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Information sharing and coordination in make-to-order supply chains

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Abstract

This research, based on our observations of an industrial vendor–manufacturer relationship, investigates the impact of information sharing and physical flow coordination in a make-to-order supply chain. We mathematically model and develop simulation-based rolling schedule procedures for analyzing the manufacturer's ordering policies, transportation activities, and the vendor's manufacturing and order fulfillment processes under five alternative integration strategies. Our objective is to measure the value of information sharing and system coordination across the strategies, identify whether the source of the benefits come from information sharing or coordination, study the allocation of system benefits among channel members, and analyze the impact of environmental factors on system cost performance. The experimental results indicate a 47.58% cost reduction moving from a traditional supply chain to a fully integrated system. While information sharing reduces costs, the main economic benefit comes from coordinated decision-making. The savings associated with system integration are not equally allocated among channel members, and vary by strategy. The procedures developed in the research provide economic insight that fosters the sharing of technological and strategic efforts.

Keywords: Supply chain management; Information technology; Batch manufacturing; Inventory management; Lot sizing; Industrial dynamics

1. Introduction

Advances in information technology are enabling firms to critically reevaluate their supply chain strategies and explore new prospects for inter-organizational cooperation. This is occurring at an opportune time, as higher levels of product variety, global marketplaces, shorter product life cycles, and demand for premium customer service are increasing supply chain complexity and cost. However, the often-conflicting objectives of the channel members pose many challenges for achieving effective system

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redesign. A better understanding of the benefits of supply chain integration promotes organizational relationships that foster the sharing of technological and strategic efforts. In this research, we consider two aspects of supply chain integration; information sharing and physical flow coordination, and examine their impact on system performance in a make-to-order vendor–manufacturer relationship.

While it is well-accepted by supply chain executives that information sharing and physical flow coordination can lead to enhanced supply chain performance (see La Londe and Ginter, 2004), the source, potential magnitude, the allocation of the improvements across channel members is not clear. As noted in Cachon and Fisher (2000), the operational benefits of information sharing and coordination vary considerably across research studies ranging from 0% to 35% of total relevant costs. The disparity of results is linked to differing supply chain structures and problem assumptions and indicates the fallacy of transferring the research findings of one problem environment onto a dissimilar environment.

Tayur et al. (1999) and Sahin and Robinson (2002) provide comprehensive surveys of the supply chain information sharing and coordination literature. Their findings, and ours as detailed in the next section, reveal a concentration of research addressing make-to-stock supply chains utilizing statistical-based inventory control procedures, which are founded on the basic assumptions of independent item control and a known stationary stochastic demand process over an infinite planning horizon. Not a single effort investigates the unique problem characteristics of upstream supply processes in a make-to-order environment, which are characterized by highly erratic and often discontinuous demand at the end item level, dependent demand relationships among items, lumpy and deterministic dynamic-demand at the component level, and short finite planning horizons. These demand and supply characteristics violate the basic assumptions of statistical inventory models and are more accurately modeled by dynamic-demand inventory models embedded within simulation-based rolling schedule planning procedures. Due to these structural differences in the two problem environments and the requisite research methodologies, the existing research findings for make-to-stock systems are not transferable to the make-to-order problem environment. As noted in Sahin and Robinson (2002), the unique opportunities for sharing MRP generated planned orders and net requirements data in make-to-order systems are not addressed in the literature. Similarly, channel coordination opportunities between manufacturers and vendors to reduce system costs associated with the vendor's equipment changeover cost, transportation delivery charges, and transaction costs are unexplored.

In this paper, we fill some of the gaps in the literature by examining the impact of information sharing and physical flow coordination on system performance in a make-to-order vendor–manufacturer relationship. The research is based on our observations of a supply channel consisting of two Fortune 500 companies in which the manufacturer applies requirements planning based procedures to schedule his internal operations and trigger vendor replenishments. For this traditional make-to-order supply relationship, we document and mathematically characterize the existing replenishment processes and propose four additional supply chain strategies based on varying levels of information sharing and decision-making coordination. Collectively, these strategies span the diversity of integration strategies applied in industry ranging from the most rudimentary to the most tightly integrated. We also expand the problem scope to consider multi-item coordination issues, where the current make-to-stock literature takes a single-item perspective.

Our objective is to provide insight into the value of information sharing and system coordination across the strategies, identify whether the source of the benefits come from information sharing or decision-making coordination, study the allocation of system benefits among channel members, and investigate the impact of environmental factors on the value of tighter system integration. In addition to our unique focus on make-to-order systems, we study performance improvement and benefit allocation at the individual channel member and provide new insights into the literature, where the common unit of analysis is the system level.

We also contribute new simulation-based experimental frameworks and modeling perspectives to the supply chain literature. We model the static replenishment problems facing the four decentralized decision-making supply chain structures as sequential two-stage mixed-integer-programming (MIP) problems and develop a simulation-based rolling schedule framework to investigate the performance of each strategy. The simulation procedures capture the dynamics of the rolling schedule process on MRP system nervousness, which are caused by incorporating new customer orders into each successive planning cycle. The experimental frameworks extend the single-enterprise rolling schedule procedures applied by Sridharan et al. (1987,1988) and others (see Yeung et al., 1998 for a review of some of the more significant research utilizing this methodology) to a supply chain context by simultaneously linking and evaluating the operational decisions and activities of the manufacturer's, transportation provider's and vendor's processes. While we tailor the frameworks to a specific two-stage problem in this research, these general procedures can be modified to accommodate other supply chain structures. In addition, for the fully coordinated (centralized decision-making) environment, we provide a general modeling representation of the coordinated lot-size problem that extends the single player perspective taken in the literature (see Robinson and Gao, 1996; Robinson and Lawrence, 2004) into a unified planning model that captures the relevant cost tradeoffs facing each channel member. We then embed this model into a simulation-based rolling schedule framework similar to that proposed by Sridharan et al. (1987).

Utilizing the simulation-based frameworks, we conducted an experimental analysis over a wide range of parameter values. The overall findings reveal that while substantial system benefits are possible if the manufacturer shares his planned order information and booked orders with the vendor, even a greater benefit is possible through system coordination. Specifically, when compared to traditional operating systems (1) operational costs are reduced by 2.33% when the manufacturer shares his planned replenishment schedules with the vendor, (2) coordination of the manufacturer's orders with transportation decisions provides a 30.69% cost reduction, (3) coordination of manufacturer's ordering process with transportation schedules plus sharing planned replenishment schedules with the vendor improves performance by 39.36%, and (4) complete information sharing and full system coordination yields a 47.58% cost improvement. Comparing these results with those reported in the literature for make-to-stock systems, illustrates that the percent performance improvement from information sharing and coordination within a make-to-order context may exceed those available in make-to-stock systems. These findings justify the separate study of make-to-order supply chains.

Other findings indicate that channel savings are not equally distributed among channel members, and the distribution of savings and value-added activities varies across supply chain strategies. Finally, disaggregating the results by experimental factor reveals that changes in the level of the coefficient of variation of demand, transportation fixed cost, and equipment setup cost impact the percent performance improvement associated with moving from lower to higher levels of information sharing and coordination.

Taking a managerial perspective, we recognize that these savings are meaningless unless mechanisms for information sharing and coordination can be worked out among channel members. However, the technology for information sharing is readily available over multiple electronic channels including email, fax, extranets, EDI, extended enterprise resource planning systems, and others. In addition, decision support for operational level coordination is possible through the models proposed in this research, which can be implemented under a variety of organizational relationships such as vendor-managed inventory (VMI), manufacturer-managed inventory (MMI), and JIT-II (Dixon and Porter, 1994).

Finally, this research provides an economic foundation for understanding the value of information sharing and physical flow coordination in make-to-order supply chains, the source of system improvements, and the potential distribution of the benefits. These findings and the simulation-based frameworks can support technological and strategic efforts seeking channel coordination and provide a foundation upon which additional research can be built.

The following section surveys the related literature and further isolates our contributions. Section 3 describes the problem environment and the supply chain strategies. Section 4 briefly describes the mathematical models and rolling schedule simulation procedures. Section 5 details the numerical study and Section 6 concludes.

2. Literature survey

Sahin and Robinson (2002) propose the degree of information sharing and decision-making coordination as two major dimensions of supply chain integration at the operational level. One extreme is represented by the traditional supply chain structure in which each channel member operates independently in his own self-interest using only locally available information. Forrester (1958) introduces this decentralized decision-making approach in his seminal work on industrial dynamics. At the other extreme is the fully coordinated decision-making approach, in which all information and decisions are aligned to accomplish the global system objectives (see Whang, 1995 for a classification of the coordination literature). This philosophy is taken in Clark and Scarf (1960), where optimal policies for a multi-echelon inventory problem are studied. In between these two extremes, a variety of approaches are possible based on varying levels of information sharing (i.e. forecasts, future planned orders, inventory policy parameters, inventory levels, etc.) and decision-making coordination (i.e. inventory replenishment, transportation, capacity planning, etc.). While there is an emerging literature base examining the performance impact of these alternative strategies, it has been slow in developing and is directed at make-to-stock supply chains without any consideration of make-to-order systems, which is the topic of this research.

Forrester (1958) identifies the natural tendency of decentralized decision-making to amplify, delay and distort demand information moving upstream in a make-to-stock supply chain, thereby causing inaccurate forecasts, inefficient asset management, and poor customer service. Lee et al. (1997a,b) label this phenomenon as the 'bullwhip' effect, provide industry examples of its occurrence, identify its potential causes, and recommend strategies for counteracting its effect. Suggested remedies include sharing point-of-sales data with suppliers and operational alignment (coordination) of channel member activities. Case analysis by Houlihan (1987), Taylor (1999), and Fransoo and Wouters (2000) further document the bullwhip effect in make-to-stock supply chains. Baganha and Cohen (1998), Graves (1996), and Cachon (1999) analytically verify increased demand volatility moving upstream in the supply chain, while Metters (1997) and Chen et al. (2000) attempt to analytically quantify the impact of the various causes of the bullwhip effect on make-to-stock system performance.

The next four papers show how sharing demand and/or inventory data can improve the supplier's order quantity decisions in two-stage serial systems in which both the supplier and retailer follow a make-to-stock strategy. Given a known and stationary retailer demand process, Bourland et al. (1996) examine periodic order-up-to inventory policies when the timing of the channel members' review periods are not synchronized, and Gavirneni et al. (1999) study the capacitated supplier case in which the retailer uses an (s, S) model and the supplier applies a modified (s, S) inventory model. In each scenario, knowledge about the retailer's inventory levels reduces the demand uncertainty faced by the supplier. Chen et al. (2000) and Lee et al. (2000) consider periodic review systems when the underlying demand process at the retailer is autocorrelated. Sharing point-of-sale demand data enables the manufacturer to improve his forecast accuracy and lower total inventory policy costs. However, centralizing customer demand information does not completely eliminate the bullwhip effect.

Hariharan and Zipkin (1995) and Gilbert and Ballou (1999) examine the value of advance order commitments to a supplier using an (s, S) inventory model when serving multiple customers. Knowing the upcoming orders reduces the supplier's demand uncertainty and lowers system costs.

Several researchers explore the value of information sharing and system coordination in make-to-stock systems assuming discrete, independent and identically distributed demand. Chen (1998) studies the value of an echelon stock policy (system coordination using complete information) over an installation stock inventory policy (decentralized decision-making) in a serial system, where each stage controls its inventory position using a reorder point/order quantity policy (R, nQ). A numerical study reveals an average 1.75% system improvement under the echelon stock inventory policy, with a maximum 9% savings. Cachon and Fisher (2000) model a single supplier, N identical retailer environment under an (R, nQ) inventory policy finding that information sharing and coordination provide an average 3.4% system cost reduction, with a maximum 12.1% savings.

Fry et al. (2001) compare the performance of retailer-managed inventory systems and VMI systems under full information sharing with typical savings ranging from 10% to 15% when moving to VMI. Aviv and Federgruen (1998) find information sharing in a VMI environment yields an average 2% system savings, while coordination lowers costs by an additional 4.7% below the information sharing case.

Several observations are possible from the literature survey. First, while the lack of information sharing and/or coordination implies the system will not perform at peak efficiency, the magnitude of the inefficiency varies widely across the research studies depending on the supply chain structure and specific problem assumptions. Chen (1998) finds benefits up to 9%, Aviv and Federgruen (1998) indicate savings of 0–5%, Lee et al. (2000) demonstrate that information sharing lowers costs from 12–23%, while Gavirneni et al. (1999) report cost reductions of 1–35% from sharing retailers' demand data. Consequently, as indicated by Cachon and Fisher (2000), the findings associated with one problem environment may not accurately transfer to another problem with dissimilar operational characteristics.

Second, the current research assumes each channel member follows a make-to-stock inventory policy, where the primary benefit of channel integration is a reduction in demand variability and hence safety stock inventory holding costs. In spite of their common occurrence in industry, not a single research project addresses the unique characteristics of make-to-order systems, which prohibit maintaining inventory in anticipation of customer demand. In these situations, material requirements planning systems and deterministic dynamic-demand inventory models are more appropriate for replenishment planning. Consequently, due to the common occurrence of make-to-order systems, the distinct differences in demand and supply factors between make-to-stock and make-to-order systems, the inability to accurately transfer research findings across supply chain structures, and the lack of any prior research considering the benefits of integration in make-to-order supply chains, this research on make-to-order systems is well-justified and considers an important gap in the literature.

3. Make-to-order replenishment processes and integration strategies

This study is based on our observations of the replenishment activities of an international manufacturer of industrial drilling equipment and a direct material vendor for metal components used in fabrication. The end items are used extensively in water-well, construction, and mining operations. Each end item is composed of assemblies (e.g., drilling tower, mainframe platform, chassis, power head) that are designed, fabricated and configured according to customer specifications. Due to the custom design nature of the product line and the low demand rate, the firm is unable to accurately forecast demand at the end item, assembly, or component level and operates on a make-to-order basis.

To insure supply continuity, the manufacturer purchases metal components for tower and chassis mainframe fabrication from three local custom metal manufacturers. Each supplier is the primary source for approximately 80 different metal components ranging in weight from 8 ounces to several hundred pounds. Typical processing operations include cutting, drilling, welding, deburring, and fabrication. Component usage rates range from 1 unit to 26 units in each end item. While most components are unique to a specific end item, some are common across a particular tower height and/or application (e.g., water well, construction, and mining blast holes). Because of high demand variability and the necessity of shipping matched sets of components, the vendor responds to the manufacturer's orders on a make-to-order basis.

We briefly describe the production and procurement processes of this supply chain, which are common to make-to-order systems in other industries. Orlicky (1975) and Vollmann et al. (1997) provide in depth discussion of make-to-order planning and control systems. Operational planning begins with an intermediate-term forecast in generic product units, which are then assigned tentative completion dates in a final assembly schedule (FAS). As customer orders are received, the generic planning units are converted to specific end items and assigned shipping dates. Any planning unit that is not replaced by a booked customer order upon reaching an order time-fence is dropped from the forecast or rescheduled to a later date. The order time-fence extends into the future at least as far as the longest cumulative stacked procurement, production

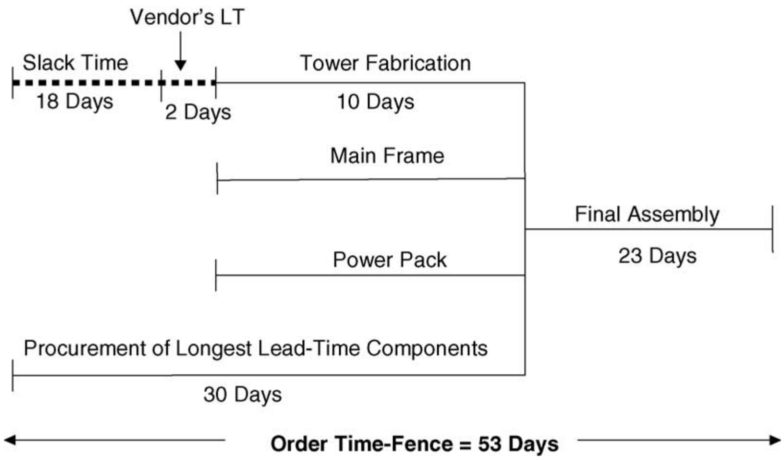

Fig. 1. Cumulative manufacturing lead-time for a drilling rig.

and assembly lead-time for any non-inventoried item in the bill of material (BOM). Once an order passes this time-fence, its configuration, quantity and due date are locked-in the production schedule and subject to change only in emergencies. This insures sufficient lead-time for supply chain activities. A master production schedule coordinates assembly operations and drives MRP.

Fig. 1 shows the lead-time relationships among the order time-fence, the longest cumulative lead-time in the BOM, final assembly, major module production and procurement. The 53-day order time-fence corresponds to the longest cumulative procurement and final assembly lead-time path of a non-inventoried component. The total lead-time for tower fabrication and final assembly is 33 days, providing a 20-day horizon from when the end item crosses the order time-fence until the manufacturer must order and receive the components for tower fabrication.

Given the highly unpredictable nature of end item and component demand, production planning is carried out on a rolling schedule basis in which a static lot-sizing problem is solved using the currently available demand data up to the order time fence. However, only the earliest orders are implemented before the static model is re-solved using updated demand data. Following this iterative procedure, production schedules are periodically updated using the most recent demand information rolling through time.

Fig. 2 illustrates the manufacturer's static lot-sizing problem and MRP record for an example metal

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Gross Requirements	2	6	16	22	4	4	12	8	16	4	6	16	4	4	10	12	8	10	6	16
Scheduled Receipt		6																		
Ending Inventory 2	0	0	0	8	4	0	8	0	10	6	0	8	4	0	12	0	16	6	0	0
Planned Order Receipt			16	30			20		26			24			22		24			16
Planned Order Release	16	30			20		26			24			22		24			16		

← Frozen orders → ← Slushy orders →

Fig. 2. Manufacturer's MRP tableau for a metal component ($T = 20$ and $n = 12$).

component. Due to the schedule stability provided by the order time-fence, all gross requirements are deterministic over the 20-day planning horizon. However, the timing and quantity of the planned orders, particularly in the later time periods, may oscillate during successive MRP record processing cycles as new orders are entered into the FAS and the MRP schedule is re-optimized. Standard practice for controlling this MRP nervousness and providing a stable planning environment is to establish an n-period frozen time fence, where $n \leq T$ and T is the length of the planning horizon (see Blackburn et al., 1986; Sridharan et al., 1987; Vollmann et al., 1997). The timing and quantity of replenishments in periods $t = 1, 2, \ldots, n$ are frozen, while orders in time periods $t = n + 1, n + 2, \ldots, T$ are considered slushy with the replenishment periods frozen in time but quantities permitted to vary in the next planning iteration (Zipkin, 2000).

Following traditional replenishment processes, the manufacturer optimizes his procurement schedule for each component, and places orders one at a time with the vendor according to the replenishment lead-time. Lacking any visibility into future orders, the vendor responds on a lot-for-lot basis. These traditional replenishment processes, as also studied by Forrester (1958), Bourland et al. (1996), and Fry et al. (2001), are characterized by decentralized decision-making with no information (NI) sharing and no coordination (NC) among channel members. The NI/NC strategy represents the most rudimentary replenishment strategy and provides a benchmark for evaluating the economic benefit of more integrated approaches.

We propose additional integration strategies based on varying levels of information sharing and coordinated decision-making. Under a partial information (PI) sharing strategy, the manufacturer releases all of the planned orders in the MRP planning horizon to the vendor as advance order commitments. This enables the vendor to apply economic lot-sizing procedures to minimize his order fulfillment costs. Following a full information (FI) sharing strategy, the manufacturer communicates all the information in the MRP record to the vendor revealing, in addition to planned orders; all gross requirements and projected inventory balances by time period. This is analogous to providing the vendor with a perfect demand forecast over the duration of the planning horizon.

We also define partial and full coordination strategies. Under partial coordination (PC), in attempt to reduce his landed product costs, the manufacturer coordinates individual item replenishment and transportation decisions. Under full coordination (FC), a single decision maker coordinates the replenishment activities of the manufacturer, transportation provider, and vendor to obtain a globally optimal replenishment schedule. Of the nine possible combined strategies, NI/FC and PI/FC are infeasible since system-wide coordination requires the sharing of all relevant system data. In addition since FI provides no economic advantage over PI when there is less than full system coordination (see Appendix A for the proof), we do not consider strategies FI/NC and FI/PC.

Table 1 defines the five relevant replenishment strategies along with the type of dynamic demand lot-sizing problem solved by each channel member. In order to uncover the basic underlying economic tradeoffs of the system, we assume the vendor is uncapacitated in the analysis. This assumption is also reflective of the actual operating environment, in which the manufacturer periodically provides the vendor with an intermediate term forecast of his capacity requirements so the vendor can maintain sufficient capacity to meet demand on a timely basis.

Table 1
Integrated information sharing and coordination strategies

Strategy	Replenishment model		
	Manufacturer	Transportation	Vendor
No information sharing/no coordination (NI/NC)	Wagner-Whitin	Ship as required	Lot-for-lot
Partial information sharing/no coordination (PI/NC)	Wagner-Whitin	Ship as required	Wagner-Whitin
No information sharing/partial coordination (NI/PC)	Coordinated replenishment		Lot-for-lot
Partial information sharing/partial coordination (PI/PC)	Coordinated replenishment		Wagner-Whitin
Full information sharing/full coordination (FI/FC)	Coordinated replenishment		

4. Model development

This section briefly describes the computer-based simulation models employed in the research. The procedures, programmed in FORTRAN, replicate the rolling schedule processes described earlier in which the static replenishment lot-sizing problems of the manufacturer, vendor and transportation provider are solved to optimality at each planning iteration. The general approach is as follows for a given K-period experimental time horizon. First, the manufacturer optimizes his static lot-sizing problem over the current T-period planning horizon according to the specific coordination strategy under investigation (e.g., NC, PC or FC). Next, the manufacturer's replenishment orders are released to the vendor according to the information-sharing schema under evaluation (e.g., NI, PI, or FI). Given the manufacturer's requirements, the vendor optimizes his production schedule and arranges for product delivery as specified by the manufacturer's due dates. This completes the planning cycle.

Next, the manufacturer rolls forward in time and initiates the next planning cycle. The beginning period for the subsequent planning cycle is determined by the earliest time period whose demand is not covered by an order in the frozen schedule and then offsetting by replenishment lead-time. Finally, the demand data for the new planning horizon is updated and the next planning cycle is executed. The procedures continue in this manner rolling through time until all K-periods of the experimental design are scheduled. Additional details describing the simulation procedures including mathematical statements of the static planning problems and the rolling schedule procedures are provided in Appendix B.

5. Experimental analysis

This section summarizes the experimental results and sheds some light on the value of information sharing and coordination for the supply chain strategies, whether the source of the benefits comes from information sharing or coordination, the allocation of benefits across channel members, and the impact of environmental factors on cost performance.

5.1. Parameters and methods

The study consists of two experiments based on data collected from the industrial equipment supply chain. However, to insure that the results are reflective of this general type of make-to-order environment, and not a specific scenario, we generated a wide range of problem instances. In the first experiment, 108 test problems are formed from all combinations of the following parameters: number of items $N \in \{1, 5, 10, 20\}$, vendor equipment changeover cost $P_{(v)ij} \in \{25, 50, 100\}$ for all i and j, fixed cost for delivery $T_i \in \{25, 75, 125\}$ for all i, and coefficient of demand variation $\mathrm{CV} \in \{1.51, 0.5, 0.2\}$. The second experiment investigates the impact of demand level on strategy performance. Two demand levels are considered: the base-case from experiment one and three times the base-case. In this experiment, CV = 0.5 for the 72 test problems, which are drawn from all combinations of $N \in \{1, 5, 10, 20\}$, $P_{(v)ij} \in \{25, 50, 100\}$, $T_i \in \{25, 75, 125\}$ and the two levels of demand.

We set CV by altering the lumpiness of the gross requirements in the manufacturer's MRP record. $\mathrm{CV} \in \{1.51, 0.5\}$ is characteristic of the demand pattern facing the vendor, while CV = 0.2 provides a less lumpy demand pattern for experimental purposes. We randomly generated each item's demand stream using procedures similar to those in Jacobs and Whybark (1992). All items within a data set have the same CV value. For a specified number of items and CV value, each item maintains the same average daily demand across data sets. In order to maintain a consistent demand level across problem sets, the average daily demand summed over all items is 27 units.

All other problem parameters are based on the supply chain's cost and operational structures, where for all i and j, S_i = US\$ 20, W_i = US\$ 45, and $P_{(m)ij}$ = US\$ 10. Per unit costs for vendor production and transportation are assumed constant over time and quantity. Hence without loss of generality, $c_{ijt} = 0$ for all i, j, and t and $a_{ij} = 0$ for all i and j. Consistent with the operating environment, we modeled same day transportation delivery. In all problems, we set $T = 20$, which corresponds to the components' MRP planning horizon (i.e., 2-day vendor lead-time plus 18-day slack time on the BOM path). The best value of n requires trading off the manufacturer's desire for scheduling flexibility in successive planning iterations (i.e., a relatively small value of n) versus the vendor's need for schedule stability (i.e., large value of n). For the single enterprise case, Sridharan et al. (1987, 1988) report that setting the frozen interval at approximately 50% of the planning horizon length provides a good balance between schedule cost and stability. As part of our preliminary analysis, we experimentally evaluated the impact of alternative values of n on cost performance in a two-stage supply chain finding that setting n slightly higher than 50% of the planning horizon provided the best performance across a broad subset of the test problems (the detailed results are available from the authors upon request). Consequently, we set $n = 12$ in the experiments.

We coded the simulation-based rolling schedule procedures in FORTRAN and solved the static lot-sizing problems using the dual-ascent based branch and bound procedures described in Gao and Robinson (1994) and Robinson and Gao (1996). Using the procedures and data described earlier, we randomly generated a unique demand stream for each CV value for an experimental horizon of $K = 200$ time periods, which provides a minimum of 10 planning cycles for each test problem. The 10 planning cycles are sufficient to diminish the end-of-horizon effect resulting from the finite experimental time interval to which the rolling schedules are applied (see Zoller and Robrade, 1988; Stadtler, 2000 for discussion).

5.2. Experimental results

Table 2 summarizes the results for the first experiment. The performance metrics, cost and percentage savings over the NI/NC benchmark, are reported at the system, channel member and component level. The last five rows in the table report the total number of purchase orders/invoices, line-item orders, shipments, equipment setups, and the average number of line items per shipment. These findings document the impact of the strategies on supply chain activities and cost and help identify the major cost drivers. The analysis considers only the operational impact of the strategies and does not consider technology or organizational costs associated with implementing the strategies.

Table 2 reports the results associated with two variants of the FI/FC strategy depending upon whether the manufacturer's ordering costs are included or not. Strategy FI/FC-V assumes the vendor coordinates all system flows, which eliminates the need for the manufacturer to place orders. Hence, the purchase order costs are set equal to zero. Strategy FI/FC-C assumes the system is centrally coordinated, but that

Table 2
Experimental results: cost performance and operational activity

Strategy	NI/NC (costs)	PI/NC (costs)	%	NI/PC (costs)	%	PI/PC (costs)	%	FI/FC-V (costs)	%	FI/FC-C (costs)	%
Mfc. inv.	6650	6650	0.00	5903	11.23	5903	11.23	14917	−124.32	15389	−131.41
Mfc. P.O.	7460	7460	0.00	1116	85.04	1116	85.04	–	100.00	666	91.07
Mfc. line item	3730	3730	0.00	4809	−28.92	4809	−28.92	2.534	32.06	2502	32.91
Mfc. total cost	17840	17840	0.00	11828	33.70	11828	33.70	17451	2.18	18557	−4.02
Transportation	10288	10288	0.00	3838	62.69	3838	62.69	2548	75.24	2404	76.63
Vendor equipm.	21733	15863	27.01	28017	−28.92	16075	26.04	13290	38.85	13148	39.50
Vendor inv.	–	4315		–		6160		–		–	–
Vendor invoice	16785	16785	0.00	2511	85.04	2511	85.04	1650	90.17	1540	90.82
Vendor total	38518	36962	4.04	30528	20.74	24746	35.75	14940	61.21	14688	61.87
Total cost	66645	65090	2.33	46194	30.69	40412	39.36	34938	47.58	35649	46.51
No. of P.O./invoices	373	373		56		56		37		34	
No. of line items	373	373		481		481		253		250	
No. of shipments	137	137		56		56		37		34	
No. of line-item per shipment	2.7	2.7		8.6		8.6		6.8		7.4	
No. of vendor setups	373	305		481		315		253		250	

the manufacturer still places orders with the vendor. While we would anticipate elimination of manufacturer-launched purchase orders in a fully automated and coordinated system, we include strategy FI/FC-C for comparative purposes as a ‘worst case’ scenario to independently isolate the advantages of system coordination and the elimination of the ordering costs. As expected, strategy FI/FC-V results in only slightly better system performance (approximately 1%) versus FI/FC-C. Consequently, we only discuss the performance of strategy FI/FC-V in the text, while analogous results for FI/FC-C can be drawn from Table 2.

The summarized findings reveal a 47.58% system-wide cost reduction when moving from a traditional NI/NC strategy to FI/FC-V, a fully coordinated supply chain. The minimum and maximum percent savings across the problem sets is 36.5% and 51.3%, respectively. This performance improvement is significantly larger than the 1.75%, 3.4% and 6.7% cost savings found by Chen (1998), Cachon and Fisher (2000), and Aviv and Federgruen (1998), respectively, in their studies of make-to-stock supply chains.

While information sharing is frequently cited as being the key to enhanced supply chain performance, the findings for the test problems indicate that tighter coordination among channel members may provide a more effective lever for cost improvement. For example, moving from NI/NC to the partial information sharing strategy PI/NC reduces costs by 2.3%, while the partial coordination strategy NI/PC yields a 30.69% cost reduction over NI/NC. Similarly going from PI/NC to PI/PC yields a 37.03% improvement, which is due to improved coordination, over NI/NC. The findings also suggest a positive interaction between information sharing and coordination as illustrated by the 8.67% incremental gain attributed to partial information sharing going from NI/PC to PI/PC. Finally, moving from the best decentralized decision-making structure, PI/PC, to fully coordinated decision-making provides an 8.22% incremental performance improvement.

Fig. 3 provides the percentage of system costs borne by each channel member under each strategy. The findings reveal that the benefits of system integration are not shared equally among participants. As expected under the decentralized decision-making strategies (NC and PC), moving from no information sharing to partial information sharing benefits only the vendor. On the other hand for a specified level of information sharing, moving from no coordination to partial coordination benefits all parties but not on an equal basis. The reallocation of the percent of system costs is quite pronounced moving from NI/NC to FI/FC-V, where the manufacturer’s percent of system costs increase from 26.8% to 49.9%. Viewed from a different perspective, the percent cost reduction over the NI/NC benchmark for the manufacturer, transportation provider, vendor and system is 2.18%, 75.24%, 61.21%, and 47.58%, respectively (see Table 2). Hence, the manufacturer’s share of the savings is negligible while the other participants receive substantial gain.

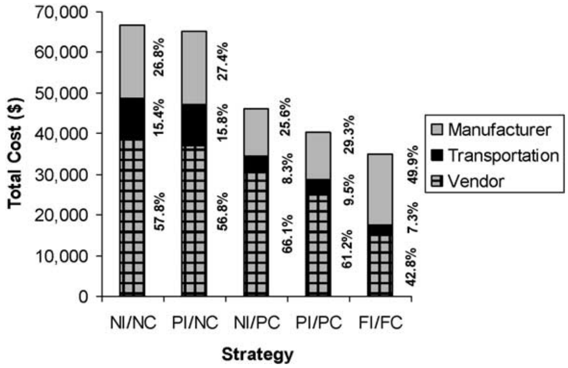

Fig. 3. Summary results by total cost and percent of total cost.

Further analysis of the experimental results in Table 2 for FI/FC reveals that value-added activities may be reassigned among channel members with a change in strategy. Under partial information sharing, PI/NC and PI/PC, the vendor aggregates the manufacturer’s orders into economic production lot-sizes, but must maintain inventory on-site since the delivery dates and quantities are specified by the manufacturer. However, the optimal system solution in FI/FC-V calls for the vendor to ship full production lot-sizes, which reduces transportation related fixed costs and overall system costs. Consequently, all system inventory is shifted to the manufacturer resulting in a 124.32% inventory cost increase over NI/NC. In addition, the manufacturer must provide a mechanism for sharing his demand and cost data with the vendor. On the positive side, the manufacturer is relieved of all ordering activity, which is now reassigned to the vendor or a centralized planner.

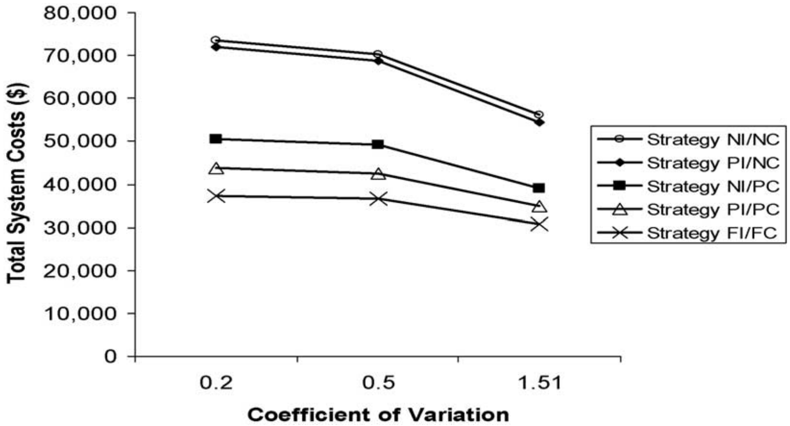

Fig. 4. Impact of the coefficient of variation of demand.

As also noted by Lee et al. (2000) and other researchers, channel improvements often call for supply chain contracts or agreements to equitably distribute the benefits and motivate optimal channel decisions. This applies to operational savings as well as investments in technology and organizational relationships. The rolling schedule procedures developed in this research can play a key role in supporting these inter-organizational efforts by making the cost and operational impact of supply chain integration readily apparent.[1]

Drawing additional insights from the study, we conclude that under a given level of coordination, incremental improvements in information sharing leads to non-increasing system costs. That is, $TC_{NI/NC} \geq TC_{PI/NC} = TC_{FI/NC}$ and $TC_{NI/PC} \geq TC_{PI/PC} = TC_{FI/PC}$. While in each test problem moving from no coordination to partial coordination lowered system cost (i.e., $TC_{NI/NC} > TC_{NI/PC}$ and $TC_{PI/NC} > TC_{PI/PC}$), this relationship may not hold due to potential network externalities. Specifically, operating under a decentralized decision-making environment the manufacturer ultimately drives the replenishment activities of the vendor, but he does not consider the impact of his order stream on the vendor's cost structure.

Figs. 4–8 examine the impact of changes in the values of the experimental factors on system performance. Fig. 4 indicates that for all strategies system costs decline with higher values of the coefficient of variation of demand. In addition, the potential benefit of integration is higher for lower values of the CV of demand. Recognizing that lumpy demand provides less opportunity for lot-size consolidation explains these counter intuitive results.

As expected, higher transportation costs provide a greater opportunity for economic improvement through partial or full system coordination. This is indicated in Fig. 5 by the widening gap between the coordinated and non-coordinated strategies with increased transportation costs. Perhaps, an even more important finding is that increased coordination mitigates the adverse impact of transportation rate increases, thereby minimizing the channel risk associated with uncertain or increasing cost structures. As illustrated in Fig. 5, increasing shipment cost from US$ 25 to 125 increases the cost of strategy NI/NC by

[1] While a detailed treatment of contracting and incentive issues is beyond the scope of this paper, we make two observations. First, the FI/FC-V strategy positions all inventory at the manufacturer's site thereby increasing his costs, while the benefits are accrued by the transportation provider and vendor. By changing the operating contract to a pull-to-pay VMI system (i.e. the vendor is paid when the items are pulled from inventory by the manufacturer), the inventory carrying costs are partially transferred to the vendor thereby better balancing the savings among partners. Second, it is common practice in make-to-order manufacturing to price output based on a flat rate per unit of capacity usage, such as direct labor. The flat rate is applied to all the vendor's activities and covers direct and indirect costs, and desired profit margin. Moving to this pricing scheme, the vendor obtains his desired profit margin, while the manufacturer accumulates the economic benefits of integration, which could then be passed on to the consumer thereby strengthening the channel's strategic position.

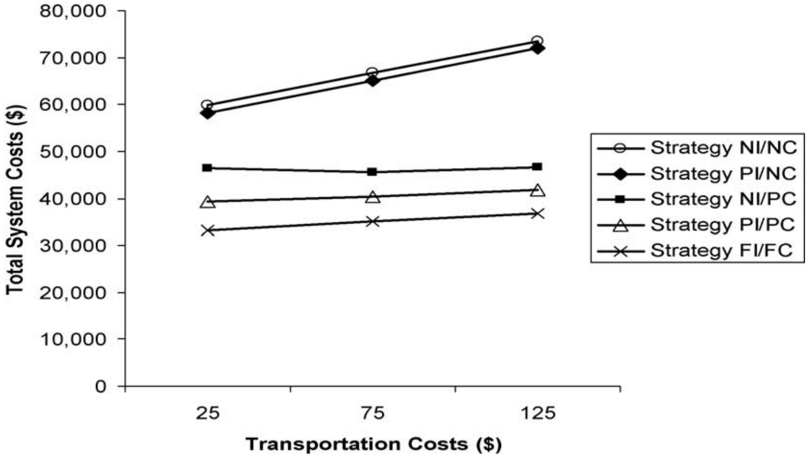

Fig. 5. Impact of transportation cost.

US$ 13,717 (23%), but only US$ 3595 (11%) for strategy FI/FC.

Due to lot-sizing economics, the absolute dollar savings derived from information sharing increases with higher equipment setup costs as illustrated by comparing NI/NC with PI/NC and NI/PC with PI/PC in Fig. 6. In addition, the percent savings over NI/NC benchmark also increases. Moving from NI/NC to PI/NC the percent savings are 0.01%, 0.1%, and 5.59%, for setup costs of US$ 25, 50, and 100, respectively. Moving from NI/PC to PI/PC, the incremental percent savings over NI/NC are 0.78%, 5.19%, and 16.58%, respectively.

Figs. 7 and 8 summarize the results for the number of items and demand level (experiment 2), where the benefit of integration increases with the number of items and demand level. Fig. 7 indicates that the system cost is approximately linear in the number of items with the more tightly integrated strategies having lower marginal rates of increase. Similar results hold for the

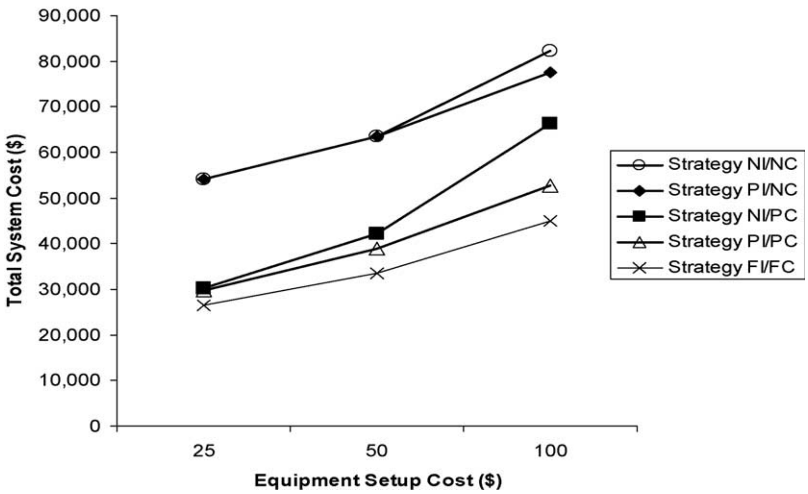

Fig. 6. Impact of equipment setup cost.

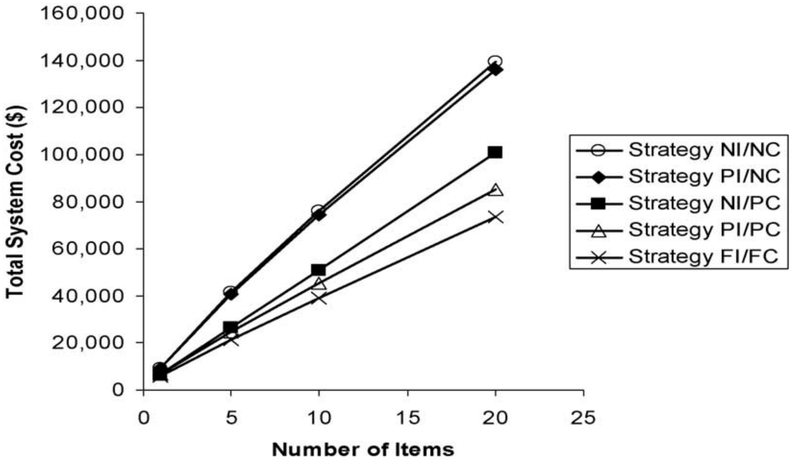

Fig. 7. Impact of the number of items.

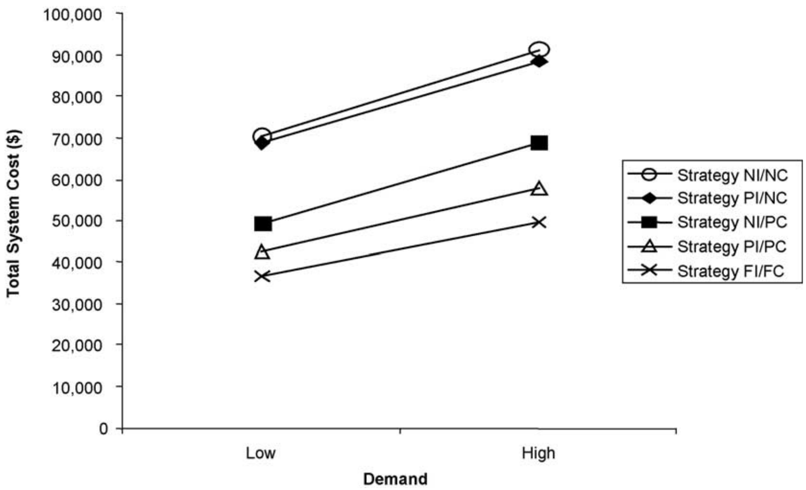

Fig. 8. Impact of demand level.

change in demand level with system costs for the more integrated strategies increasing at a lower marginal rate.

6. Discussion

Tighter supply chain integration in make-to-order supply chains through information sharing and physical flow coordination provides substantial opportunities for improved economic performance. While prior research focuses on make-to-stock systems, this research considers the unique demand and operational characteristics of make-to-order supply chains. We mathematically formulate five supply chain strategies based on different levels of information sharing and coordination, develop simulation-based rolling schedule procedures for their analysis, and report the findings of an experimental study that analyzes the relative cost performance of the strategies and the impact of changes in environmental parameters.

The experimental results are promising, indicating an average cost reduction of 47.58% when moving from a traditional to a fully integrated system. However, the savings are not equally allocated across channel members calling for realignment of incentive systems or contracts to insure that system objectives are met. The findings also indicate that the major benefit of supply chain collaboration in this particular environment comes from improved coordination, while information sharing unlocks only a small portion of the potential benefits associated with channel integration. However, the relative benefit of information sharing increases with higher equipment setup costs at the vendor.

A major hurdle in establishing collaborative supply chain relationships is a better understanding of the potential benefits of the relationship and the distribution of the benefits among players. The simulation-based frameworks provide an effective decision support tool for gaining the economic insight necessary to evaluate collaborative supply agreements in make-to-order manufacturing environments. The technology for implementing the strategies is readily available over existing electronic medium.

While this research considered only a single vendor–manufacturer relationship, the benefits scale to other trading partners. From the manufacturer's perspective, expanding the system to include all primary vendors leverages the technology investment and the firm's technological expertise. Dell Computer's supplier oriented extranet provides an example of this occurring in an assemble-to-order environment. Early involvement by the vendor in such a program not only strengthens his relationship with the manufacturer, but also strategically positions him to pursue similar opportunities with other customers.

As an initial research endeavor investigating the operational impact of information sharing and physical flow coordination in make-to-order supply chains we provide insight into a variety of research questions, but leave many unanswered. First, our results are based on specific problem assumptions and parameter settings. Additional research based on data drawn from different operating environments is worthwhile. These could include different operating cost structures or operational constraints, such as capacity limitations on the vendor's manufacturing operations, transport vehicles, or inventory storage. Second, the rolling schedule procedures developed in this research extend the single-enterprise frameworks reported in the literature to a multiple player supply chain environment. A formal study investigating the impact of operational parameters, such as the length of the planning horizon, frozen time fence and re-planning frequency, on system performance seems well-justified. Third, our findings indicate that improving channel integration may reallocate costs and value-added activities among participants in unexpected and undesirable ways. Mechanisms for equitably sharing benefits and other methods for facilitating inter-organizational relationships merit additional research. Finally, the acid test for any new operational procedure or concept is adaptation by industry. Empirical research documenting the implementation and management of information sharing and coordination strategies in industry is needed.

Acknowledgement

We wish to express our appreciation to Dr. Li-Lian Gao at Hofstra University for his assistance in developing the computer codes used in this research.

Appendix A

Theorem. *Full information sharing provides no incremental benefit over partial information sharing in a less than fully coordinated environment. That is, the optimal solutions of PI/NC and FI/NC are identical, as are those of PI/PC and FI/PC.*

Proof. The manufacturer's replenishment policy and transportation costs are identical for PI/NC and FI/NC and for PI/PC and FI/PC. Moving from partial to full information sharing, the vendor receives the manufacturer's gross requirements (D_{jt}) in addition to the replenishment requirements (Q_{ij}). However, the vendor cannot exploit this information to reduce his costs since he must ship according to the manufacturer's specified delivery schedule. Let t^* and t^{**} denote two consecutive optimal replenishment periods for the manufacturer under strategy PI/NC or PI/PC. Define an intermediate period t^+ with positive gross requirements where $t^* < t^+ < t^{**}$. Due to the single sourcing and exact requirements properties in Wagner and Whitin (1958) we know there is no economic incentive for the vendor to produce in period t^+ for shipment in period t^{**} since doing so would increase inventory costs without any reduction in setup costs.

Appendix B

This appendix details the simulation model for replicating the rolling schedule planning procedures. For each replenishment strategy, we first present the static two-stage MIP replenishment problems that are solved for each MRP planning cycle and then present the simulation-based framework that incorporates the dynamics of the rolling schedule replenishment processes. To simplify the presentation of the concepts and without loss of generality, we assume replenishment lead-time is zero. Backlogging at the vendor is not permitted since it would disrupt the execution of the manufacturer's production schedule.

B.1. Strategy NI/NC

Consider a K-period problem solved on a T-period rolling schedule basis. In each planning cycle, potential replenishment periods are denoted by $i = i_{\text{beg}}, \ldots, i_{\text{end}}$ and demand periods by $t = i_{\text{beg}}, \ldots, i_{\text{end}}$. For each 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 lot-sizing problem (MLSP(j, r)) as defined in Eqs. (B.1)–(B.5). Demand, D_{jt}, for product j in time period t is deterministic, varies with time and must be satisfied. The manufacturer's fixed cost for replenishing item j in time i includes an order processing cost, S_i and a line item cost, $P_{(m)ij}$, for product handling and inspection. The per-unit inventory holding cost for serving demand for product j in period t with product procured in time period i is h_{ijt}. Y_{ij} is a binary decision variable, where $Y_{ij} = 1$ if j is replenished in period i, and 0 otherwise. X_{ijt} is the fraction of demand in period t for product j that is supplied from replenishment in time period i. The manufacturer's costs associated with the ordering decisions up to the frozen time fence are gathered in Eq. (B.6) 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. Eq. (B.7) tabulates the manufacturer's total costs over the N items and IT_j planning cycles.

The manufacturer releases orders one at a time, causing the vendor to respond on a lot-for-lot basis. The vendor's costs for item j in planning cycle r are detailed in Eq. (B.8). The component costs include equipment setup, $P_{(v)ij}$, for item j in time period i, an invoice cost W_i in period i, a per-unit replenishment cost, c_{ijt}, for item j replenished in time period i to meet demand in time period t. The vendor's total costs for the planning cycles are gathered in Eq. (B.9).

Truck deliveries are scheduled according to the manufacturer's specified replenishment due dates. Transportation costs are accumulated in Eqs. (B.10)–(B.13), where a_{ij} is the per-unit cost for item j in time period i, T_i is the fixed shipment cost in time i, and V_i is a decision variable, where $V_i = 1$ if a shipment is made in period i, and 0 otherwise. Variable transportation costs are calculated by item j and planning iteration r in Eq. (B.10) and summed in Eq. (B.11). Eq. (B.12) collects the fixed transportation costs, where multiple items shipped in the same time period share the fixed cost. Total system costs are gathered by Eq. (B.14).

Manufacturer's lot sizing problem (MLSP)

problem MLSP(j, r)

$$\text{Min} \sum_{i=i_{\text{beg}}}^{i_{\text{end}}} (S_i + P_{(m)ij}) Y_{ij} + \sum_{i=i_{\text{beg}}}^{i_{\text{end}}} \sum_{t=i}^{i_{\text{end}}} h_{ijt} D_{jt} X_{ijt} \tag{B.1}$$

$$\text{subject to} \quad \sum_{i=i_{\text{beg}}}^{t} X_{ijt} = 1 \quad \forall\, t \tag{B.2}$$

$$X_{ijt} \le Y_{ij} \quad \forall\, i, t \tag{B.3}$$

$$X_{ijt} \ge 0 \quad \forall\, i, t \tag{B.4}$$

$$Y_{ij} \in \{0, 1\} \quad \forall\, i \tag{B.5}$$

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

$$\mathrm{TC}_{\mathrm{MLSP}} = \sum_{j=1}^{N} \sum_{r=1}^{\mathrm{IT_j}} C_{\mathrm{MLSP}(j,r)} \tag{B.7}$$

Vendor's lot-for-lot costs (VLFL)

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

$$TC_{\mathrm{VLFL}} = \sum_{j=1}^{N} \sum_{r=1}^{\mathrm{IT}_j} C_{\mathrm{VLFL}(j,r)} \tag{B.9}$$

Transportation—variable costs (TRV)

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

$$\mathrm{TC}_{\mathrm{TRV}} = \sum_{j=1}^{N} \sum_{r=1}^{\mathrm{IT}_j} C_{\mathrm{TRV}(j,r)} \tag{B.11}$$

Transportation—fixed costs (TRF)

$$\mathrm{TC}_{\mathrm{TRF}} = \sum_{i=1}^{K} T_i V_i \tag{B.12}$$

where

$$V_i = \begin{cases} 1 & \text{if} \sum_{j=1}^{N} \hat{Y}_{ij} > 0 \\ 0 & \text{otherwise} \end{cases} \quad \forall i \tag{B.13}$$

Total system cost

$$\mathrm{TC}_{\mathrm{NI/NC}} = \mathrm{TC}_{\mathrm{MLSP}} + \mathrm{TC}_{\mathrm{VLFL}} + \mathrm{TC}_{\mathrm{TRV}} + \mathrm{TC}_{\mathrm{TRF}} \tag{B.14}$$

The rolling schedule procedures simulate the operating processes of strategy NI/NC and capture the system dynamics.

Rolling schedule planning procedures for NI/NC

1. Initialize K, N, T, n, set $V_i = 0\ \forall i$, $\mathrm{IT}_j = 0\ \forall j$, $j = 0$, $C_{\mathrm{M}} = C_{\mathrm{TRV}} = C_{\mathrm{V}} = \mathrm{TC}_{\mathrm{NI/NC}} = 0$, randomly generate D_{jt} for $j = 1, 2, \ldots, N$ and $t = 1, 2, \ldots, K$.
2. Set $j = j + 1$. If $j > N$, then go to Step 9. Otherwise, $r = 0$, $i_{\mathrm{beg}} = 1$.
3. Set $i_{\mathrm{end}} = i_{\mathrm{beg}} + T - 1$, $i_z = i_{\mathrm{beg}} + n - 1$, $i^* = 0$, $r = r + 1$. If $i_z > K$, set $i_z = K$. If $i_{\mathrm{end}} > K$, set $i_{\mathrm{end}} = K$.
4. Solve MLSP(j, r) for $\hat{Y}_{ij}$ and $\hat{X}_{ijt}$. Calculate $C_{\mathrm{MLSP}(j,\,r)}$ by Eq. (B.6) and set $C_{\mathrm{M}} = C_{\mathrm{M}} + C_{\mathrm{MLSP}(j,\,r)}$.
5. For $i = i_{\mathrm{beg}}, \ldots, i_z$, set $V_i = 1$ if $\hat{Y}_{ij} > 0$. Calculate $C_{\mathrm{TRV}(j,\,r)}$ by Eq. (B.10). Set $C_{\mathrm{TRV}} = C_{\mathrm{TRV}} + C_{\mathrm{TRV}(j,\,r)}$.
6. Calculate $C_{\mathrm{VLFL}(j,\,r)}$ by Eq. (B.8) and set $C_{\mathrm{V}} = C_{\mathrm{V}} + C_{\mathrm{VLFL}(j,\,r)}$.
7. Set $i^* = \mathrm{Min}\ i > i_z$ such that $\hat{Y}_{ij} > 0$. If $i^* > 0$, set $i_{\mathrm{beg}} = i^*$. Otherwise, $i_{\mathrm{beg}} = i_{\mathrm{end}} + 1$.
8. If $i_{\mathrm{beg}} > K$, set $IT_j = r$, then go to Step 2, otherwise go to Step 3.
9. Calculate $\mathrm{TC}_{\mathrm{TRF}}$ by Eq. (B.12) and set $TC_{\mathrm{NI/NC}} = C_{\mathrm{M}} + C_{\mathrm{TRV}} + \mathrm{TC}_{\mathrm{TRF}} + C_{\mathrm{V}}$ and stop.

B.2. Strategy PI/PC

In strategy PI/PC, the manufacturer coordinates his item replenishment schedules in consideration of transportation costs, and shares all of his planned orders with the vendor. Problem MCRP(r), as stated in Eqs. (B.15)–(B.22), models the coordinated replenishment problem in planning cycle r and records the relevant costs. A purchase order, with fixed cost S_i, covers all items jointly replenished in time period i. The binary decision variable U_i is set equal to 1 if an order is placed in time i, and 0 otherwise. All other variables and parameters are as defined earlier. Eq. (B.21) collects the manufacturer's replenishment costs for planning cycle r. These include the fixed order and delivery costs of any orders committed to in the slushy time periods. Total replenishment costs are modeled in Eq. (B.22), where due to coordination, all items run the same number of planning cycles, IT.

Each planning cycle r, the vendor solves N Wagner-Whitin type lot-sizing problems as defined in Eqs. (B.23)–(B.27). A_{ji} is the vendor's demand for item j that is due in time period i, where $A_{ji} = \sum_{t=i}^{i_{\mathrm{end}}} D_{jt}\hat{X}_{ijt}$. 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. Eq. (B.28) tabulates the vendor's costs for planning cycle r, while Eq. (B.29) gathers the vendor's total costs over K periods. As indicated, the vendor issues a single invoice for each purchase order. Total system costs are given in Eq. (B.30).

Manufacturer's coordinated replenishment problem (MCRP)

problem MCRP(r)

$$\text{Min}\sum_{i=i_{\text{beg}}}^{i_{\text{end}}}(T_i+S_i)U_i+\sum_{i=i_{\text{beg}}}^{i_{\text{end}}}\sum_{j=1}^{N}P_{(m)ij}Y_{ij}+\sum_{i=i_{\text{beg}}}^{i_{\text{end}}}\sum_{j=1}^{N}\sum_{t=i}^{i_{\text{end}}}(h_{ijt}+a_{ij})D_{jt}X_{ijt} \tag{B.15}$$

$$\text{subject to}\quad \sum_{i=i_{\text{beg}}}^{t}X_{ijt}=1\quad \forall j,t \tag{B.16}$$

$$Y_{ij}\le U_i\quad \forall i,j \tag{B.17}$$

$$X_{ijt}\le Y_{ij}\quad \forall i,j,t \tag{B.18}$$

$$X_{ijt}\ge 0\quad \forall i,j,t \tag{B.19}$$

$$Y_{ij},U_i\in\{0,1\}\quad \forall i,j \tag{B.20}$$

$$C_{\text{MCRP}(r)}=\sum_{i=i_{\text{beg}}}^{i_{\text{end}}}(T_i+S_i)\hat{U}_i+\sum_{i=i_{\text{beg}}}^{i_{\text{end}}}\sum_{j=1}^{N}P\hat{Y}_{ij}+\sum_{i=i_{\text{beg}}}^{i_z}\sum_{j=1}^{N}\sum_{t=i}^{i_{\text{end}}}(h_{ijt}+a_{ij})D_{jt}\hat{X}_{ijt} \tag{B.21}$$

$$\text{TC}_{\text{MCRP}}=\sum_{r=1}^{\text{IT}}C_{\text{MCRP}(r)} \tag{B.22}$$

Vendor's lot-sizing problem (VLSP)

$$\text{problem VLSP}(j,r)\quad \text{Min}\sum_{f=i_{\text{beg}}}^{i_{\text{end}}}P_{(v)fj}F_{f}j+\sum_{f=i_{\text{beg}}}^{i_{\text{end}}}\sum_{i=f}^{i_{\text{end}}}(c_{fji}+h_{fji})A_{ji}G_{fji} \tag{B.23}$$

$$\sum_{f=i_{\text{beg}}}^{i}G_{fji}=1\quad \forall i \tag{B.24}$$

$$G_{fji}\le F_{fj}\quad \forall f,i \tag{B.25}$$

$$G_{fji}\ge 0\quad \forall f,i \tag{B.26}$$

$$F_{fj}\in\{0,1\}\quad \forall f \tag{B.27}$$

$$C_{\text{VLSP}(j,r)}=\sum_{f=i_{\text{beg}}}^{i_z}P_{(v)fj}\hat{F}_{fj}+\sum_{f=i_{\text{beg}}}^{i_z}\sum_{i=f}^{i_{\text{end}}}(c_{fji}+h_{fji})A_{ji}\hat{G}_{fji} \tag{B.28}$$

$$\text{TC}_{\text{VLSP}}=\sum_{j=1}^{N}\sum_{r=1}^{\text{IT}}C_{\text{VLSP}(j,r)}+\sum_{i=1}^{K}W_i\hat{U}_i \tag{B.29}$$

Total system cost

$$\text{TC}_{\text{PI/PC}}=\text{TC}_{\text{MCRP}}+\text{TC}_{\text{VLSP}} \tag{B.30}$$

The rolling schedule simulation procedures for PI/PC follow.

Rolling schedule planning procedures for PI/PC

1. Initialize K, N, T, n, set $C_{\text{M}} = C_{\text{V}} = \text{TC}_{\text{PI/PC}} = 0$, randomly generate D_{jt} for $j = 1, 2, \ldots, N$ and $t = 1, 2, \ldots, K$.
2. Set $i_{\text{beg}} = 1$, IT = 0, $r = 0$, $B_{fj}(r) = 0\ \forall f, j$.
3. Set $i_{\text{end}} = i_{\text{beg}} + T - 1$, $i_z = i_{\text{beg}} + n - 1$, $i^* = 0$, $i_j^* = f_j^* = 0\ \forall j$, $r = r + 1$. If $i_z > K$, set $i_z = K$. If $i_{\text{end}} > K$, set $i_{\text{end}} = K$.
4. Solve MCRP(r) for $\hat{U}_i$, $\hat{Y}_{ij}$ and $\hat{X}_{ijt}$, set $Q_{ij} = \sum_{t=i}^{i_{\text{end}}} D_{jt}\hat{X}_{ijt}\ \forall i, j$, calculate $C_{\text{MCRP}(r)}$, set $C_{\text{M}} = C_{\text{M}} + C_{\text{MCRP}(r)}$, and fix open all orders scheduled in the slushy time periods. For $i = i_z + 1, \ldots, i_{\text{end}}$ if $\hat{U}_i = 1$, set $(T_i + S_i) = 0$. For $i = i_z + 1, \ldots, i_{\text{end}}$ and $j = 1, \ldots, N$ if $\hat{Y}_{ij} = 1$, set $P_{(m)ij} = 0$.
5. Solve VSLP.
   a. Set $j = 0$.
   b. Set $j = j + 1$, if $j > N$ go to Step 5d. Set $A_{ji} = Q_{ij} - B_{ij}(r - 1)\ \forall i$.
   c. Solve VLSP(j, r) for $\hat{F}_{fj}$ and $\hat{G}_{fji}$. Define production quantities $B_{fj}(r) = \sum_{i=f}^{i_{\text{end}}} A_{ji}\hat{G}_{fji}\ \forall f$ Calculate $C_{\text{VLSP}(j,\ r)}$ by Eq. (B.28) and set $C_{\text{V}} = C_{\text{V}} + C_{\text{VLSP}(j,\ r)}$. Go to Step 5b.
   d. $\text{CV} = \text{CV} + \sum_{i=1}^{i_z} W_i\hat{U}_i$..
6. Next planning cycle's start date. For all j, set $i_j^* = \text{Min}\ i > i_z$ such that $\hat{Y}_{ij} > 0$. Set $i^* = \text{Min}\{i_j^*\ \forall j\}$. If $i^* > 0$, set $i_{\text{beg}} = i^*$. Otherwise, $i_{\text{beg}} = i_{\text{end}} + 1$. If $i_{\text{beg}} > K$, set IT = r and go to Step 10.
7. Adjust manufacturer's net requirements to reflect any demand beyond the frozen time fence that is covered from the previous cycle's frozen replenishment schedule. For each j, if $i_j^* > 0$ and $i_j^* \neq i^*$,

set $D_{jt} = 0$ for $t = i_{\text{beg}}, \ldots, i_j^* - 1$. If $i_j^* = 0$, set $D_{jt} = 0$, for $t = i_{\text{beg}}, \ldots, i_{\text{end}}$.

8. For $j = 1, \ldots, N$, if $i^* > 0$ and:
   a. $f_j^* = \text{Min } f > i_z$ such that $\hat{F}_{fj} > 0$ and $f_j^* \neq i^*$, set $B_{ij}(r) = A_{ji}$ for $i = i^*, i^* + 1, \ldots, f_j^* - 1$.
   b. $f_j^* = 0$, set all $B_{ij}(r) = A_{ji}$ for $i = i_{\text{beg}}, \ldots, i_{\text{end}}$.
9. Go to step 3.
10. Set $\text{TC}_{\text{PI/PC}} = C_{\text{M}} + C_{\text{V}}$ and stop.

B.3. Strategies PI/NC and NI/PC

The static problem formulations for strategies PI/NC and NI/PC are presented in this section. The associated rolling schedule simulation procedures are not presented since they are straightforward manipulations of those previously described for strategies NI/NC and PI/PC.

In strategy PI/NC, the manufacturer solves a Wagner-Whitin lot-sizing problem for each item and captures the order cycle's costs as defined in Eqs. (B.1)–(B.7). He then communicates his planned orders to the vendor as advance order commitments. Next, the vendor solves a Wagner-Whitin lot-sizing problem for each item as defined in Eqs. (B.23)–(B.27). The vendor's total production and invoice costs are collected in Eqs. (B.28) and (B.31). The vendor ships product according to the manufacturer's stated due dates incurring the transportation costs detailed by Eqs. (B.10)–(B.13). Total system costs are given in Eq. (B.32)

$$\text{TC}'_{\text{VLSP}} = \sum_{j=1}^{N}\sum_{r=1}^{\text{IT}} C_{\text{VLSP}(j,r)} + \sum_{j=1}^{N}\sum_{i=1}^{K} W_i \hat{Y}_{ij} \tag{B.31}$$

$$\text{TC}_{\text{PI/NC}} = \text{TC}_{\text{MLSP}} + \text{TC}'_{\text{VLSP}} + \text{TC}_{\text{TRV}} + \text{TC}_{\text{TRF}} \tag{B.32}$$

In strategy NI/PC, the manufacturer solves a multi-item coordinated replenishment problem trading off ordering, inventory holding, and transportation costs as defined in Eqs. (B.15)–(B.20) and tabulated in Eqs. (B.21)–(B.22). Since the vendor does not receive any forward visibility into future orders he responds on a lot-for-lot basis as defined below. Eq. (B.33) captures the vendor's equipment setup and variable costs for item j in iteration r and Eq. (B.34) collects the production and invoice costs over all products and all planning iterations. Total system costs are collected in Eq. (B.35)

$$C'_{\text{VLFL}(j,r)} = \sum_{i=i_{\text{beg}}}^{i_z} (P_{(v)ij}\hat{Y}_{ij} + \sum_{i=i_{\text{beg}}}^{i_z}\sum_{t=i}^{i_{\text{end}}} c_{ijt} D_{jt} \hat{X}_{ijt} \tag{B.33}$$

$$\text{TC}'_{\text{VLFL}} = \sum_{j=1}^{N}\sum_{r=1}^{\text{IT}_j} C'_{\text{VLFL}(j,r)} + \sum_{i=1}^{K} W_i \hat{U}_i \tag{B.34}$$

$$\text{TC}_{\text{NI/PC}} = \text{TC}_{\text{MCRP}} + \text{TC}'_{\text{VLFL}} \tag{B.35}$$

B.4. Strategy FI/FC

Strategy FI/FC represents system-wide coordination. Any channel member or a third party could perform this service. The planner utilizes all system data including the manufacturer's gross requirements, which are analogous to a perfect forecast of component usage. We formulate the static problem as a dynamic demand coordinated replenishment problem in Eqs. (B.36)–(B.41). The manufacturer's order processing cost, the fixed delivery cost, and the vendor's invoice processing cost are shared among all items replenished in a common time period. In addition, each replenished item incurs an equipment setup cost at the vendor and a material handling cost at the manufacturer. Eq. (B.42) captures planning cycle r's costs and Eq. (B.43) collects total system costs over the K-period horizon.

System coordinated replenishment problem (SCRP)

$$\text{problem SCRP}(r) \quad \text{Min} \sum_{i=i_{\text{beg}}}^{i_{\text{end}}} (S_i + T_i + W_i)U_i + \sum_{i=i_{\text{beg}}}^{i_{\text{end}}}\sum_{j=1}^{N} (P_{(v)ij} + P_{(m)ij})Y_{ij} + \sum_{i=i_{\text{beg}}}^{i_{\text{end}}}\sum_{j=1}^{N}\sum_{t=i}^{i_{\text{end}}} (c_{ijt} + h_{ijt} + a_{ij})D_{jt}X_{ijt} \tag{B.36}$$

$$\text{subject to} \quad \sum_{i=i_{\text{beg}}}^{t} X_{ijt} = 1 \quad \forall j, t \tag{B.37}$$

$$Y_{ij} \leq U_i \quad \forall i, j \tag{B.38}$$

$$X_{ijt} \leq Y_{ij} \quad \forall i, j, t \tag{B.39}$$

$$X_{ijt} \geq 0 \quad \forall i, j, t \tag{B.40}$$

$$Y_{ij}, U_i \in \{0, 1\} \quad \forall\, i, j \tag{B.41}$$

$$C_{\mathrm{SCRP}(r)} = \sum_{i=i_{\mathrm{beg}}}^{i_z} (S_i + T_i + W_i)\hat{U}_i + \sum_{i=i_{\mathrm{beg}}}^{i_z}\sum_{j=1}^{N} (P_{(m)ij} + P_{(v)ij})\hat{Y}_{ij} + \sum_{i=i_{\mathrm{beg}}}^{i_z}\sum_{j=1}^{N}\sum_{t=i}^{i_{\mathrm{end}}} (c_{ijt} + h_{ijt} + a_{ij})D_{jt}\hat{X}_{ijt} \tag{B.42}$$

Total system cost

$$\mathrm{TC}_{\mathrm{FI/FC}} = \sum_{r=1}^{\mathrm{IT}} C_{\mathrm{SCRP}(r)} \tag{B.43}$$

The rolling schedule simulation procedures for FI/FC follow.

Rolling schedule procedures for FI/FC

1. Initialize K, N, T, n, set $\mathrm{TC}_{\mathrm{FI/FC}} = 0$, randomly generate D_{jt} for $j = 1, 2, \ldots, N$ and $t = 1, 2, \ldots, K$.
2. Set $i_{\mathrm{beg}} = 1$, $r = 0$, $\mathrm{IT} = 0$.
3. Set $i_{\mathrm{end}} = i_{\mathrm{beg}} + T - 1$, $i_z = i_{\mathrm{beg}} + n - 1$, $i^* = 0$, $i_j^* = 0\ \forall j$, $r = r + 1$. If $i_z > K$, set $i_z = K$. If $i_{\mathrm{end}} > K$, , set $i_{\mathrm{end}} = K$.
4. Solve SCRP(r) for $\hat{U}_i$, $\hat{Y}_{ij}$ and $\hat{X}_{ijt}$, calculate $C_{\mathrm{SCRP}(r)}$, and set $\mathrm{TC}_{\mathrm{FI/FC}} = \mathrm{TC}_{\mathrm{FI/FC}} + C_{\mathrm{SCRP}(r)}$.
5. Starting period for next planning cycle. For all j, set $i_j^* = \mathrm{Min}\ i > i_z$ such that $\hat{Y}_{ij} > 0$. Set $i^* = \mathrm{Min}\{i_j^*\ \forall j\}$. If $i^* > 0$, set $i_{\mathrm{beg}} = i^*$. Otherwise, $i_{\mathrm{beg}} = i_{\mathrm{end}} + 1$. If $i_{\mathrm{beg}} > K$, set IT = r and go to Step 8.
6. Adjust manufacturer's net requirements to reflect any demand beyond the frozen time fence that is covered from the previous cycle's frozen replenishment schedule. For each j, if $i_j^* > 0$ and $i_j^* \neq i^*$, set $D_{jt} = 0$ for $t = i_{\mathrm{beg}}, \ldots, i_j^* - 1$. If $i_j^* = 0$, set $D_{jt} = 0$, for $t = i_{\mathrm{beg}}, \ldots, i_{\mathrm{end}}$.
7. Go to step 3.
8. Stop.

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