

Collaboration and Information Sharing in Global Contract Manufacturing Networks

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Abstract—In the semiconductor and telecommunications industry original equipment manufacturers (OEMs) outsource manufacturing to contract manufacturers who are specialist electronic manufacturing service providers. There are a large number of such specialists in existence who collaborate with the original equipment manufacturers at one end and the component suppliers at another end and provide engineering, manufacturing and distribution services. But there do not exist good theoretical developments supporting these real world operations. Here, we consider a global manufacturing system consisting of the contract manufacturer, logistics provider, and OEM and study the influence of sharing scheduling and demand information over the Internet.

More specifically, we consider an OEM operating an Internet-based private exchange as a channel master with its contract manufacturers and their suppliers participating by sharing information. We develop a linear program based optimization model for this environment. Specifically, our LP model calculates the quantity of raw materials that is to be procured in each time period from each of the suppliers in order to meet the given demand. We compare these results with traditional make-to-stock linear supply chains with sequential order flow. Our numerical experiments show that information sharing results in cost and inventory reduction.

Index Terms—Collaborative scheduling, contract manufacturing, information sharing, internet-enabled manufacturing networks, private electronic marketplaces.

I. INTRODUCTION

THE ADVENT of the Internet has radically transformed the manner in which businesses and supply chains are being managed today. The universal reach of the Internet has made possible the ubiquitous, uninterrupted and opportune flow of information enabling new business models and greater efficiencies in existing processes. In fact the influence of the Internet is evident on many different levels in the operations of leading businesses and supply chain networks. For instance, at the strategic level in the management of relationships and development of new products; at the tactical level, in demand forecasting and inventory management; and at the operational level, in integrated scheduling and track and trace of goods movement in the supply chain are just some of the illustrations where the Internet is used as the platform for coordinating activities between various supply chain partners [1].

The Intranet, an information network for communications within an enterprise, has brought about great efficiencies within

organizations. But the Internet has had an even greater impact, which can to a large extent be attributed to the success of the Extranet in enabling coordination across entire supply chains. The Extranets of today provide a platform for sharing information between business partners through the Internet infrastructure. More significantly, the ubiquitous availability of information allows integrated, informed and intelligent decision-making for better management of global supply chains prevalent today. For example, consider a scenario where an end-customer places an order for a customized computer through an original equipment manufacturer's (OEMs) website. The OEMs information system can, through its Extranet, identify if there is enough stock to meet the order at the warehousing facility of its distributor and in the case of inadequate stock can initiate steps to manufacture a new unit of the computer. The system could, through the Extranet, look up the manufacturing schedules of all the OEM contract manufacturers and identify an ideal location and time at which to schedule the production of the computer and generate the necessary orders for the contract manufacturer. It could even go to the extent of scheduling the procurement of subassemblies and components to the contract manufacturer and the scheduling of logistics from the manufacturer to the end-customer. Based on the manner in which the system, with the help of the Extranet, decides to fulfill the customer, it could get back to the customer with an expected delivery date, thereby leading to greater customer satisfaction. Hence, a well-designed Extranet can facilitate among other things improved utilization and efficiency of resources, lower inventory, shorter lead-times and greater customer satisfaction and loyalty.

Another form of the Extranet, which will drive the supply chain networks of tomorrow, is the Electronic Marketplace. Electronic Marketplaces are very good examples of Extranets that act as information and transaction nodes for coordinating activities within the supply chain. These electronic marketplaces in their various incarnations as public and private exchanges provide rich tools for collaboration in new product development, supply chain performance measurement and in supply chain planning and execution. However, in terms of manufacturing, the two most commonly referred facets of Internet manufacturing include, using the Internet as a medium to share program and data files in product development or using a private exchange to share data and information to undertake integrated scheduling and inventory management. In this paper, we deal with the second aspect.

One of the industries that has passionately adopted the Internet in the daily operations of their supply chains is the hi-tech and electronics industry. This is a very competitive industry and in order to maintain and increase the efficiency of their

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supply chains a significant portion of their interaction between the ever-growing number of business partners has moved to the Internet. Hence, this industry provides the ideal background to study the impact of information sharing and to understand the partner selection problems in an Internet-based manufacturing environment.

A. Contract Manufacturing

The tide of constant innovation, changing market paradigms and competitive dimensions and rising customer expectations has transformed the hi-tech and electronics industry into one of the most competitive industries. Challenges in dealing with mass customization, rapidly shrinking product life cycles, rapid inventory depreciation, and handling complex multisourced supply chains have required the use of very sophisticated tools and strategies for meeting the rising expectations of customers in a cost-efficient manner. Among other approaches, the electronics industry has tackled this problem through focus on core competencies, outsourcing of nonvalue-adding activities, multistage manufacturing and built-to-order strategies [2].

Increasingly the OEM are focusing on the high-value design and marketing aspects of the business, while outsourcing the manufacturing of their products to contract manufacturers who have core-competencies in large-scale production of mass customized products. These contract manufacturers in turn outsource some of their component production and assembly to smaller suppliers. Thus, outsourcing of activities ensures that each business within the supply chain is focussed on certain products and services delivering highest revenue to them, while employing the least amount of capital and resources [2].

Furthermore, instead of storing huge amounts of expensive and rapidly depreciating inventory the supply chains are designed such that the contract manufacturers produce the goods only when the customer orders them. This postponed production allows the customization of the product to the precise requirements of the customer. The key however to the success of these outsourcing, postponement and customization strategies is close coordination between the OEM, the contract manufacturer and the component suppliers. Close coordination between the various participants allows the electronics supply chain to quickly react to changing market requirements [2].

In practice, the participants in the electronics supply chain achieve this close coordination by sharing information through an Internet-based Extranet system. The information that is normally shared between them for operational management includes details on the production and transportation capacities, costs and schedules, inventory levels and forecasted demand patterns. Hence, such an environment provides the ideal setting to understand the impact of new generation Internet-based supply chain technologies and strategies on the efficiency and profitability of e-supply chain networks [2].

B. Scope and Literature Survey

This paper deals with partner selection and scheduling problems that arise in environments that are typical in contract manufacturing or private exchanges operated by a channel master. We develop a linear program where information sharing using

the Internet is considered. We compare the results of this with traditional linear supply chains adopting sequential order flow. Our numerical experiments show that information sharing results in cost and inventory reduction.

The study of information sharing in supply chains is the subject of several recent contributions. All the contributions consider the manufacturer-retailer combinations and study the effect of sharing point-of-sale information with the manufacturers. Lee *et al.* [3] use shared information to improve the supplier's order quantity decisions in a serial system with a known autoregressive demand process. Cachon and Fisher [4] show analytically how the manufacturer can benefit from using information about the retailer's inventory levels when the retailers use a batch ordering policy. Next, Gavirneni *et al.* [5] consider the case in which the manufacturer has limited capacity. In addition, they consider two cases of information sharing between the manufacturer and the retailer. In the first case, the manufacturer obtains information from the retailer about the parameters of the underlying demand distribution and the value of the (s, S) ordering policy adopted by the retailer. In the second case, the manufacturer obtains additional information from the retailer about the period-to-period inventory level. By considering various types of demand distributions in their numerical experiments, they examine the conditions under which gaining information about the retailer's inventory level is beneficial. Relative to the existing literature that examines the benefit of information sharing in a manufacturing-retailer environment, our current paper examines a different situation of the OEM supply side.

In the process of solving our LP model for a supply chain we also provide a basis for selection of partners (suppliers in this case) such that the total cost of operations is minimized. Specifically, our LP model calculates the quantity of raw materials that is to be procured in each time period from each of the suppliers in order to meet the given deterministic demand. There is a significant amount of literature existing on partner selection in the operations research and management science literature. Weber and Current [6] discuss a multi-criteria analysis for vendor selection. They develop a model for minimizing total cost, late deliveries and supply rejection given the infrastructure constraints and constraints imposed by the company's policy. Chaudhry *et al.* [7], consider the problem of vendor selection where buyers need to choose order quantities with vendors in a multisourcing network. Narasimhan and Stoyoff [8] present a model for optimizing aggregate procurement allocation keeping in mind contract requirements, supplier capacities and economic manufacturing quantity related constraints. Erenguc *et al.* [9] review and evaluate some of the relevant literature on production and distribution planning at each stage of the supply chain. The interested reader might find [10] useful for a comprehensive classification of publications on vendor selection criteria.

In the remaining three Sections of this paper we develop a framework for studying the impact of information sharing in an Internet-based discrete-manufacturing environment. We begin by describing in Section II the two environments that we wish to model. We also formulate linear programming models for an integrated supply chain and a make-to-stock supply chain with limited visibility. We briefly describe the ILOG tools used in

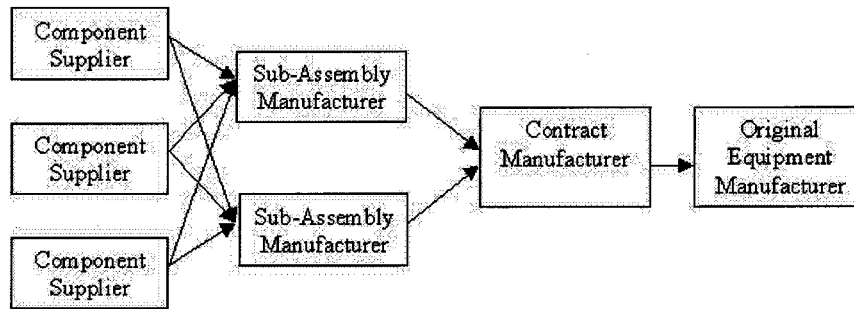


Fig. 1. Supply chain network.

solving the model. We then proceed to present and discuss the results of some of our numerical experiments performed on the models in Section III. And finally we conclude the paper with a summary of our contributions and suggestions for future work in Section IV.

II. PROBLEM FORMULATION

We quantify the impact of collaborative integrated supply chain planning in the context of the hi-tech industry, by comparing the costs of operating a built-to-order supply chain in an environment with ubiquitous information, against the costs of operating a traditional make-to-stock supply chain with no information-sharing between partners. In reality both the scenarios of ubiquitous information and total lack of information are extreme. In our study here we make the distinction between the two cases based on whether the supply chain partners share schedule, capacity and pricing information in real-time with other participants in the chain. In supply chains held together by private marketplaces this kind of visibility is common, whereas in traditional supply chains partners can hardly gain access to such proprietary information in a real-time basis.

In both the cases we consider a contract manufacturer offering its production facilities, where a range of product models can be assembled, to an OEM with a certain demand pattern. The demand as input into the model is deterministically known. In make-to-order supply chains this is a realistic scenario. However, in other supply chains the expected value of demand as calculated from forecasting models can also be considered. The variety of subassemblies required by the contract manufacturer for the assembly of these product models is supplied by a number of subassembly manufacturers. The subassembly manufacturers in turn are supplied a range of components by a number of different component suppliers. Inventory is held for the various product models, subassemblies and components both at the point of production and the point of consumption. The participants in the supply chain are all connected through a logistics network. The required logistics network in global manufacturing networks is normally provided by a group of third-party logistics service providers. A representation of the supply chain is presented in Fig. 1.

We proceed by developing a model for integrated supply chain planning, for a manufacturing enterprise where information is freely shared between the partners through an Internet based platform. The instantaneous availability of

demand information allows the OEM, contract manufacturer and their suppliers to adopt a built-to-order strategy and fulfill all customer orders at minimal operating cost. Furthermore, the sharing of operational information between the partners allows supplier selection and integrated scheduling for the entire supply chain, with a resultant reduction in total landed cost of goods and reduced inventory. Hence, we assume that the Internet is used as a platform for sharing information and making intelligent decisions for the coordination and synchronization of the various manufacturing and distribution activities in the supply chain. Such a platform would ideally be implemented as a private marketplace wherein collaborative scheduling and planning and product development and design applications would be available to all the partners through a web-based interface or would integrate with their backend systems. The kind of information that would be shared in a supply chain for the sake of integrated scheduling includes the costs for production at each level, transportation costs between all partners, the schedules of all manufacturing and logistics partners and their inventory levels.

One of the greatest success stories in this regard has been the Internet based private marketplace developed by Dell Computers, for the production of their customized built-to-order computer equipment. Their strategy based on harnessing the power of supply chain visibility through a private marketplace has allowed them to become the market leader in their industry.

The other scenario we consider is a traditional supply chain where the OEM, contract manufacturer and their suppliers do not share with each other information on the activities, schedules and flows. There is a sequential flow of orders from the OEM to the contract manufacturer and then on to the suppliers. Consequentially, to counter this uncertainty all the participants in the supply chain tend to hold a certain amount of inventory of their finished goods at their output end and of the components that they need in their near future production. These inventory levels are dependent on the expected demand. Additionally, due to the bullwhip effect, the level of inventory holding in the supply chain at each additional level away from the customer increases. To model such an environment, we include additional constraints in our model for an integrated supply chain. These constraints model limitations imposed on the minimum inventory holdings levels at each stage of the supply chain.

Finally, we compare the performance of the supply chains in both scenarios for various demand patterns and try to quantify

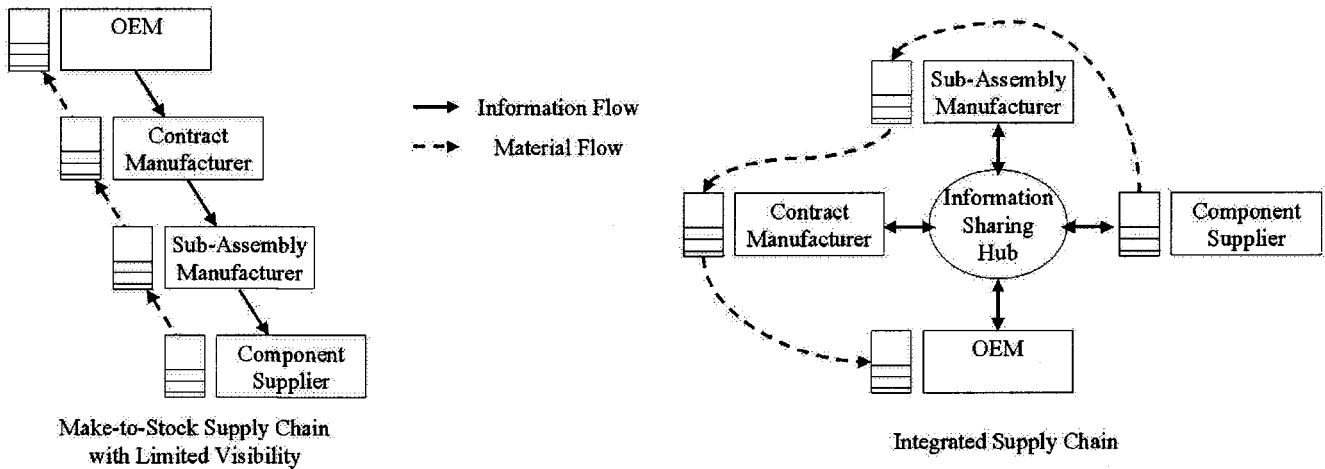


Fig. 2. Representation of an integrated supply chain and a make-to-stock supply chain possessing limited visibility.

the impact of Internet manufacturing on traditional supply chain configurations.

A. Notation

For development of a mathematical model for Fig. 2, the following notations were used.

Identifiers:

- r component-type identifier;
- v component suppliers identifier;
- i subassembly-type identifier;
- j subassembly manufacturers identifier;
- l brand identifier;
- t time period identifier;
- R number of component types;
- V number of component suppliers;
- I number of subassembly types;
- J number of subassembly manufacturers;
- L number of brands;
- T total time horizon of the model.

Superscript Identifiers:

- K contract manufacturer identifier;
- M OEM identifier.

Parameters:

- C_{abt} maximum production capacity available for component/subassembly of type a offered by component suppliers/subassembly manufacturers b in time period t ;
- P_{ab} unit cost price for component/subassembly of type a procured from component supplier/subassembly manufacturer supplier b ;
- T_{abdt} maximum transportation capacity for shipment of component/subassembly of type a from component supplier/subassembly manufacturer b to its customer d in time period t ;
- L_{bd} transportation lead-time for shipment from component supplier/subassembly manufacturer b to its customer d ;
- U_{abdt} unit transportation cost for shipment of component/subassembly of type a from component

supplier/subassembly manufacturer b to its customer d in time t ;

- W_{ab} unit inventory cost incurred for component/subassembly of type a in the possession of component supplier/subassembly manufacturer b ;
- R_{ab} units of component type a required in the production of one unit of subassembly b ;
- M_{ab} units of subassembly type a required in the production of 1 unit of brand type b ;
- n_{ab} number of time-periods to be considered for the forecasting of inventory level requirements for component/subassembly a at component supplier/subassembly manufacturer b ;
- D_{it}^M demand of OEM M for product l on the due-date t .

Variables:

- Q_{abt} quantity produced for component/subassembly of type a by component supplier/subassembly manufacturer b in time period t ;
- I_{abt} inventory of component/subassembly of type a with component supplier/subassembly manufacturer b in time period t ;
- S_{abdt} quantity shipped of component/subassembly of type a from component supplier/subassembly manufacturer b to its customer d in time period t ;
- S'_{abdt} quantity received of component/subassembly of type a from component supplier/subassembly manufacturer b to its customer d in time period t .

In summary, a listing of the various variables and parameters considered in the development of the model are presented in Table I.

B. LP Model for Integrated Supply Chain Planning

We now develop a linear programming model for a supply-chain where information is freely shared between all the participants, through some kind of Internet-based platform. The objective of the model was to minimize the cost of procurement for the OEM, while satisfying the demand of the OEM, subject to various capacity constraints, production and logistics schedules and flow balancing constraints.

TABLE I
FEATURES OF THE LINEAR PROGRAMMING MODEL FOR AN INTEGRATED SUPPLY CHAIN

Supply Chain Information Shared	Decisions to be Made
1. Available-to-Promise Manufacturing Capacity for each Suppliers.	1. Determination of multiple plant schedules.
2. Fixed Airline Schedules.	2. Determination of multi-period schedules.
3. Complex product structure with multiple components, sub-assemblies, brands.	3. Allocation of procurement quantities amongst multiple suppliers.
4. Inventory costs at multiple levels.	
5. Transportation costs.	
6. Production costs.	

Objective Function: The procurement cost was calculated [see (1) at the bottom of the page], as the sum of the production, transportation and inventory costs. The first term in the equation represents the transportation, and production costs for the component suppliers, subassembly manufacturers, and the contract manufacturer, respectively, while the second term refers to the in-bound and out-bound inventory costs at the component suppliers, subassembly manufacturers, contract manufacturer and the OEM. The transportation cost considered in this model is the average per unit cost of transportation. It needs to be pointed out that this is an approximation. Nevertheless, third-party logistics providers frequently quote transportation costs on a per unit transportation cost when not much investment in fixed assets is required on their part.

There are various capacity constraints on the component suppliers and subassembly manufacturers and the logistics service providers feeding the contract manufacturer that make the solution nontrivial.

Component Supplier Constraints: The component suppliers cannot produce more than their maximum production capacity. Hence,

$$Q_{rvt} \leq C_{rvt} \quad \text{for all } r \in R, v \in V \& t \in T. \quad (2)$$

The components produced are held at the component suppliers end until they are shipped off to the subassembly manufacturers. The production of new components adds to the inventory held by the component supplier at the end of each time, while the products sold and shipped to the subassembly manufacturers in each time period reduces the component suppliers inventory

$$I_{rv(t-1)} + Q_{rvt} = \sum_{j=1}^J S_{rvjt} + I_{rvt}, \quad \text{for all } r \in R, v \in V, j \in J \& t \in T. \quad (3)$$

However, the quantity that can be transported in a single period is constrained by the maximum capacity of the transportation infrastructure. Considering our scenario with fixed shipping schedules, in time-periods when the service is available the transportation capacity is nonzero. However, for time-periods where particular flights or shipments are not scheduled the transportation capacity is zero. Hence the transportation of the component types from the component suppliers to the subassembly manufacturer's site is bound by the constraint given as follows:

$$S_{rvjt} \leq T_{rvjt}, \quad \text{for all } r \in R, v \in V, j \in J \& t \in T. \quad (4)$$

Subassembly Manufacturer Constraints: The shipped components reach the subassembly manufacturers after a certain amount of time, which relates to the transportation lead-time

$$S'_{rvjt} = S_{rvj(t-L_{vj})}, \quad \text{for all } r \in R, v \in V, j \in J, i \in I \& t \in T. \quad (5)$$

Once the components reach the subassembly manufacturers from the component suppliers it adds to the subassembly manufacturer's inventory, which is then consumed by the production process. However before the production process can start and the component type can be consumed, the subassembly manufacturer will need to check adequate availability of all components that will be used in the assembly-part production process. This imposes the following constraint on the component availability and the assembly-part production:

$$I_{rj(t-1)} \geq \sum_{i=1}^I R_{ir} Q_{ijt}, \quad \text{for all } r \in R, i \in I, j \in J, t \in T. \quad (6)$$

$$\text{MinCOST} = \left[\begin{aligned} & \sum_{r=1}^R \sum_{v=1}^V \sum_{j=1}^J \left(\sum_{t=1}^T S_{rvjt} U_{rvjt} + P_{rv} \sum_{t=1}^T S_{rvjt} \right) \\ & + \sum_{i=1}^I \sum_{j=1}^J \left(\sum_{t=1}^T S_{ijt}^K U_{ijt}^K + P_{ij} \sum_{t=1}^T S_{ijt}^K \right) \\ & + \sum_{l=1}^L \left(\sum_{t=1}^T S_{lt}^{KM} U_{lt}^{KM} + P_l^K \sum_{t=1}^T S_{lt}^{KM} \right) \end{aligned} \right] \\ + \left[\begin{aligned} & \sum_{i=1}^I \left(\sum_{r=1}^R \sum_{v=1}^V W_{rv} I_{rvt} + \sum_{r=1}^R \sum_{j=1}^J W_{rj} I_{rjt} \right) \\ & + \sum_{i=1}^I \left(\sum_{j=1}^J W_{ij} I_{ijt} + \sum_{i=1}^I W_i^K I_{it}^K \right) \\ & + \sum_{l=1}^L \left(W_l^K I_{lt}^K + \sum_{l=1}^L W_l^M I_{lt}^M \right) \end{aligned} \right] \quad (1)$$

However: once the production process begins the inventory drops. The inventory status for component types with the sub-assembly manufacturer can be determined as

$$I_{rj(t-1)} + \sum_{v=1}^V S'_{rvjt} = \sum_{i=1}^I R_{ir} Q_{ijt} + I_{rjt},$$

for all $r \in R, v \in V, j \in J, i \in I \& t \in T$. (7)

The capacity constraints and the inventory constraints that apply to the component suppliers apply to the subassembly manufacturers as well.

The maximum production of subassemblies is constrained by the production capacity of the subassembly manufacturers

$$Q_{ijt} \leq C_{ijt}, \quad \text{for all } i \in I, j \in J \& t \in T. \quad (8)$$

The inventory of subassemblies at the subassembly manufacturer's end increases at the end of each period by the quantity produced and decreases by the amount of subassembly shipped out to the contract manufacturer, in that time period

$$I_{ij(t-1)} + Q_{ijt} = S_{ijt}^K + I_{ijt}, \quad \text{for all } i \in I, j \in J \& t \in T. \quad (9)$$

The quantity of assembly parts that can be shipped is constrained by the capacity of the transportation infrastructure

$$S_{ijt}^K \leq T_{ijt}^K, \quad \text{for all } i \in I, j \in J \& t \in T. \quad (10)$$

Contract Manufacturer Constraints: The shipped assembly-parts reach the contract manufacturer after a certain amount of time

$$S_{ijt}^{iK} = S_{ij(t-L_{jK})}^K, \quad \text{for all } r \in R, v \in V, j \in J, i \in I \& t \in T. \quad (11)$$

The shipped assembly-parts will be stored at the contract manufacturer. The contract manufacturer will produce a variety of brands, which will use up the inventory of the subassemblies in the process. However, only in the case of sufficient availability of all the needed subassemblies will production of the brands take place

$$I_{i(t-1)}^K \geq \sum_{l=1}^L M_{li} Q_{lt}^K, \quad \text{for all } i \in I, l \in L \& t \in T. \quad (12)$$

As regards the inventory levels of subassemblies at the contract manufacturer incoming stocks will add to the inventory and subassembly stocks will be used up in the production of the various brand types. The inventory status for subassemblies at the contract manufacturer can be determined as given in (13)

$$I_{i(t-1)}^K + \sum_{j=1}^J S'_{ijt}^K = \sum_{l=1}^L M_{li} Q_{lt}^K + I_{it}^K,$$

for all $i \in I, j \in J, l \in L \& t \in T$. (13)

The supply hub cannot produce the different brand types, in a quantity more than its maximum production capacity. Hence,

$$Q_{lt}^K \leq C_{lt}^K, \quad \text{for all } l \in L \& t \in T. \quad (14)$$

The manufactured units of the brands are stored at the contract manufacturer awaiting delivery to the OEM. The inventory level of the brands obeys the following flow constraint:

$$I_{l(t-1)}^K + Q_{lt}^K = S_{lt}^{KM} + I_{lt}^K, \quad \text{for all } l \in L \& t \in T. \quad (15)$$

The transportation capacity constraint for the movement of the brands from the contract manufacturer to the OEM site will be governed by the below transportation capacity constraint

$$S_{lt}^{KM} \leq T_{lt}^{KM}, \quad \text{for all } l \in L \& t \in T. \quad (16)$$

OEM Constraints: The brands reach the OEM after a certain transportation lead-time

$$S_{lt}^{KM} = S'_{l(t-L_{KM})}^{KM}, \quad \text{for all } l \in L \& t \in T. \quad (17)$$

The brands will be stored at the OEM location to be used in their processes

$$I_{l(t-1)}^M + S_{lt}^{KM} = I_{lt}^M, \quad \text{for all } l \in L \& t \in T. \quad (18)$$

Finally, the entire process of procuring the product types, assembling and delivering the finished brands to the OEM needs to be completed by the date specified by the OEM and the number of units of the various brands required by the OEM should be available to her on the specified date

$$I_{lt}^M = D_{lt}^M, \quad \text{for all } l \in L \& t \in T. \quad (19)$$

The model can be easily adapted to consider more than one customer, with their own respective demands for each brand. Constraints (15) and (16) will apply to all of them. Such a model is presented in [22]. However, for easy of analysis in the current context only a single OEM has been considered.

Transportation lead times are considered in our model. The supply chain configuration we assume is such that the material is collected by the transportation system from the output buffer of one stage and delivered to the input buffer of the subsequent stage after a designated period equivalent to the transportation lead-time.

C. LP Model for Supply Chains With No Information Sharing

In order to model a linear make-to-order supply chain with limited visibility additional constraints were included to model the decisions made in maintaining a minimum inventory level at each stage of the supply chain. Each of the individual organizations within the supply chain based on their service level commitment, decide how much this minimum inventory should be. In the simplest scenario, minimum inventory levels are calculated from historical demand and set equal to the demand they may have fulfilled in the previous n periods, where n is to be determined from the service level.

Component Suppliers Inventory Constraints: The component suppliers maintain an inventory of components at the facility, which is greater than or equal to the total number of components supplied by them to all their customers in the previous n_{rv} periods

$$I_{rvt} \geq \sum_{q=t-n_{rv}}^t \sum_{j=1}^J S_{rvjq}, \quad \text{for all } r \in R, v \in V, j \in J \& t \in T. \quad (20)$$

Subassembly Manufacturer Inventory Constraints: The subassembly manufacturers will for their in-coming component inventory levels have a strategy whereby they will keep enough inventory of components to satisfy a demand equivalent to their sales in the previous n_{rj} time periods

$$I_{rjt} \geq \sum_{q=t-n_{rj}}^t \sum_{k=1}^K \sum_{i=1}^I R_{ir} S_{ijkq},$$

for all $r \in R, v \in V, j \in J, i \in I, k \in K \& t \in T$. (21)

The subassembly manufacturer will also maintain a certain minimum level of inventory for subassemblies that it has manufactured. This level will be determined by the sales that the subassembly manufacturer has made in the past n_{ij} time periods

$$I_{ijt} \geq \sum_{q=t-n_{ij}}^t \sum_{k=1}^K S_{ijkq}, \text{ for all } i \in I, j \in J, k \in K \& t \in T. \quad (22)$$

Contract Manufacturer Inventory Constraints: Similarly the contract manufacturer will also maintain a certain minimum level of inventory for subassemblies and finished brands based on its sales in the previous time-periods. The inventory level decision for subassemblies at the contract manufacturer is given by the following equation:

$$I_{it}^K \geq \sum_{q=t-n_i^K}^t \sum_{l=1}^L M_{li} S_{lq}^{KM}, \text{ for all } i \in I, l \in L \& t \in T \quad (23)$$

and, the inventory level for finished brand goods in the contract manufactures inventory will be governed by the following constraint:

$$I_{it}^K \geq \sum_{q=t-n_i^K}^t S_{lq}^{KM}, \text{ for all } l \in L \& t \in T. \quad (24)$$

Hence, the above constraints requiring the maintenance of inventory based upon previous history can be used to model supply chain invisibility with regards to the demand patterns at the customer end and to model a supply chain with a make-to-stock strategy.

D. Model Solution

The above linear models were developed and optimized in the commercial optimization program, OPL Studio available from ILOG. ILOG provides a very comprehensive library of optimization algorithms implemented in C++. These algorithms can be used for the solution of a varied number of large-scale linear, integer or constraint programming models. ILOG also incorporates a set of modeling concepts, such as activities and resources, which are very useful in the solution of scheduling and allocation problems. ILOG studio utilizes the Optimization Programming Language (OPL) for modeling of problems. User-defined search strategies for each model can be specified in order to reduce the computational power required for the solution.

The previous LP models were solved for a scenario with 3 component suppliers supplying 3 different components to 2 subassembly manufacturers. These subassemblers supply

2 different subassemblies to a single contract manufacturer to be used in the production of a single brand for a single OEM. The time line for the model was taken as 20 periods. The number of variables encountered in the solution of the model for integrated scheduling was 3234 and the constraints numbered 3670. For the model of a make-to-stock supply chain with limited visibility the number of variables were 3234 and there were 4066 constraints.

III. COMPUTATIONAL RESULTS

In order to compare the implications of Internet manufacturing through information sharing in supply chain management, both the models developed in earlier sections were solved for a variety of demand patterns. The solutions to the LP models provide the production and inventory levels at each facility in the supply chain and the quantity of goods transported between the facilities in each period. The costs incurred in both the scenarios, supply chain operation with and without visibility, were compared to quantify the impact of information sharing. The experiments were performed on a supply chain network with 3 component suppliers, 2 subassembly manufacturers, 1 contract manufacturer and 1 OEM. Parts of the network are described in the Appendix.

A. Numerical Experiment 1: Load Analysis

The supply chain network was exposed to a series of demand patterns (step inputs of varying magnitude, from time periods 7–19) and the cost of operating the supply chain was observed for each case. The reason it was decided to input a step input at time period 7 was because the latency of the system, due to transportation lead-times was found to be of the order of 6 time periods. Step inputs of magnitudes 50, 60, 70, 80, 90, and 100 units of demand were considered.

The costs for meeting these demand patterns are presented in Table II and the graph for these observations follows in Fig. 3.

It may be noticed from the above results that in terms of cost there is not much difference when the demand is very low. However, when the demand increases the cost of operating the supply chain without information sharing increases exponentially whereas the cost of operating a supply chain with integrated scheduling and visibility increases only linearly. This may be explained as follows. In case of a make-to-stock supply chain where there is limited supply chain visibility, when the loads are low the inventory that the supply chain participants need to hold is also low due to the fact that their sales are not so high. However, when the demand increases the flow through the network increases and as a result the participants need to keep a much higher level of inventory to maintain their service levels. This results in the exponential increase in costs. On the other hand, when we consider integrated supply chain planning, the products are built-to-order and there is no need to hold any inventory. As a result the costs only increase linearly, corresponding to the cost of material and production costs for the goods. Hence, in case of low loads the impact of information sharing may not be significant, but for higher demands it definitely is advantageous to share data between supply chain partners and adopt integrated scheduling methods.

TABLE II
COMPARISON OF SUPPLY CHAIN COSTS WITH AND WITHOUT INFORMATION SHARING

Load (Demand per Time-period)	Cost with Integrated Scheduling	Cost in case of no Information Sharing	Difference (%) (Integrated Scheduling – No Info Sharing)/ No Info Sharing
50	704,528	774,538	-9.03894
60	718,868	801,068	-10.2613
70	733,538	852,357	-13.9401
80	752,728	946,434	-20.4669
90	772,618	1,107,565	-30.2417
100	799,176	1,311,201	-39.0501

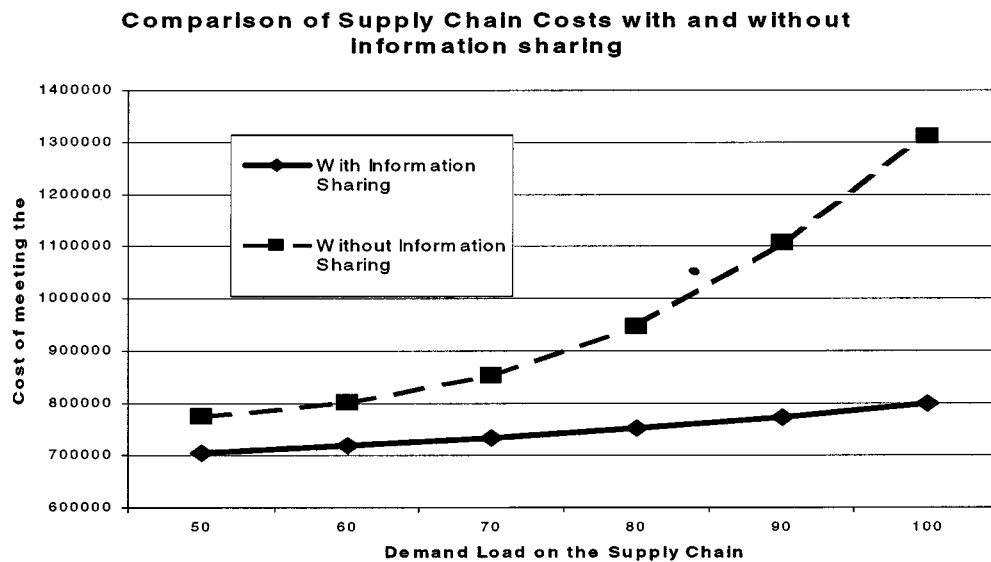


Fig. 3. Costs with and without information sharing.

TABLE III
MAXIMUM LOAD FOR THE SUPPLY CHAIN WITH AND WITHOUT INFORMATION SHARING

	Integrated Scheduling	No Information Sharing	Difference (Integrated Scheduling – No Info Sharing)/ No Info Sharing
Maximum Load per Time Period	228 units	102 units	126 units
Total Cost	\$ 1,541,736	\$ 1,383,711	11.42038 %
Total Revenue*	\$ 2,904,264	\$ 605,289	379.8144 %

Assuming per unit of final product sold is worth \$1,500

B. Numerical Experiment 2: Maximum Load Analysis

The supply chain was tested to determine the maximum load handling capability of the network. Through some trial and error, the maximum step input demand level for a supply chain with integrated scheduling and for a supply chain with limited visibility was determined. The step-input demand was fed from time-periods 7–19. It was found that the maximum load that the supply chain with limited visibility could handle was of the order of 102 units per time period from time periods 7–19 at a cost of \$ 1 383 711. Similarly, the maximum demand that an Internet-based supply chain with integrated scheduling could handle was 228 units per time period from time periods 7–19 at a cost of \$ 1 541 736. If we consider that the final goods were

worth \$1500 per unit the maximum revenue that the supply chain with limited visibility could generate was \$ 605 289, as compared to \$ 2 904 264 that could be generated by a supply-chain adopting integrated scheduling through information sharing. Hence, as a result by moving from make-to-stock to built-to-order through information sharing the supply chain network can realize a profit increase of 380% at an additional cost of 12%. These results are summarized in Table III.

It may also be noticed from the data for the supply chain given in the Appendix that the bottleneck in the supply chain exists at the level of the subassembly manufacturers who have a capacity of roughly around 90 units per time period. The capacity of the supply chain with limited visibility is very close to this bottleneck capacity, whereas the capacity of the supply chain with in-

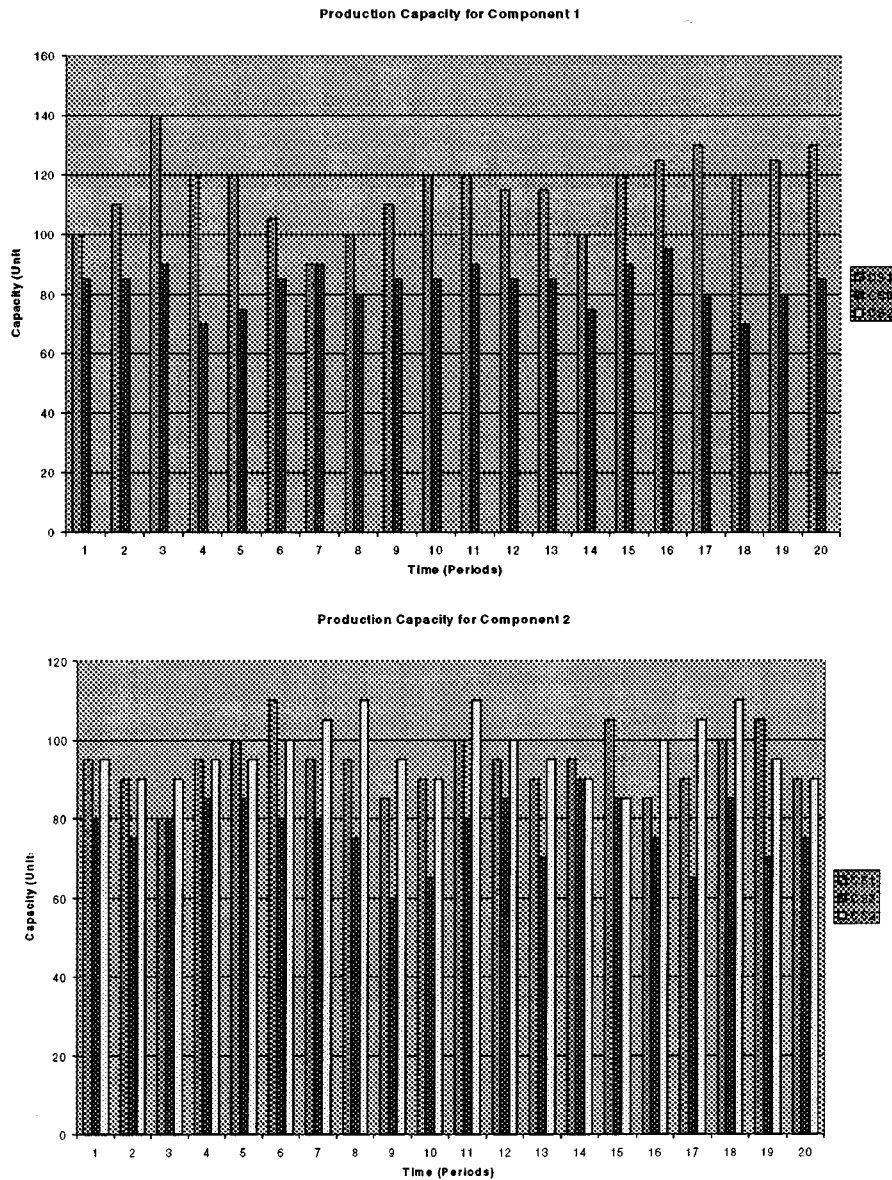


Fig. 4. Production capacity for components 1 and 2 at the production facilities of component suppliers, CS1, CS2, and CS3.

formation sharing and integrated scheduling is roughly around $2\frac{1}{2}$ times the bottleneck capacity.

This phenomenal capacity of the supply chain with supply chain visibility, is due to the fact that all the resources within the supply chain are used at an optimal rate. In case of heavy loads, since schedules for all partners are known it is possible to identify partners with spare capacity and to transfer the production to their facility. Such a decision to efficiently use resources can also be made when the future demand is known. In fact, some of the production can be scheduled in advance to meet future demand. Also, the entire production capacity of the supply chain is geared toward meeting customer orders in a built-to-order fashion. On the other hand when supply chain visibility is lacking, it is not possible to identify locations for production where there is excess capacity. As a result even though demand may exist, it may not be fulfilled due to the fact that excess capacity could not be identified and hence production could not be undertaken. Also, such a supply chain will lack the ability to use current excess capacity for the purpose of meeting future

demand. Another reason for the limited capacity of the supply chain when information is not shared is the fact that the production of the supply chain is geared toward maintaining inventory levels at each stage, as against meeting customer orders. Hence, a lot of production capacity is wasted within the supply chain itself. In summary, it must be said that information sharing can phenomenally increase the capacity of the supply chain.

C. Other Observations

One of the observations from noticing the results of the models was the fact that in case of integrated scheduling, the inventory held within the supply chain at any given time was minimal. This may hint at the need for very limited warehousing requirements.

On the other hand, the inventory held in the make-to-stock supply chain was significant. The model for a supply chain with no information sharing was also solved for a demand pattern, which was variable with respect to time. From a study of the inventory holding levels at the various stages of the supply chain, it was noticed that the variability of demand showed itself on the

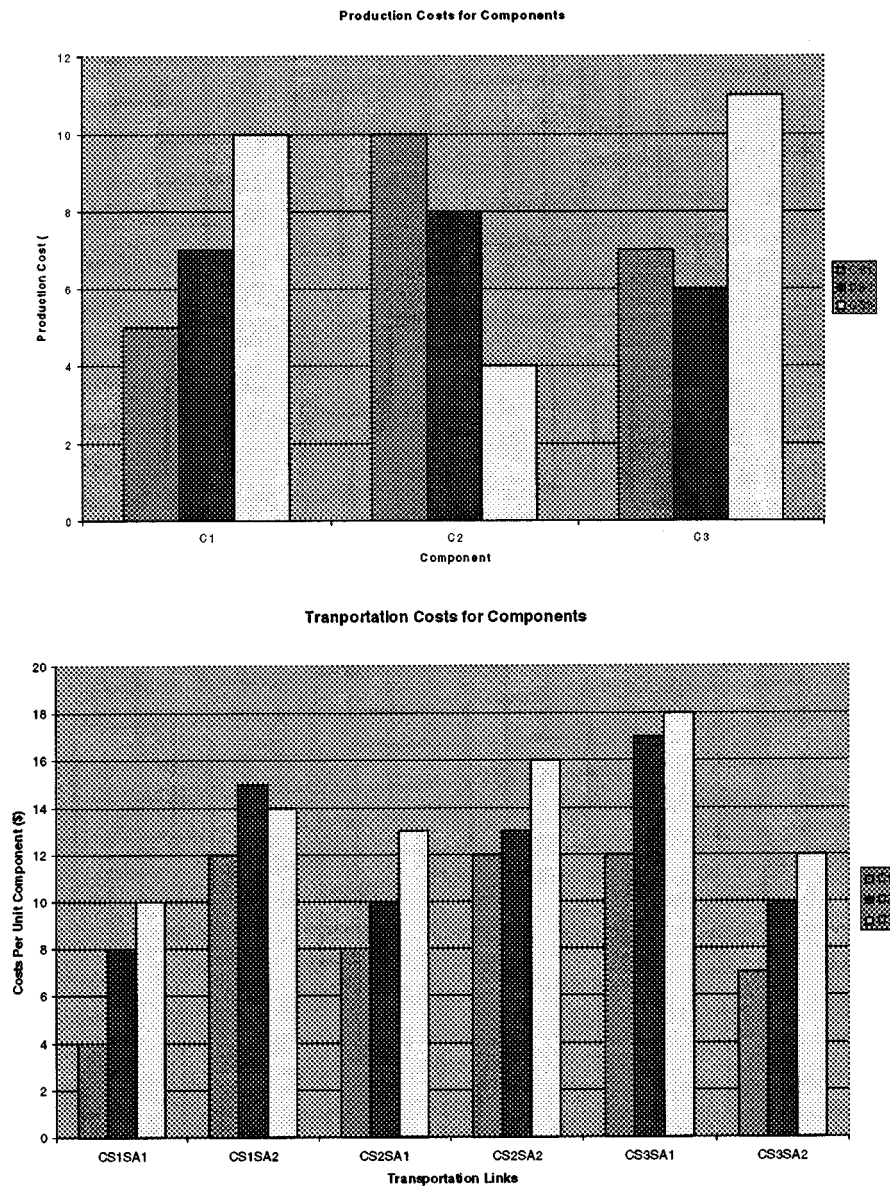


Fig. 5. Production costs for components at the facilities of component suppliers, CS1, CS2 and CS3 and the transportation costs for transportation of components to subassembly manufacturers SA1, SA2, SA3.

fluctuations in the inventory holdings at each stage. These fluctuations were smaller closer to the customer and increased at stages away from the customer. This is the classic bullwhip effect.

IV. CONCLUSIONS

In this paper, we have developed an LP-based optimization model for Internet-based supply chain operations. More specifically, we show that information sharing has a tremendous impact on profitability in comparison with a traditional make-to-stock linear supply chain model where no information is shared between the partners. Our contribution is significant in at least the following two ways.

- 1) We provide a theoretical basis for an Internet-based contract manufacturer's operations.
- 2) We analyze the effect of information sharing on the in-bound supply chain as opposed to previous attempts on distributor-retailer systems.

There are several directions in which our model can be improved. Firstly, by making more realistic assumptions on transportation and inventory costs we can model the above manufacturing system as a mixed integer program with a nonlinear objective function. The solution of this model would be of interest. Hence, in this regard, the LP model presented here is only an approximation. Secondly, there is scope to add a forecasting model into the supply chain optimization model. Finally, we would like to conduct discrete event simulation studies on the above model to study the lead-time and inventory behavior with and without information sharing.

APPENDIX

Figs. 4 and 5 represent data for a supply chain network in a contract manufacturing environment with 3 component suppliers, 2 subassembly manufacturers, 1 contract manufacturer, and 1 OEM. The data presented is for components and the fa-

ILITIES of component suppliers (see Figs. 4 and 5). Similar operational data on the subassembly manufacturers and contract manufacturer and OEM is also assumed to be available. Hopefully this representative data will give the reader a better feel for the problem considered in this paper.

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