Modeling the Dynamics of Supply Chains *

Jayashankar M. Swaminathan, Stephen F. Smith, Norman M. Sadeh
The Robotics Institute
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, Pennsylvania 15213-3891

February 7, 1995

Abstract

It is estimated that, on average, 60-70% of the costs of manufactured goods come from raw materials and purchased components [Har92]. As industry moves toward an increasingly more global market economy in which companies focus more on the production of core high-value-adding components, this figure can only increase. This in turn will further increase the interdependence between manufacturers and their suppliers when it comes to improving due date performance, reducing costs or increasing quality and will put a premium on the ability of managers to grasp the full complexity of the supply chain environment in which their companies operate. Current supply chain analysis techniques and tools often prove inadequate in this regard, due to modeling limitations (e.g. fixed leadtimes, inability to account for finite capacities, steady state assumptions, omission of important costs), an inability to take advantage of opportunities provided by Electronic Data Interchange (EDI) technology and a lack of support for operationalizing recent manufacturing philosophies (e.g. "Lean Production",TQM and JIT).

This paper reviews important research issues in supply chain management and presents initial work towards the development of decision support tools for analysis of supply chain dynamics. Our approach relies on the development of an extensible multi-agent simulation testbed in which a wide range of supply chain problems can be quickly and accurately modeled, and alternative solutions to these problems can be compared via simulation. We summarize initial results obtained with an early prototype that indicate some performance effects of different information sharing protocols.

1 Objectives and Motivations

To remain competitive, industrial organizations are continually faced with challenges to reduce product development time, improve product quality, and reduce production costs and leadtimes. Increasingly, these challenges cannot be effectively met by isolated change to specific organizational units, but instead depend critically on the relationships and interdependencies among different organizations (or organizational units). With the movement toward a global market economy, companies are increasingly inclined toward specific, high-value-adding manufacturing niches. This, in turn, increasingly transforms the above challenges into problems of establishing and maintaining efficient material flows along product supply chains. The ongoing competitiveness of an organization is tied to the dynamics of the supply chain(s) in which it participates,

*This research was supported by the Advanced Research Projects Agency under contracts F30602-91-F-0016 and F30602-90-C-0119.

and recognition of this fact is leading to considerable change in the way organizations interact with their supply chain partners.

Broadly speaking, supply-chain management can be subdivided into three inter-related topics:

1. *Supply Chain Configuration*: Decisions here relate to determination of an optimal number of suppliers as well as the selection of specific suppliers (internal or external) based on considerations such as quality, leadtimes, costs, reliability, expected learning curves, locations, capacities, earlier experiences, etc.

2. *Buyer-Supplier Relations*: These decisions have to do with assessing the merits of alternative contracts and agreements between buyers and suppliers. They include understanding tradeoffs involved in setting up cost-sharing agreements, determining the length of contracts, agreeing to share different types of information (e.g. open-book audits of suppliers), or committing to buying a percentage of the supplier's capacity.

3. *Buyer-Supplier Coordination*: Here buyers and suppliers are concerned about identifying efficient coordination policies to maintain a smooth flow of materials and products through the supply chain, avoiding stockouts while keeping inventories to as low a level as possible. Decisions of interest at this level include the selection of proper inventory policies and associated reordering policies (how much to reorder and when) as well as evaluating the impact of different information exchange protocols.

In this paper, we summarize ongoing work aimed at the development of an extensible modeling and simulation framework for analyzing supply chain management problems. Our objectives are two-fold:

1. First, we are interested in providing new insights into the nature of tradeoffs in currently ill-understood aspects of supply chain coordination such as buyer-supplier information exchange, buyer-supplier contractual agreements and buyer-supplier decisions under dynamically changing supply chain relationships. Analyses conducted to date in each of these areas has either suffered in their relevance to practical industrial situations, due to the limiting assumptions that are necessary to construct tractable analytical models, or have been retroactive and limited in applicability, relying on post hoc trend analysis of specific organizational entities. Our work, in contrast, seeks to construct and analyze models that capture the assumptions and dynamics of these decision tradeoffs in actual organizational decision-making contexts, and to provide relevant, prescriptive advice in different decision-making circumstances.

2. More generally, we are interested in increasing the relevance of analysis results to practical decision-making contexts, and in providing practical decision-support tools to supply chain management decision-makers. In developing our modeling and simulation testbed, our goal is a modular framework for specifying models of arbitrary fidelity to a given application context; allowing analysis of decision tradeoffs under assumptions that match the actual circumstances facing supply chain managers and their decision-making requirements. We expect, as a by product of investigating the above mentioned tradeoffs, to produce an extensible library of model building blocks (e.g., supplier/buyer agents, reordering policies, contractual agreements, information exchange protocols) for subsequent adaptation and re-use. In the longer term, we envision this research leading to the development of practical decision support tools, directly accessible to supply chain managers and integrated with the EDI capabilities of industrial organizations.

The balance of this paper is organized as follows. Section 2 briefly introduces concepts and issues in supply chain management and reviews existing research and approaches in this area. Section 3 summarizes the multi-agent modeling and simulation testbed we are developing. In Section 4, we present initial results obtained with an early prototype. Future work is discussed in section 5.

2 Supply Chain Management

A supply chain can be defined as a network of autonomous or semi-autonomous business entities collectively responsible for the procurement, manufacturing and distribution activities associated with one or more families of related products. Different entities in a supply chain typically operate subject to different sets of constraints and objectives. Even when belonging to the same company, supply chain entities often report to different divisions. Supply chain entities are highly inter-dependent when it comes to improving due date performance, increasing quality or reducing costs. As a result, the welfare of any entity in the system directly depends on the performance of the others and their willingness and ability to coordinate. For instance, the ability of a supplier to meet the demand from a customer depends on the willingness and ability of the customer to communicate its demand to the supplying organization in an accurate and timely fashion. In the absence of such communication, the supplier may be forced to operate with higher finished-goods inventories and with high costs. These higher inventory costs eventually find their way back to the customer organization in the form of price hikes.

With the emergence of new manufacturing philosophies such as Lean Production, TQM or JIT, western manufacturers are re-examining the way they interact with their supply chain partners [1]. Short-term adversarial relations are giving way to longer-term strategic alliances based on more complex considerations [WJR90, LKJ90, Hel91]. While in the past, supplier/consumer relations had often been dominated by price considerations, factors like quality, delivery performance or commitment to work together and improve performance over time are now playing a more important role in these decisions [Hal87, Har92, Lee92]. As we move towards an increasingly more global market economy, where margins for error are getting narrower, all these parameters need to be carefully weighted in every supply chain decision. Concurrently, advances in areas such as Electronic Data Interchange (EDI) have opened the door to new ways of conducting business, whose costs and potential benefits are not yet very well understood (e.g. [Udo93, SKMng]).

Supply chain management has been the subject of considerable research over the years. One can distinguish between two broad approaches: benchmarking efforts aimed at analyses of current practice in various sectors of industry and more theoretically oriented studies involving the development of analytical models, possibly in combination with some simulation studies.

Recent discussions of new trends and philosophies in supply chain management based on comparative analyses of current practice in different countries and different sectors of industry include those reported in [Hal87, LKJ90, WJR90, Hel91, Har92, SKMng]. This line of approach has had a strong impact on current practice and led to significant changes in industry. Unfortunately, while providing general guidelines and identifying elements of "best practice", this approach is of limited help to managers who are looking for specific quantitative solutions to every day problems.

On the analytical front, research on multiechelon inventory problems has a long history [CS58] (See [Cla72] for an early survey of this field or [SZ91] for an example of more recent work in this area). A multiechelon system is one in which each location has a unique predefined

[1] See also [Lee92] for an insightful survey of common pitfalls in current supply chain management practice.

supplier. This line of work further assumes centralized control of the supply network, thus overlooking the possibility that decisions found to be optimal for the overall supply chain may actually be detrimental to individual entities within the system. Work on multiechelon systems has traditionally been restricted to the study of uncapacitated single-product problems. Work on less restricted versions of the multiperiod multilocation inventory problem in which a location is allowed to order from multiple suppliers is discussed in [Kar81, FZ83, Kar87]. Recent analytical work on the problem of integrating ordering and production decisions within a company also includes that of Federgruen and Zipkin [FZ86] and Bassok and Akella [BA91]. Initial comparative analyses of diversification strategies under supply uncertainty have been discussed in [AA93, RP91]. Lee and Billington also reported an insightful study in which they combined analytical models and simulation to help Hewlett Packard assess different tradeoffs involved in setting up the supply chain for one of their new printers [LB93].

The above studies provide valuable insights into the different issues that they consider. However, they are limited by simplified assumptions and have generally ignored the impact of analyzed policies on other entities in the supply chain. Most of those studies that have utilized simulation have done so to answer specific questions, developing hard-wired simulation models that cannot be easily adapted to new problems. This generally explains why these techniques have not gained a wide acceptance. To this day, practical supply chain decision-making remains an art rather than a science, where decision-makers still rely on the results of broad benchmarking studies and make "gut-feeling" assumptions to identify a small subset of what they believe are key parameters on which they can base their decisions.

3 A Testbed for Modeling Supply Chain Dynamics

The use of simulation as a vehicle for understanding issues of organizational decision-making has gained considerable attention and momentum in recent years (e.g., [Mal87, KOP93, LB93]). The complex interdependencies between organizational structures, coordination knowledge and policies, and overall performance in such applications typically prohibits the development of insightful analytic models, and simulation provides a practical basis for realistically analyzing the performance tradeoffs associated with different organizational decision-making assumptions. The field of Distributed Artificial Intelligence has demonstrated the usefulness of multi-agent computational environments in the study of broad classes of coordination issues involving multiple autonomous or semi-autonomous problem-solving agents [BG88].

Recognizing that supply chain management is fundamentally concerned with coherence among multiple decision-makers, we have similarly adopted a multi-agent modeling framework based on explicit communication between constituent decision-making agents (manufacturers, suppliers, distributors). In doing so, we emphasize models that capture the locality that typically exists with respect to the purview, operating constraints and objectives of individual supply chain entities, and promote analyses of supply chain performance from a variety of organizational perspectives (e.g., individual nodes, confederated subchains, overall network). From a system development standpoint, our approach follows the configurable systems perspective of [SO93]; we are developing an extensible infra-structure for model specification and configuration based on differential analysis and reuse of libraries of model components. In the subsections below, we briefly outline the agent and communication structures defined in the modeling and simulation testbed.

3.1 Agents

Agents represent the entities (nodes) that comprise the supply chain being modeled. Agent descriptions provide a basic structure for specifying both static and dynamic characteristics of various supply chain entities, and are specialized according to their intended roles in the supply chain (e.g., manufacturer agents, transportation agents, raw material vendor agents, distribution center agents, retailer agents, end-customer agents, etc.). The description of an agent i is comprised of several sub-components:

- $State_{i,t}$ - The local state of agent i is a set of attributes that characterize its (simulated) state at time t. State attributes include base information about an agent's processing state (e.g., current pending orders, current product inventories, costs, cash, etc) as well as aggregated information relevant to agent decision-making. Associated with each aspect of local state are methods for accessing and (in the case of dynamic parameters) updating current values. Dynamic parameters change over time either as the result of internally triggered events (e.g. an order has been processed and gets transferred from Work-In-Process inventory into Finished-Goods inventory or a fraction of an agent's capacity becomes unavailable) or as a result of interactions with other agents (e.g. receipt of an order from a customer, shipment of an order to a customer, payment for an order delivered to a customer, etc.)

  We make an explicit distinction between the current state of an agent and the current local knowledge that an agent has available for use in decision making, providing the possibility to restrict an agent's visibility in decision-making to a subset of the attributes defined in $State_{i,t}$. Besides knowledge about its own state, supply chain agents can also maintain knowledge about other agents. This knowledge may be provided up-front by the user, when creating the model (e.g. knowledge that a given agent is a possible supplier), or may be acquired by the agent during the simulation (e.g. through information exchange or by monitoring the behavior of another agent such as monitoring the leadtime performance of a supplier).

- $InteractionConstraints_i$ - Another component of an agent description is a specification of its structural relationships with other agents in the supply chain network: which agents it has associations with and the conditions of these associations. Each agent description designates the set of agents with which it can interact, and for each, indicates (1) its relationship to this agent (e.g., customer, supplier), (2) the nature of the agreement that governs interaction (e.g., production guarantees, agreement length) and inter-agent information access rights (i.e., which aspects of that agent's local state are accessible for consultation during local decision-making).

- $InteractionPolicy_{i,m}$ - An agent i's interaction with one or more other agents in a given decision-making context m is governed by a set of specified interaction policies. Interaction policies are methods, defined with respect to local and externally visible state and objective information, that are triggered in response to the receipt of messages, and produce messages for transmission to other agents. Examples of interaction policies include re-ordering policy (when to re-order, how much, when), information sharing policies (e.g. when to communicate demand to other agents, when to communicate available capacity information to other agents, when to notify agents of delays in shipments, etc.), and methods of payment policies (e.g. when to pay suppliers).

3.2 Interaction Protocols: Simulating Material Flows, Information Flows and Cash Flows via Message Passing

Interactions between supply chain agent are simulated via exchange of messages between agents. A basic set of *message classes* defines the types of interactions that can take place within the network. All message classes share specific common attributes, including the (simulated) time at which they are posted, the posting agent and the recipient agent. Associated with each message class, in addition to any content specific parameters, is a method which defines its message processing semantics, dictating the specific agent interaction, state updating, and statistics gathering methods to be applied by the recipient node in response to a given message.

We recognize three broad categories of message classes, each associated with the simulation of a specific type of flow through the supply chain:

1. *Material flows*: Messages in this category relate to the delivery of goods by one agent to another. The processing semantics associated with material delivery messages minimally dictate adjustment to inventories of the posting and recipient agents by the quantity specified in the message. However, it can also trigger messages relevant to other supply chain flows (e.g., cash transactions) as well as local processing activities (e.g., determination of whether all the components required to initiate the assembly of a product are now available). Material delivery messages can be either sent directly by a supplier agent to a consumer agent (in cases where simulation of transportation delays and costs are not relevant) or may involve an intermediate transportation agent.

2. *Information flows:* This category of messages models the exchange of information between supply chain agents, and will eventually become the richest of the three categories of messages. This category includes "request for goods" messages (i.e., flow of demand). It also includes request for/transfer of capacity and demand-related information (e.g. regular communication of demand forecasts, communication of expected available capacity, expected delivery dates, etc.). Other messages that fall in this category include order cancellation messages and order modification messages (e.g. modified quantity or due date),etc. The processing semantics associated with this message will often be more complex than for other categories of messages. For instance, upon receipt of a "request for goods" message, an agent might perform a series of MRP-like computations and determine whether it needs to order additional raw materials or components from its own suppliers and might in turn issue "request for goods" messages to one or more of its suppliers.

3. *Cash flows:* The final category of message classes concern the movement of capital through the supply chain. This category includes a "Payment" message sent by customer agents to their supplier upon delivery of goods or according to more complex methods of payment, if appropriate.

As indicated above, within this multi-agent framework, simulation of a given supply chain configuration or scenario centers around the posting and processing of messages over time. Currently, the simulator proceeds at time step t by sending input demand messages to recipient agents for processing. Processing of a message by an agent (i.e., application of its associated message processing method) can result in the posting of new messages. The time step ends upon receipt of goods (or indication of no delivery) by all end-customers for that period. The simulation terminates when the global clock exceeds a pre-specified time horizon.

4 Using the Tesbed: An Example

We have developed an initial version of the testbed and have applied it to conduct an initial analysis of the impact of information sharing on supply chain performance [SSS94]. In this study, we considered a supply chain consisting of a single manufacturer who orders components from two alternative suppliers. It is a common practice in Japanese automotive industry to have two main suppliers for each of the component. This arrangement protects the buyer against unforeseen supply interruptions. The manufacturer faces a stochastic demand. The suppliers supply parts to more than one manufacturer. As a result, the capacity that a supplier allocates to a manufacturer is not constant over time, but depends on factors such as demand faced from other manufacturers, real-time machine breakdowns at the factory, priority assigned to the particular manufacture etc. Hence, the manufacturer faces uncertainity about the supplier's capacity allocation while reordering goods. We analyze the effect of sharing supplier information in such a situation.

We considered a scenario where there are four sites (excluding the one that supplies raw materials). First site is the retail outlet from where the demand for final goods gets generated. The second site is a manufacturing unit. The third and the fourth sites are alternative suppliers to the manufacturing site. The suppliers differ in terms of cost, quality of service as well as the capacity allocations. We integrate the supplier information with the decision process of the manufacturer and analyze the effect of having information about the capacity of the supplier, on the cost incurred and quality of services provided by the supply chain. We studied two alternative models; in Model-I, the suppliers share only the average allocation figures as a result there is no dynamic information sharing whereas, in Model-II, the suppliers are more closely linked with the manufacturer and are willing to provide their current capacity allocation. We analyzed how the two models differ in terms of cost incurred by the manufacturer, the suppliers and the supply chain as a whole, as well as, the quality of services provided by the supply chain, which is measured as a percentage of demand for goods that were delivered on time.

Through simulation of these two models, we found that information sharing has a significant effect on the performance of different entities present in the supply chain. The manufacturer incurs a lower cost when information is shared (Model-II) as compared to operating under assumptions about capacity (Model-I), consistent with our expectations. We also found that information-sharing reduces the total cost incurred in the supply chain, improves the quality of services, and increases the profits of supplier1. However, the results also indicated that the profit earned by supplier2 is significantly reduced in Model-II. It appears that the competitive advantage of supplier2, i.e., its ability to deliver the goods more reliably than supplier1, is lost in Model-II because of the information transfer that occurs between the manufacturer and the suppliers. The manufacturer has full information on the capacity allocations before making the reordering decision and uses the information effectively to reduce its cost and provide better services. The less expensive supplier would incline to share information once the advantages are explicitly stated. As far as the more expensive supplier is concerned, it may not be willing to share the information. However, this turns out not to matter because supplier2 has no control over whether supplier1 decides to share capacity information. To confirm this fact, we constructed a third scenario (say Model-III) where only supplier1 shares information with the manufacturer, and conducted the same set of experiments under these conditions. We found that supplier2 makes even less profit by not sharing information than it would if it shared information, given that supplier1 shares the information. Thus, supplier2 is also inclined to share information in such a situation, even though its profits are lower than in Model-I (where no suppliers share information). This result is very similar to the practices in Japanese supplier groups ("keiretsu") where suppliers may suffer from lack of business because of their inability to meet the manufacturer's requirements. In such a situation Japanese automakers like Nissan and Toyota often help the weaker of the two suppliers in order to improve the production process.

Our study indicates that sharing of information reduces the cost incurred in the supply chain and at the same time improves the service levels. We find information sharing benefits supplier1 and as a result the supplier is inclined to share information. Interestingly, we find that sharing of information by supplier1 forces supplier2 to share the information. Eventually, both the suppliers share the information with the manufacturer. In practical settings, one often does not find alternative suppliers to be willing to share capacity information. We believe that this is due to three reasons: (1) accurately determining plant capacity is a difficult task, (2) capacity allocation information is sometimes considered strategic and, as a result, "unsharable", and (3) managers are unable to evaluate the magnitude of reduction in cost of operations due to information sharing. In this last regard, results such as those summarized above can provide valuable insight to managers about the implications of information sharing on the dynamics of the supply chain and the performance of their individual sites.

5 Future Research

As manufacturers attempt to move away from short-term one-sided/adversarial relations with their suppliers and look for ways to increase supply chain performance, there is a critical need to gain a deeper understanding of the ways various supply chain decisions affect their operations of as well as those of their partners. We have summarized ongoing research aimed at addressing this need, through the development of a multi-agent framework for accurately modeling various supply chain management practices in specific application contexts and the use of the framework to analyze specific decision-making tradeoffs. Our approach underscores the importance of models in which different partners operate subject to their own local constraints and objectives and have different local views of the world, and the need to understand performance from a variety of organizational perspectives. We believe these points are crucial to the development of practical decision support models.

Our initial work has focused on the impact of exchanging capacity information on supply chain performance. We are currently engaged in further development of the modeling and simulation testbed, to support investigation of the following set of issues:

1. **Information Exchange Issues**: There is ample evidence that exchange of demand and capacity information can significantly improve supply chain performance. We wish to analyze impact of the information such as future demand schedules that the manufacturer may share with the suppliers. In fact, many times the information that is shared may not be exact. In such cases, it would be interesting to see what kind of information "filters" are necessary to support efficient and effective operation. Another important issue is to analyze the effect of information exchange rate on the performance.

2. **Buyer-Supplier Agreements**: A common approach to reducing inventory investments at the supplier end and optimizing capacity investments is to grant discounts to manufacturers willing to commit to purchasing specified quantities over some extended period of time. Buyer-Supplier agreements are not limited to "one-shot" discount and purchase commitments but may also include clauses that specify cost-reduction curves over the life of a product [2]. There is no doubt that long-term relations with loyal suppliers can potentially lead to significant savings (e.g., [CY84]). It is also clear that these relations can have disadvantages, as they imply a loss of flexibility both on the part of the manufacturer and supplier. While electronics and automative industries tend to emphasize longer-term agreements for the procurement of key components or subassemblies, other more flexible manufacturing industries lean towards more dynamic arrangements. For instance, Piore and Sabel describe US mini steel mills, French and Italian textile firms and Japanese tool makers as examples of flexible industries where variability of demand results in the constant rearrangement of subcontracting patterns [PS84]. We wish to analyze the trade-off between these arrangements under specific supply chain configurations.

[2] Clearly there are many stronger forms of agreements between manufacturers and their suppliers as well. Examples include long-term collaborations involving joint development of new products or processes, equity investments, etc.

3. **Supply Chain Configuration - Supplier/Subcontractor Selection Issues** This set of issues is related to the first two, but is concerned specifically with the tradeoffs associated with selecting specific suppliers (based on considerations such as capacity, quality, leadtime, price, and proximity). We are particularly interested in analyzing the tradeoffs of adaptive selection strategies, involving choices between longer term contractual agreements and state dependent (re)establishment of partners, under scenarios that involve interacting (and) competing product supply chains.

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