $\in \{1.51, 0.2\}$, equipment setup cost $P_{(v)ij} \in \{\$25, \$50, \$100\}$ and fixed transportation cost $A_i \in \{\$75, \$125\}$. The actual parameter values collected from the construction supply chain are CV $= 1.51$, $P_{(v)ij} = \$50$, and $A_i = \$75$. Including a CV $= 0.2$ provides a smoother demand pattern in addition to the lumpy pattern of CV $= 1.51$. Within a data set, all items have the same CV value. To insure the results are comparable across data sets, the total demand of both data sets is equal regardless of CV value. We model 10 purchased items in the experiments. The demand level of each purchased component is reflective of its usage rate in the bills of materials. The usage rates of the 10 components are 7, 7, 16, 13, 4, 24, 18, 9, 16, and 26 units per drilling tower. For the experiments, each component's demand stream is randomly generated using procedures similar to those in Jacobs and

Whybark (1992). The fixed replenishment cost for order processing and material handling, $P_{(m)ij}$, is \$10 for each i and j. Per unit costs for vendor production (c_{ijt}) and transportation (a_{ij}) are assumed constant over time and are set at zero in the experiments since they do not impact the optimal replenishment schedule. We assume each component's value as \$60 per unit with an annual holding cost of 40% of item value. As the fixed ordering cost and per unit holding cost are constant across all items in the experiments, the differences in the items' demand rates (i.e., usage rates) provide a variety of natural order cycle lengths for the components.

Consistent with the operating environment, and without loss of generality, we model same-day transportation delivery and set the manufacturer's planning horizon for the components at $T = 20$. The length of the frozen order interval, n, is set at 12 time periods, which coincides with the results in Sridharan et al. (1987) that the manufacturer's cost of freezing orders is low when ~50% of the planning horizon is frozen.

Using the procedures and data described earlier, we randomly generated demand for 200 time periods for each of the CV values. The 200 time periods provides a minimum and maximum number of planning cycles of $\lceil K/T \rceil = 10$ and $\lceil K/n \rceil = 17$ per data set, where the static problem solution of each planning cycle provides one observation of system performance. Consequently, each combination of experimental factors yields 10–17 observations of replenishment activity for each item over the experimental horizon providing a robust view of system performance.

Traditional Decentralized System Experimental Results

The experimental results for the traditional decentralized system are summarized in Table 1, where each table entry represents the average results associated with 12 test problems. The cost metrics are stated in dollars and the percent improvement over the M/M (\$75/\$75) strategy. A negative value indicates a cost increase. The cost allocation metrics are broken out by channel member and indicate each member's costs as a percentage of total system costs. Operational metrics include the number of line item orders, vendor equipment setups, POs, vendor invoices, truck shipments, and the average number of line items per shipment.

The first phase of the analysis investigates the impact of the manufacturer's procurement strategy on system and individual channel member performance. Consider columns (1)–(5) in Table 1 in which the vendor follows a manual fulfillment process. As expected, decreasing the PO transaction cost from \$75 to \$10 to \$3 triggers more frequent replenishments of smaller order quantities. The number of POs increases from 248 to 467 to 588, whereas the manufacturer's inventory costs fall from \$14755 to \$5101 to \$3116. Using M/M as a benchmark, increasing automation provides the manufacturer with a cost reduction of 59.7% and 70.0% moving to a semi-automated (S/M) and automated (A/M) procurement strategy, respectively. The manufacturer's operational activity and performance is identical for the semi-automated (columns 6–11) and automated (columns 12–17) fulfillment strategies.

An opposite relationship holds for the vendor, where the manufacturer's increased ordering frequency drives up the vendor's equipment setup and invoice costs. Under the manual fulfillment strategy, the vendor's costs increase by 88.5%

Table 1: Experimental results for the traditional decentralized supply chain structure.[a]

Strategy: Mfg/Ven. P.O./Invoice Cost	M/M 75/75 (1)	S/M 10/75 (2)	(%) (3)	A/M 3/75 (4)	(%) (5)	M/S 75/10 (6)	(%) (7)	S/S 10/10 (8)	(%) (9)	A/S 3/10 (10)	(%) (11)	M/A 75/3 (12)	(%) (13)	S/A 10/3 (14)	(%) (15)	A/A 3/3 (16)	(%) (17)
	Benchmark																
Cost Metrics																	
Mfg. Inv.	14,755	5,101	65.4	3,116	78.9	14,755	0.0	5,101	65.4	3,116	78.9	14,755	0.0	5,101	65.4	3,116	78.9
Mfg. P.O.	18,563	4,665	74.9	1,763	90.5	18,563	0.0	4,665	74.9	1,763	90.5	18,563	0.0	4,665	74.9	1,763	90.5
Mfg. Line Item	2,475	4,665	−88.5	5,875	−137.4	2,475	0.0	4,665	−88.5	5,875	−137.4	2,475	0.0	4,665	−88.5	5,875	−137.4
Manufacturer Total	35,792	14,431	59.7	10,754	70.0	35,792	0.0	14,431	59.7	10,754	70.0	35,792	0.0	14,431	59.7	10,754	70.0
Transportation	13,200	18,100	−37.1	19,100	−44.7	13,200	0.0	18,100	−37.1	19,100	−44.7	13,200	0.0	18,100	−37.1	19,100	−44.7
Vendor Equipm.	14,438	27,213	−88.5	34,271	−137.4	14,438	0.0	27,213	−88.5	34,271	−137.4	14,438	0.0	27,213	−88.5	34,271	−137.4
Vendor Inv.	–	–		–		–		0		0		–		–		–	
Vendor Invoice	18,563	34,988	−88.5	44,063	−137.4	2,475	86.7	4,665	74.9	5,875	68.4	743	96.0	1,400	92.5	1,763	90.5
Vendor Total	33,000	62,200	−88.5	78,333	−137.4	16,913	48.8	31,878	3.4	40,146	−21.7	15,180	54.0	28,612	13.3	36,033	−9.2
Total Cost	81,992	94,731	−15.5	108,187	−31.9	65,905	19.6	64,409	21.4	69,999	14.6	64,172	21.7	61,143	25.4	65,887	19.6
Operational Metrics																	
Number of Line Items/ Vendor Setups	248	467	−88.5	588	−137.4	248	0.0	467	−88.5	588	−137.4	248	0.0	467	−88.5	588	−137.4
Number of Purchase Orders/Invoices	248	467	−88.5	588	−137.4	248	0.0	467	−88.5	588	−137.4	248	0.0	467	−88.5	588	−137.4
Number of Shipments	132	181	−37.1	191	−44.7	132	0.0	181	−37.1	191	−44.7	132	0.0	181	−37.1	191	−44.7
Number of Items/Shipment	1.9	2.6	−37.5	3.1	−64.0	1.9	0.0	2.6	−37.5	3.1	−64.0	1.9	0.0	2.6	−37.5	3.1	−64.0
Cost Allocation Metrics																	
Manufacturer	44%	15%		10%		54%		22%		15%		56%		24%		16%	
Transportation	16%	19%		18%		20%		28%		27%		21%		30%		29%	
Vendor	40%	66%		72%		26%		49%		57%		24%		47%		55%	

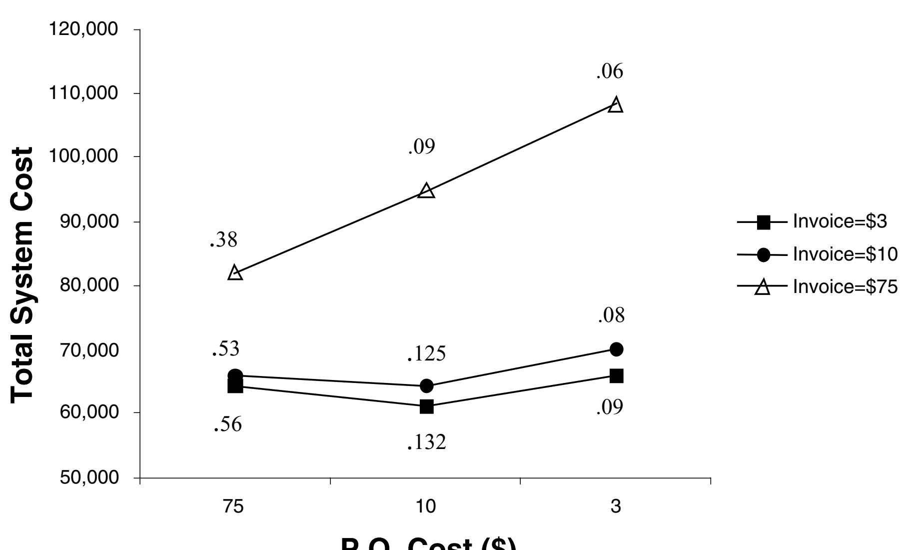
[a]Each table entry is the average value of 12 test problems.

and 137.4% with each increased level of procurement automation by the manufacturer. Similar results hold for the other fulfillment strategies; the manufacturer's costs fall with increased automation, whereas the vendor's costs increase. Enhancements in e-procurement automation are also accompanied with an increase in the number of shipments, which rise from 132 to 181 to 191, respectively, for manual, semi-automated, and automated systems. Although shipment consolidation partially mitigates the impact of more frequent orders, the transportation costs for the semi-automated and automated procurement strategies still increase by 37.1% and 44.7% above the manual system under all fulfillment alternatives.

At the system level, the results are mixed and unexpected. Conventional wisdom associates enhanced information technologies with improved channel cost performance. However, this wisdom may not always hold under a decentralized decision-making supply chain structure. The summary results in Table 1 illustrate this point, where total costs increase by 15.5% and 31.9% when the manufacturer migrates from the M/M to the S/M and then to the A/M strategy. Hence, an investment in e-procurement technology by the manufacturer may lower his costs, but be detrimental to the overall supply chain performance. Mixed results occur for the semi-automated and automated fulfillment strategies, where system costs initially decline moving from a manual to a semi-automated procurement strategy, and then increase under the automated procurement strategy.

Figure 2 summarizes these results, where the impact of different levels of procurement technology on system costs is related to the flexibility of the transportation provider and vendor. The channel flexibility ratio, FLEX $= (S_i + P_{(m)ij})/(W_i + P_{(v)ij} + A_i)$, provides a metric reflecting the capability of the system to efficiently respond to the increased order activity associated with introducing an

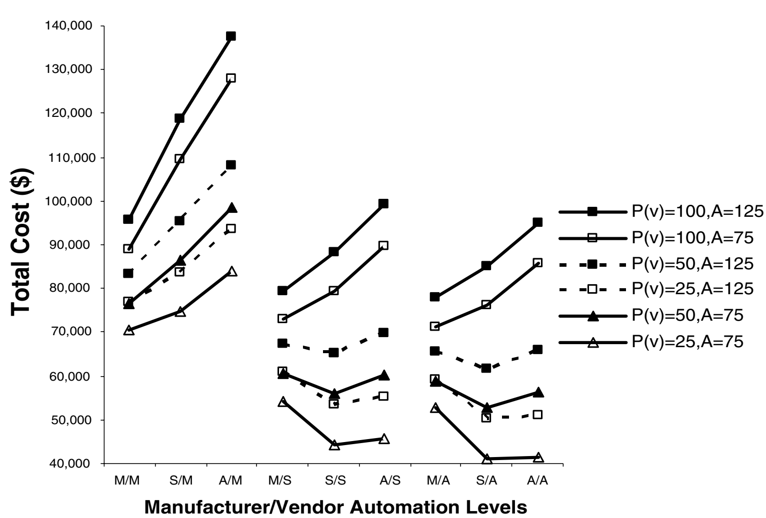
Figure 2: Impact of e-replenishment strategy on the traditional supply chain.



e-procurement process. Higher values of FLEX indicate greater system flexibility and an increased potential for total costs to decrease with increased procurement automation. This is illustrated in Figure 2, where the FLEX ratios are provided in the graph for each e-replenishment strategy. Owing to the problem characteristics (i.e., lumpy and dynamic demand, finite planning horizons, rolling schedule planning, and multiple products), we were unable to specify a closed-form expression indicating a threshold value for FLEX at which system costs would increase. However, the value FLEX = 0.11 emerged from the experiments as a barometer indicating whether additional levels of procurement automation would increase or decrease system costs. As illustrated in the Figure 2, system costs decline when moving to a more highly automated procurement system when the new value of FLEX is >0.11, otherwise the system costs increase. Although we recognize that the threshold value of FLEX = 0.11 is specifically related to the experimental problem environment and test problems, the broader findings on the relationship between channel flexibility and the capability of supply chains to efficiently respond to enhanced e-procurement automation can be generalized across make-to-order supply chains operating under decentralized decision-making structures.

Figure 3 provides a more detailed analysis of the experimental results, where the findings are disaggregated by PO, invoice, transportation, and equipment setup

Figure 3: Impact of e-replenishment in a traditional decentralized supply chain.



Manufacturer/Vendor Automation Levels	M/M	S/M	A/M	M/S	S/S	A/S	M/A	S/A	A/A
$P_{(v)}$=100, A=125	0.283*	0.067	0.043	0.362	0.085	0.055	0.373	0.088	0.057
$P_{(v)}$=100, A=75	0.340	0.080	0.052	0.459	0.108	0.070	0.478	0.112	0.073
$P_{(v)}$=50, A=125	0.340	0.078	0.051	0.447	0.105	0.068	0.464	0.109	0.071
$P_{(v)}$=25, A=125	0.378	0.089	0.058	0.531	0.125	0.081	0.556	0.131	0.085
$P_{(v)}$=50, A=75	0.425	0.100	0.065	0.630	0.148	0.096	0.664	0.156	0.102
$P_{(v)}$=25, A=75	0.486	0.114	0.074	0.773	0.182	0.118	0.825	0.194	0.126

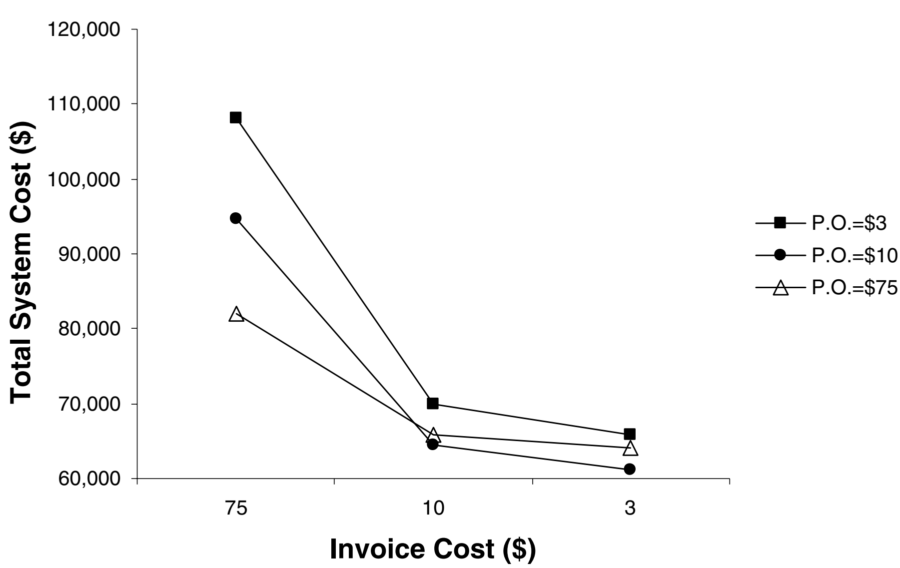
*Each cell represents FLEX value.

fixed costs. The vertical axis provides system costs, whereas the nine replenishment strategies are ordered by the manufacturer's and then by the vendor's automation level on the horizontal axis. Each line in the graph is associated with a specific combination of transportation and vendor setup fixed costs and presents the average results for the two CV values. The slope of the cost curves denotes the rate of increase in the system cost, where the rate of increase tends to be less for the lower cost curves owing to greater channel flexibility. As illustrated in the figure for the manual fulfillment process (i.e., the first three cases on the x-axis), system costs increase for all problems when the manufacturer moves to a more highly automated procurement process. In these instances, the increase in fulfillment costs exceeds the decrease in the manufacturer's procurement costs.

When the vendor follows a semi-automated fulfillment process and the manufacturer moves from a manual to a semi-automated policy, system costs may either increase or decrease depending upon the channel flexibility. The two highest fixed cost structures yield higher system costs moving from a M/S to an S/S policy, whereas the other four indicate reduced system costs. When moving from an S/S to an A/S policy, all of the cost structures indicate an increase in system costs. Similar observations hold when the vendor is operating under an automated fulfillment policy. These results highlight the importance of considering the multiple determinants of channel flexibility when evaluating e-replenishment systems in traditional decentralized supply chains.

Figure 4 illustrates that for a given procurement strategy, total system costs decrease monotonically with an increase in fulfillment automation. This is as expected, because the number of POs, invoices, and shipments are not influenced

Figure 4: The impact of fulfillment automation in a traditional decentralized supply chain.



by the specific fulfillment process. Hence, fulfillment technology decisions can be made independently, without explicitly considering the impact on the operational activities of immediate downstream channel members.

The least cost e-replenishment strategy, S/A, for the traditional supply chain utilizes a semi-automated procurement and automated fulfillment strategy for an average 25.4% reduction in system costs over the M/M benchmark. The manufacturer's costs decrease by 59.7%, transportation costs increase by 37.1%, and the vendor's costs decrease by 13.3%. The cost allocation metrics in Table 1 reveal that each channel member's cost as a percentage of total systems costs for the M/M and S/A strategies are: manufacturer, 44% and 24%; transportation, 16% and 30%; and vendor, 40% and 47%. The operational activity of all players is significantly increased; the number of POs, invoices, and equipment setups each increase by 88.5%, the number of shipments by 37.1%, and the number of line items per shipment by 37.5%.

Decentralized Decision-Making with Information Sharing Experimental Results

Table 2 summarizes the results for the decentralized system with information sharing. In this environment, the manufacturer provides the vendor with the timing and quantity of all orders in the planning horizon. Those in the frozen time interval are fixed and not subject to change in the next MRP update cycle, whereas those in the nonfrozen interval are fixed in timing, but subject to changes in quantity. Sharing the planned order information increases the vendor's scheduling flexibility by permitting him to implement economic lot-sizing procedures. As illustrated in the experimental results, this increased scheduling flexibility enhances the efficiency of the vendor's fulfillment processes to respond to the increasing number of orders launched by the manufacturer under the adoption of e-replenishment technology. However, the basic results are similar to those for the traditional decentralized system in which independent decision-making by the manufacturer can cause unintended channel inefficiencies. As for the traditional supply chain, the optimal e-replenishment strategy for the decentralized system with information sharing is the S/A strategy. However, the system cost of the A/A strategy is nearly identical.

As indicated in Table 2, the manufacturer's operational activities and cost performances are identical under the traditional decentralized and decentralized with information sharing supply chain structures. Only the vendor's operational activities change, where the ability to aggregate the manufacturer's orders into more economic lot-sizes dampens the adverse impact of the increased number of orders when moving to more advanced procurement technologies. However, under the manual fulfillment strategy, the vendor still cannot effectively respond to a shift by the manufacturer from a manual to a semi-automated or automated e-replenishment technology as evidenced by his cost increases of 78.0% and 112.7%, respectively. System costs increase 11.4% and 22.1% when moving from a M/M to a S/M to an A/M replenishment strategy.

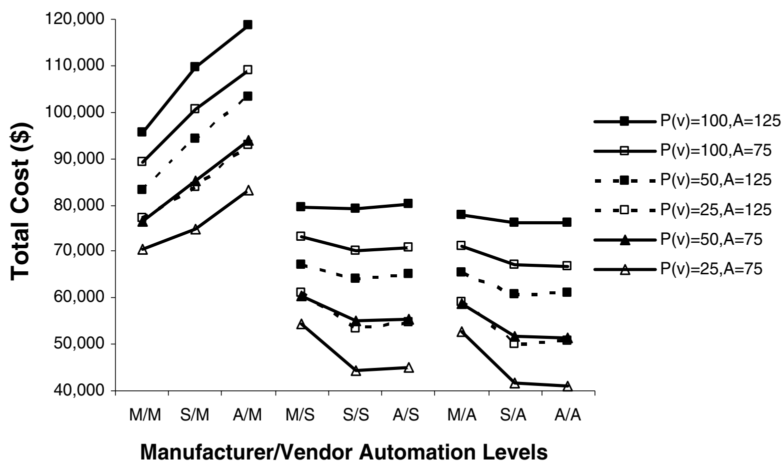
Under the semi-automated and automated fulfillment strategies, system costs decrease moving from a manual to semi-automated procurement strategy, but increase moving from a semi-automated to an automated procurement system. These

Table 2: Experimental results for the decentralized supply chain structure with information sharing.[a]

	Benchmark																
Strategy: Mfg/Ven.	M/M 75/75	S/M 10/75	(%)	A/M 3/75	(%)	M/S 75/10	(%)	S/S 10/10	(%)	A/S 3/10	(%)	M/A 75/3	(%)	S/A 10/3	(%)	A/A 3/3	(%)
P.O./Invoice Cost	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Cost Metrics																	
Mfg. Inv.	14,755	5,101	65.4	3,116	78.9	14,755	0.0	5,101	65.4	3,116	78.9	14,755	0.0	5,101	65.4	3,116	78.9
Mfg. P.O.	18,563	4,665	74.9	1,763	90.5	18,563	0.0	4,665	74.9	1,763	90.5	18,563	0.0	4,665	74.9	1,763	90.5
Mfg. Line Item	2,475	4,665	−88.5	5,875	−137.4	2,475	0.0	4,665	−88.5	5,875	−137.4	2,475	0.0	4,665	−88.5	5,875	−137.4
Manufacturer Total	35,792	14,431	59.7	10,754	70.0	35,792	0.0	14,431	59.7	10,754	70.0	35,792	0.0	14,431	59.7	10,754	70.0
Transportation	13,200	18,100	−37.1	19,100	−44.7	33,200	0.0	18,100	−37.1	19,100	−44.7	13,200	0.0	18,100	−37.1	19,100	−44.7
Vendor Equipm.	14,188	17,804	−25.5	17,921	−26.3	14,188	0.0	17,804	−25.5	17,921	−26.3	14,188	0.0	17,804	−25.5	17,921	−26.3
Vendor Inv.	284	6,024		8,281		284		6,024		8,281		284		6,024		8,281	
Vendor Invoice	18,563	34,988	−88.5	44,063	−137.4	2,475	86.7	4,665	74.9	5,875	68.4	743	96.0	1,400	92.5	1,763	90.5
Vendor Total	33,034	58,816	−78.0	70,264	−112.7	16,946	48.7	28,494	13.7	32,077	2.9	15,214	53.9	25,228	23.6	27,964	15.3
Total Cost	82,026	91,347	−11.4	100,118	−22.1	65,938	19.6	61,025	25.6	61,930	24.5	64,206	21.7	57,759	29.6	57,818	29.5
Operational Metrics																	
Number of Line Items/ Vendor Setups	248	348	−40.3	348	−40.3	245	1.2	348	−40.3	348	−40.3	245	1.2	348	−40.3	348	−40.3
Number of Purchase Orders/Invoices	248	467	−88.3	588	−137.1	248	0.0	467	−88.3	588	−137.1	248	0.0	467	−88.3	588	−137.1
Number of Shipments	132	181	−37.1	191	−44.7	132	0.0	181	−37.1	191	−44.7	132	0.0	181	−37.1	191	−44.7
Number of Items/Shipment	1.9	2.6	−37.3	3.1	−63.9	1.9	0.0	2.6	−37.3	3.1	−63.9	1.9	0.0	2.6	−37.3	3.1	−63.9
Cost Allocation Metrics																	
Manufacturer	44%	16%		11%		54%		24%		17%		56%		25%		19%	
Transportation	16%	20%		19%		20%		30%		31%		21%		31%		33%	
Vendor	40%	64%		70%		26%		47%		52%		24%		44%		48%	

[a]Each table entry is the average value of 12 test problems.

Figure 5: Impact of e-replenishment in a decentralized supply chain with information sharing.



Manufacturer/Vendor Automation Levels	M/M	S/M	A/M	M/S	S/S	A/S	M/A	S/A	A/A
$P_{(v)}$=100, A=125	0.283*	0.067	0.043	0.362	0.085	0.055	0.373	0.088	0.057
$P_{(v)}$=100, A=75	0.340	0.080	0.052	0.459	0.108	0.070	0.478	0.112	0.073
$P_{(v)}$=50, A=125	0.340	0.078	0.051	0.447	0.105	0.068	0.464	0.109	0.071
$P_{(v)}$=25, A=125	0.378	0.089	0.058	0.531	0.125	0.081	0.556	0.131	0.085
$P_{(v)}$=50, A=75	0.425	0.100	0.065	0.630	0.148	0.096	0.664	0.156	0.102
$P_{(v)}$=25, A=75	0.486	0.114	0.074	0.773	0.182	0.118	0.825	0.194	0.126

*Each cell represents FLEX value.

unexpected results mirror those for the traditional decentralized system; however, the vendor's and system costs are substantially lower under the information sharing environment.

Figure 5 provides the experimental findings disaggregated by transportation and equipment setup fixed costs. Comparing the results in Figures 3 and 5, illustrates that the enhanced scheduling flexibility provided by the shared order information allows the vendor, and consequently the system, to more efficiently respond to the increased order flow associated with moving to e-procurement technologies.

Managerial Implications for Decentralized Supply Chains

The research findings provide several implications for the management of e-replenishment technology in decentralized supply chains. First, when evaluating an e-procurement technology investment, it is myopic to focus solely on the potential transaction cost reduction. The technology may have a far greater impact on channel activities including ordering, transportation, and vendor fulfillment activities. Consequently, a well-intended investment by the manufacturer in automation to optimize his procurement costs can have an adverse impact on all upstream channel members leading to suboptimal system performance. Not all investments in e-replenishment technology, even though they may reduce transaction costs, lead to system improvement.

Although not expected, these findings are not totally surprising as it is documented in the literature that supply chain performance can be suboptimal when each channel member optimizes his individual objective function. In this research, the potential network externalities result when the manufacturer launches more frequent and smaller size orders than his channel partners can efficiently accommodate. These results complement other studies addressing the limitations of decentralized decision-making in supply chain management including Forrester's (1958) analysis of information distortion and supply inefficiencies moving upstream in a serial supply chain as the result of independent lot-sizing decisions made by downstream channel members; the "double marginalization" results in Spengler (1950), where the retailer does not consider the supplier's profit margin when setting his order quantity, so he orders too little product for system optimization; Jeuland and Shugan's (1983) application of quantity discounts to align retailers' purchasing incentives to seek system optimization; and Pasternack's (1985) development of buy-back contracts for short shelf life situations that seeks to obtain system optimization by allowing a retailer to return any portion of his initial order quantity at a pre-specified price.

A second finding is that the introduction of e-replenishment technology can impact the financial performance of each channel member differently such that the gains from the technology investment are not equally shared. All participants should understand the potential for cost reallocation so that savings sharing and/or investment contracts can be established prior to moving forward with system redesign.

Third, as illustrated by the optimal S/A strategy, increased automation of all replenishment activities may not yield the most efficient system. Full automation may be more effective for one channel member, whereas a semi-automated process is better for another. Consequently, software vendors are justified in developing Enterprise Application Integration (EAI) software for interconnecting manual, semi-automated, and automated replenishment processes, which facilitate the implementation of hybrid strategies.

Fourth, the manufacturer's e-procurement strategy must be aligned with the channel's flexibility, where lower transportation, vendor setup, and invoicing fixed cost structures favor the implementation of e-procurement technologies.

Finally, alternative channel relationships, such as the sharing of future orders, can enhance the vendor's scheduling flexibility enabling him to more efficiently respond to the increased order flow associated with e-procurement implementation; thereby expanding the economic advantages of the e-replenishment technologies for the channel.

Coordinated Supply Chain Results

Table 3 summarizes the findings for the coordinated supply chain control structure. In this environment, the manufacturer executes optimal system-wide replenishment orders. Consequently, there are not any economic externalities at the system level that are associated with the manufacturer seeking to optimize his individual cost

Table 3: Experimental results for the coordinated supply chain structure.[a]

Strategy P.O./Invoice Cost	Benchmark M/M 75/75 (1)	S/M 10/75 (2)	(%) (3)	A/M 3/75 (4)	(%) (5)	M/S 75/10 (6)	(%) (7)	S/S 10/10 (8)	(%) (9)	A/S 3/10 (10)	(%) (11)	M/A 75/3 (12)	(%) (13)	S/A 10/3 (14)	(%) (15)	A/A 3/3 (16)	(%) (17)
Cost Metrics																	
Mfg. Inv.	18,156	17,399	4.2	17,228	5.1	17,399	4.2	15,909	12.4	15,825	12.8	17,228	5.1	15,825	12.8	15,558	14.3
Mfg. P.O.	2,488	364	85.4	111	95.5	2,731	−9.8	431	82.7	132	94.7	2,775	−11.6	438	82.4	136	94.5
Mfg. Line Item	2,604	2,644	−1.5	2,668	−2.4	2,644	−1.5	2,769	−6.3	2,770	−6.4	2,668	−2.4	2,770	−6.4	2,788	−7.0
Manufacturer Total	23,247	22,407	12.2	20,006	13.9	22,774	2.0	19,109	17.8	18,726	19.4	22,670	2.5	19,033	18.1	18,481	20.5
Transportation	3,300	3,590	−8.8	3,638	−10.2	3,590	−8.8	4,240	−28.5	4,308	−30.6	3,638	−10.2	4,308	−30.6	4,438	−34.5
Vendor Equipm.	13,996	14,029	−0.2	14,088	−0.7	14,029	−0.2	14,433	−3.1	14,467	−3.4	14,088	−0.7	14,467	−3.4	14,594	−4.3
Vendor Inv.	–	–		–		–		–		–		–		–		–	
Vendor Invoice	2,488	2,731	−9.8	2,775	−11.6	364	85.4	431	82.7	438	82.4	111	95.5	132	94.7	136	94.5
Vendor Total	16,483	16,760	−1.7	16,863	−2.3	14,393	12.7	14,864	9.8	14,905	9.6	14,199	13.9	14,598	11.4	14,730	10.6
Total Cost	43,031	40,757	5.3	40,506	5.9	40,757	5.3	38,213	11.2	37,940	11.8	40,506	5.9	37,940	11.8	37,648	12.5
Operational Metrics																	
Number of Line Items/ Vendor Setups	260	264	−1.5	267	−2.7	264	−1.5	277	−6.5	277	−6.5	267	−2.7	277	−6.5	279	−7.3
Number of Purchase Orders/Invoices	33	36	−9.1	37	−12.1	36	−9.1	43	−30.3	44	−33.3	37	−12.1	44	−33.3	45	−36.4
Number of Shipments	33	36	−9.1	37	−12.1	36	−9.1	43	−30.3	44	−33.3	37	−12.1	44	−33.3	45	−36.4
Number of Items/Shipment	7.9	7.3	6.9	7.2	8.4	7.3	6.9	6.4	18.2	6.3	20.1	7.2	8.4	6.3	20.1	6.2	21.3
Cost Allocation Metrics																	
Manufacturer	54%	50%		49%		56%		50%		49%		56%		50%		49%	
Transportation	8%	9%		9%		9%		11%		11%		9%		11%		12%	
Vendor	38%	41%		42%		35%		39%		39%		35%		38%		39%	

[a]Each table entry is the average value of 12 test problems.

performance. System costs monotonically decrease with increases in replenishment automation. This is illustrated in Table 3 where for a given fulfillment (procurement) strategy, total system costs decline with higher levels of procurement (fulfillment) automation.

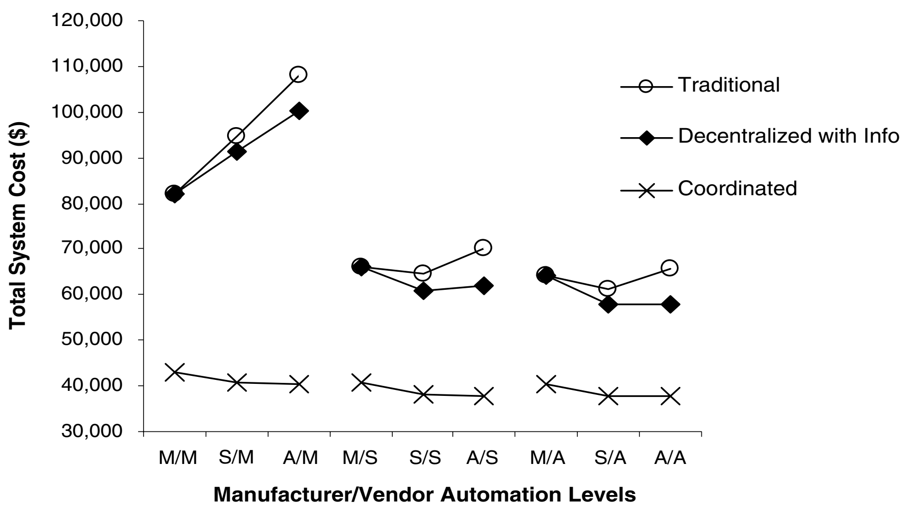
Moving from a fully manual to fully automated e-replenishment strategy yields a 12.5% system cost reduction. The manufacturer's costs decrease by 20.5%, transportation costs increase by 34.5%, and the vendor's costs decrease by 10.6%. Each channel member's costs as a percentage of total system costs for the M/M and A/A strategies are: manufacturer 54% and 49.0%; transportation 8.0% and 12.0%; and vendor 38.0% and 39.0%. The degree of cost re-allocation is less than that for the decentralized systems. As in the two decentralized systems, enhanced automation increases the operational activity levels of all participants. The number of POs, invoices, and shipments increase by 36.4%, the number of equipment setups and line items ordered increases by 7.3%, and the number of line/items per shipment decreases by 21.3%.

Managerial Implications for Coordinated Supply Chains

Comparing the experimental results for the coordinated and decentralized supply chain structures provides additional insights into the implementation of e-replenishment technology, and the performance of decentralized and coordinated systems. First for the test problems, the average percent cost improvement is smaller for the coordinated system (i.e., 12.5% for the coordinated system versus 25.4% and 29.6% for the decentralized systems), but the centralized system starts from a much lower M/M cost benchmark (i.e., $43031 for the coordinated system versus $81992 and $82026 for the decentralized systems). In addition, both the magnitude of cost reallocation among channel members and the increased operational activity are less pronounced when introducing e-replenishment systems in the coordinated control system. Whereas the manufacturer's technology decision drives channel replenishment activities and creates potential network externalities in the decentralized systems, the global optimization of replenishment schedules eliminates the potential for system suboptimality in the coordinated system. Consistent with the results for the decentralized supply chains, lower invoice transaction processing costs reduce total system costs in the coordinated system. However, since the invoice cost in the coordinated environment influences the global replenishment decisions, decreasing invoice processing costs results in more frequent orders of smaller size. Changes in the invoice costs have no impact on the number or size of orders in the decentralized supply chains.

Figure 6 summarizes the results in Tables 1–3 and provides a clearer understanding of the relative benefits associated with the application of e-replenishment technology and channel integration. First, as expected, the performance of the decentralized system with information sharing exceeds that of the traditional decentralized system in all cases. For a specified e-fulfillment strategy, the benefit of information sharing between the channel members increases when moving to more highly automated e-procurement system (at lower FLEX values), because enhancing the supplier's production scheduling flexibility at least partially counteracts the larger number of POs.

Figure 6: Impact of e-replenishment on total system costs in different supply chain structures.



Second, although the operational cost improvement from e-replenishment is significant for the decentralized supply chains, an even greater benefit is possible from system coordination. This is illustrated by the 25.4% performance improvement associated with moving from a M/M strategy to an A/A strategy in the traditional decentralized system versus the 47.5% cost reduction that is available moving from a manual traditional decentralized system to a manual coordinated system. Migrating from the traditional decentralized M/M strategy to the best coordinated strategy (A/A) provides a 54.1% cost reduction for even greater system benefit.

CONCLUSIONS AND IMPLICATIONS

Advances in enterprise resource planning, EAI, automatic identification and data capture, and e-replenishment software are rapidly converting traditional paper-based processes to e-replenishment systems. A prominent advantage of e-replenishment is the cost and lead-time reduction due to the automation of internal and external business processes. Although in the past, interoperability among trading partners proved to be a significant hurdle, today the availability of the Internet and the falling costs of B2B server-to-server integration bring the cost of connectivity into the reach of most channel partners (Brown, 2001).

Numerous authors, both in the trade press and academic literature, proclaim the benefits of electronic replenishment systems. However, past research is targeted at transaction cost reduction with little effort directed at understanding the impact of e-replenishment on operational activity and performance at the system level. This research fills some of the gaps in the literature and provides a platform for additional research by studying manual, semi-automated, and automated e-replenishment strategies in a make-to-order supply chain under traditional decentralized, decentralized with information sharing, and coordinated supply chains. We proposed simulation-based rolling schedule experimental frameworks to mathematically characterize system costs in both decentralized and coordinated supply chain structures under the alternative e-replenishment technologies. The proposed frameworks take a channel perspective and are applied to experimentally evaluate the relationship between e-replenishment strategy and supply chain performance, for which basic theoretical and managerial insights are developed.

Our findings for the decentralized structure, under which most firms operate today, indicate that technology investment decisions require careful consideration of supply chain dynamics and cost structures. A well-intended decision by a manufacturer to reduce his operating costs can create rippling inefficiencies throughout the channel culminating in higher system costs, and/or a major re-distribution of costs among channel members. However, the decision could just as easily improve supply chain performance and enhance system profitability. The outcome depends on the flexibility of upstream channel members, particularly on invoice, delivery, and equipment setup fixed costs, and whether the manufacturer's future orders are shared with the vendor.

Our findings also provide comparative insights into decentralized and coordinated supply chains. Decentralized systems have higher system costs and are subject to system suboptimization and substantial reallocation of operational costs and operational activity among channel members owing to unilateral decision-making by the manufacturer. However, under the coordinated decision-making structure, the reallocation of costs and operational activities among channel members owing to e-replenishment investment is not as pronounced, and any improvement in transaction processing capability provides a system benefit and not merely a reshuffling of costs.

Overall, the findings indicate that a significant economic benefit is associated with moving to e-replenishment across all organizational structures. The average cost reduction associated with moving from a fully manual to an automated e-replenishment system is 19.6%, 29.5%, and 12.5%, respectively, for the traditional decentralized, decentralized with information sharing, and coordinated supply chain structures. However, the costs of the traditional decentralized structure are further reduced to 25.4% below the manual system if the manufacturer foregoes full automation and utilizes a semi-automated e-procurement system, whereas the vendor employs an automated fulfillment system. Although these specific findings are associated with the industrial supply chain studied in this research and the experimental test problems, they clearly indicate the potential benefits and pitfalls associated with e-replenishment systems.

The results reported in this article, when coupled with those in the literature provide additional insights into the economic impact of information sharing, e-replenishment, and coordination on supply chain performance and provide groundwork for continued research. In contrast to Cachon and Fisher's (2000) analysis of a make-to-stock system consisting of a single item, single supplier, and multiple identical retailers, we find that moving to an e-procurement system can potentially increase system costs in a make-to-order supply chain. Although we cannot directly account for the differences in these research findings, we suspect, as suggested by Cachon and Fisher (2000), that they are related to differences in the operational characteristics of make-to-stock and make-to-order supply chains, the particular supply chain environments studied, and/or the specific data sets employed. Research clarifying the differences in these results is warranted. Additional research addressing the impact of supply chain flexibility on system performance in decentralized and coordinated decision-making environments is also worthwhile. Finally, the specific cost savings reported in this study are associated with the cost structures and processes observed in the make-to-order equipment supply chain. The study of e-replenishment strategy in other industries and supply chain settings is necessary in order to draw more general conclusions. [Received: April 2003. Accepted: August 2004.]

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

Funda Sahin is an assistant professor of logistics in the College of Business, at the University of Tennessee. She received her PhD from Texas A&M University. Her research and teaching interests are in logistics and transportation, operations and supply chain management, inventory planning and control, and information technology applications in supply chain management. Her publications are in *Decision Sciences* and *Production and Inventory Management Journal.* She is a member of CLM, DSI, INFORMS.

Li-Lian Gao is an associate professor of operations management in the Frank G. Zarb School of Business at Hofstra University. He earned his PhD from Indiana University. His research interests are in combinatorial optimization, multi-echelon location analysis, inventory control and management information systems. His publications are in *Decision Sciences*, *Management Science*, *Naval Research Logistics*, *Interfaces*, and *European Journal of Operational Research* among others.