Simulation of Order Fulfillment in Divergent Assembly Supply Chains

Abstract

Management of supply chains is a difficult task involving coordination and decision-making across organizational boundaries. Computational modeling using multi-agent simulation is a tool that can provide decision support for supply chain managers. We identify the components of a supply chain model and implement it in the Swarm multi-agent simulation platform. The model is used to study the impact of information sharing on order fulfillment in divergent assembly supply chains (commonly associated with the computer and electronics industries). We find that efficient information sharing enables inventory costs to be reduced while maintaining acceptable order fulfillment cycle times. This is true because information, which provides the basis for enhanced coordination and reduced uncertainty, can substitute for inventory.

Keywords:
supply chain management, multi-agent simulation, Swarm, decision support systems, electronic commerce, computer industry, electronics industry

Introduction

1.1

Supply chain management is a difficult task involving coordination and decision making across organizational boundaries. It is an outgrowth of organizations realizing that efficiency of individual business units alone is insufficient for maintaining competitiveness in today's business climate.

The revolution of the 1990s is driven not by changes in production and transportation but by changes in coordination. Whenever people work together they must somehow communicate, make decisions, allocate resources and get products and services to the right place at the right time. Managers, clerks, salespeople, buyers, brokers, accountants - in fact, almost everyone who works - must perform coordination activities (Malone and Rockart, 1991).

Coordination in the past was facilitated through large hierarchical organizational structures. Today,
large hierarchies are separating into smaller specialized companies where coordination can not be mandated. This has created a situation where uncoordinated interorganizational business processes result in unacceptable overall organization performance even if individual business units are operating efficiently.

1.2 Supply chain management expands the scope of the organization being managed beyond the enterprise level to include interorganizational relationships. Examples include improving coordination between suppliers and manufacturers, as well as between manufacturers and distributors. As improvements in information technology have enabled the costs of coordination to decrease (Malone, Yates and Benjamin, 1987), there has been a general movement toward organizing as partnerships between more specialized firms or business units. Supply chain management is an important topic to study because it is an instance of these partnerships.

1.3 Most MIS research related to supply chain management has concentrated on identifying the information requirements of local supply chain node decision-making (Billington, 1994; Davis, 1993; Lee and Billington, 1992; Lee and Billington, 1993; Lee, Billington and Carter, 1993; Swaminathan, Smith and Sadeh, 1994). Often this involved development of models of material and information flow through the supply chain network (SCN). The purpose of our research is twofold.

1.4 First we investigate the feasibility of using multi-agent systems to simulate order fulfillment in supply chains to provide a decision support tool for managers. Multi-agent systems are appropriate for modeling supply chains because they involve divisible processes with loosely coupled command and control. Multi-agent techniques are most useful for modeling these processes. Traditional operations research methods were useful for simulating hierarchical production systems where decision making is centralized. A supply chain, with its decentralized command and control, is more appropriately modeled as a social simulation. Our multi-agent system is simplistic, but it does provide a basis for modeling negotiation between supply chain partners, as well as supply chains where there are power differentials between partner firms (for example a supply chain involving large companies like Wal-Mart or General Motors, and a number of smaller firms).

1.5 Our second purpose is to use the system to identify the impact that information sharing has on the performance of divergent assembly supply chains commonly associated with the computer and electronics industries. A link to the simulation code is provided in Section 4.3 where the verification and validation of the model are discussed.

1.6 We investigate the impact of several characteristics of supply chain management in an environment of electronic commerce. These include (1) centralized, global business and management strategies (e.g. make-to-order, assembly-to-order and make-to-stock), (2) on-line, real-time distributed information processing to the desktop, providing total supply chain information visibility, and (3) the ability to manage information not only within a company but across industries and enterprises (Kalakota and Whinston, 1996). Within an overall framework for studying electronic commerce, our research is at the application level (e.g. supply chain management) enabled by the information superhighway, multimedia content and network publishing, messaging and information distribution, and common business services infrastructures (Applegate, Holsapple, Kalakota, Radermacher and Whinston, 1996).

1.7 We discuss our findings in the following sections. In Section 2 we present a brief overview of
Supply chain management to provide background for understanding the later material. In Section 3 we discuss the information technology currently available that enables information sharing across organizational boundaries. In Section 4 we illustrate, through a set of simulations, how information-sharing impacts overall supply chain network performance and in Section 5 we present our conclusions.

Supply Chain Management (Scm)

2.1
We introduce supply chains by presenting (1) a general overview of supply chain management, and (2) a summary description of supply chain management.

General Overview Of Supply Chain Management

2.2
A supply chain is a network of facilities that procures raw materials, transforms them into intermediate subassemblies and final products and then delivers the products to customers through a distribution system (Billington, 1994). It is commonly referred to as a network because it involves bi-directional flows of materials, information and payments. Supply chains exist in virtually every industry, especially industries that involve product manufacturing, and management of supply chains is not an easy task because of the large amount of activities that must be coordinated across organizational and global boundaries. The most common problems involve coordinating materials inventory and production capacity availability across several organizations to produce products that can satisfy forecasted demand in an environment with a high level of uncertainty.

2.3
Several factors are making supply chain management an important issue for today's managers. These factors include (1) more instances of multisite manufacturing, where several independent entities are involved in the production and delivery process, (2) increasingly cut-throat marketing channels, (3) the maturation of the world economy, with heightened demand for "local" products, and (4) competitive pressures to provide exceptional customer service, including quick, reliable delivery (Davis, 1993). In the past, management would concentrate on making each node of the supply chain network efficient. What managers are now realizing is that efficiency at each node does not result in the supply chain as a whole operating optimally. Increasingly, the challenges related to improved product quality, customer service and operating efficiency 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) (Swaminathan, Smith and Sadeh, 1994). Supply chain management is a management process that attempts to optimize the operation of the entire supply chain. 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 (Swaminathan, Smith and Sadeh, 1994).

2.4
Specifically, supply chain management involves balancing reliable customer delivery with manufacturing and inventory management costs (Billington, 1994). Two metrics commonly used to measure overall supply chain performance are (1) order fulfillment cycle time, and (2) inventory level and cost. One major problem involved in supply chain management is understanding and managing the uncertainties involved in the supply chain. This is especially true in industries such as
fashion skiwear where demand is heavily dependent on a variety of factors that are difficult to predict - weather, fashion trends, the economy - and the peak of the retail selling season is only two months long (Fisher, Hammond, Obermeyer and Raman, 1994). Three fundamental sources of uncertainty exist along a supply chain. They include demand (volume and mix), process (yield, machine downtimes, transportation reliabilities), and supply (part quality, delivery reliabilities) (Billington, 1994; Lee and Billington, 1993; Lee, Billington and Carter, 1993). Inventories are often used to protect the chain from these uncertainties. Another major problem involved in supply chain management is the management of lead-time. A role of information technology (IT) in supply chain management is to assist managers in managing uncertainty and lead time through improved collection and sharing of information between supply chain nodes. It is felt that this will result in better customer service, through better coordination, and improve asset management, by giving decision-makers the information necessary to optimize inventory and capital asset costs. Many of these improvements occur because IT enables changes to be made in inventory management and production planning dynamically. The difficulty arises when trying to design an information system that can handle the information needs of each of the supply chain nodes to allow efficient, flexible, and decentralized supply chain management. The information technology that enables information sharing across a supply chain is discussed in Section 3.

Summary Description Of Supply Chain Management

2.5

The information infrastructure that is required by supply chain management is by nature supported by a distributed information system. Because of this, we feel that a distributed system model is most appropriate to describe a supply chain network. Distributed problem solving is the cooperative solution of problems by a decentralized and loosely coupled collection of knowledge sources (KS's) located in a number of distinct processor nodes (Smith and Davis, 1988). Distributed problem solving is often necessary because no one node has sufficient information to solve the entire problem. The components of a distributed, coordination intensive, problem include goals, activities, actors, and interdependencies (Malone and Crowston, 1990). We feel that a supply chain can be described by identifying its actors, activities, interdependencies, goals and objective. Our supply chain description is summarized in Table 1.

Table 1: Supply Chain Management Summary Description

<table>
<thead>
<tr>
<th>1. Actors</th>
<th>Suppliers, manufacturers, assemblers, distributors, and customers</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Activities</td>
<td>Material and information processing</td>
</tr>
<tr>
<td>3. Interdependencies</td>
<td>Material shipments and orders, Funds transfer, Information sharing, and Command and control</td>
</tr>
<tr>
<td>4. Goals</td>
<td>Minimize order fulfillment cycle time, Minimize inventory levels and costs, Minimize uncertainty, and Preserve robustness</td>
</tr>
<tr>
<td>5. Overall Objective</td>
<td>Balance individual goals based on priorities to produce the best &quot;average&quot; performance, or the best &quot;worst case&quot; performance.</td>
</tr>
</tbody>
</table>
2.6

The overall supply chain objective is to balance each of the goals based on their importance to supply chain managers. In some situations costs may be the priority, while in other situations customer service may be the priority. In all situations it is important to operate in a manner that allows the supply chain to adapt to changes in the business environment.

Current Technology That Enables Supply Chain Information Sharing

3.1

In this section we discuss current technologies that enable information sharing across supply chains. Details of how to implement these systems into a complete supply chain information infrastructure are outside the scope of this paper. The technologies that we discuss include electronic data interchange (EDI), the Internet-based World Wide Web (WWW), intranets, and extranets.

3.2

EDI is an existing information technology that provides a method of electronic transaction transfer. It is the process of computer-to-computer business-to-business transaction transfer. EDI involves the direct routing of information from one computer to another without interpretation or transcription by people, and to achieve this the information must be structured according to predefined formats and rules which a computer can use directly (Holland, Lockett and Blackman, 1992). One example of where EDI has been shown to improve part of supply chain management is in inventory management, specifically a just-in-time (JIT) system. EDI technology was shown to facilitate accurate, frequent, and timely exchange of information to coordinate material movements between trading partners. Suppliers receiving JIT schedule information achieved better shipping performance. Similarly, suppliers with the ability to directly map incoming information to internal production control systems were found to enjoy even greater benefits. Moreover, as the supplier handles a higher fraction of customers electronically, it was found that shipment errors continued to diminish (Srinivasan, Kekre and Mukhopadhyay, 1993). Each year the use of EDI increases as organizations look for methods to improve enterprise integration and interorganizational coordination. Numerous studies have been done on various aspects of EDI and they all draw the same conclusion. EDI increases the speed and the accuracy of processes compared with non-electronic transfer of information (Snapp, 1990), and it is a potential source of competitive advantage (Johnston and Vitale, 1988). When a supplier and a procurer use information technology to create joint, interpenetrating processes at the interface between value-adding stages, they are taking advantage of the electronic integration effect. This effect occurs when information technology is used not just to speed communication, but to change - and lead to tighter coupling of - the processes that create and use information. One simple benefit of this effect is the time saved and the errors avoided by the fact that data need only be entered once (Malone, Yates and Rockart, 1991). This is just one of several benefits derived from supply chain partners using more highly integrated information systems.

3.3

A practical problem that must be addressed when designing an EDI process is the lack of a globally recognized standard format for data storage and transfer (Snapp, 1990). Because of this lack of standards, organizations must agree upon the translation software and data format on a project by project basis. Without an agreement upon a standard the EDI process will not work. This is one of the reasons why there will be a general movement away from these transaction specific connections to more flexible methods of electronic information transfer. One solution that has been considered by a number of businesses is using the Internet-based WWW and Net browsers (such as Netscape Navigator).
3.4

The Internet is an example of a global information network composed of an existing set of information technologies that provide a method for electronic information sharing. One component of the Internet is the WWW. Although the WWW was not developed specifically for sharing of information among supply chain partners, it provides a model for these types of systems. The Web was developed to be a pool of human knowledge, which would allow collaborators in remote sites to share their ideas and all aspects of a common project (Berners-Lee, Cailliau, Luotonen, Nielsen and Secret, 1994). Because supply chain management is similar to the projects the WWW was designed for (remote sites, shared knowledge, common project) it can serve as a method for sharing of information in a supply chain. Netscape Navigator is an example of a WWW browser (which can also be viewed as a global network interface) that provides seamless access to a wide range of data through the WWW. The major problem with using the Internet for supply chain management is security. This includes security of information stored in databases as well as transfers of information between servers. Experts say reports of Internet-related security breaches are rising. Nearly one in four respondents to an Information Week survey conducted in February 1996 say fear of Net break-ins is keeping them from using the Net (Violino, 1996). The solution seems to be a more secure version of the Internet, an intranet.

3.5

An intranet is essentially any site based on Internet technology but placed on private servers and designed not to allow outsiders in (Miller, 1996). The outsiders in this case would be individuals and companies not directly involved in the management of the supply chain. Intranets use Web-based and Internet technology to inexpensively and easily share [organizational] data across a private network (Carr, 1996). We feel that the "organization" can encompass several separate firms such as in a supply chain. Intranet usage is predicted to overwhelm external Internet usage before the turn of the century. The key enablers of WWW growth are: (1) the proliferation of PCs, LANs, and modems, (2) open standards such as TCP/IP, HTTP, and HTML, (3) cross-platform support, (4) multimedia support and ease of use, and (5) support for secure transactions. [Organizational] intranets can provide information in a way that is immediate, cost-effective, easy to use, rich in format, and versatile (Netscape, 1996). What we have described is an extended intranet (or extranet). This is in line with the third wave of Internet usage identified by Netscape's Marc Andreessen. "We are ready for a new era: the emergence of the extranet, or extended intranet, connecting companies with their suppliers and customers via Web links" (Karpinski, 1997). Extranets, utilizing the WWW, its middleware, and browser software, provide a set of existing technologies that make supply chain information sharing feasible.

Performance Improvements Enabled By Information Sharing

4.1

In this section we describe our supply chain management computational model and how it is used to identify the performance gains arising from information sharing. We focus on one of the core business processes, the order fulfillment process (OFP), and use the Swarm simulation platform (Santa Fe Institute, 1996) to simulate the OFP in supply chain networks (Lin, 1996; Lin, Tan and Shaw, 1996). Swarm is a multi-agent simulation platform developed for the study of complex adaptive systems. It was developed at the Santa Fe Institute and aims at providing a general-purpose tool for building simulation models. A detailed description of Swarm is outside the scope of this paper, but can be found in Lin, Tan and Shaw (1996). Our implementation of SCNs in Swarm is described in more detail in paragraph 4.2. An order fulfillment process begins with receiving orders from customers and ends with having the finished goods delivered (Lin, 1996). It consists of several activities (sub-processes), such as order management, manufacturing, and distribution. The main objectives of the OFP can be generalized into two dimensions (Christopher, 1993; Goldman, Nagel and Preiss, 1995; Lin, 1996):
1. delivering qualified products to fulfill customer orders at the right time and right place, and
2. achieving agility to handle uncertainties from internal and external environments.

Issues In Managing SCNs For Supporting The OFP

4.2

Because of the complexity of a SCN, it is a challenge to coordinate the actions of entities within the network to perform in a coherent manner. When orders come into an entity in a SCN, the lead time for delivering products (called the order fulfillment cycle time) is composed of (1) order processing times, including the order transfer time from customers to manufacturers or distributors, and the due date assignment process, (2) material lead times, including material planning and purchase lead time, supplier lead time, transport lead time, receipt and inspection lead time, assembly release time, and material order picking time, (3) assembly lead times, including waiting time, processing times, and transport time to the next stage, (4) distribution lead times, including dispatch preparation time (documents, packages), and transportation time to the customer, and (4) installation lead times. These components of the order fulfillment cycle time distribute across the network, and the variation of lead times at any stage will affect the execution of the other stages and result in uncertainties for the overall order cycle time. This is called the ripple effect.

4.3

Take, for example, a product that is assembled by component parts from several different suppliers. The cycle time for assembling the product can be affected by the lead-time of material supply from different suppliers. If parts from some of the suppliers come later than the other parts for assembly, the assembly will be delayed due to the unavailability of required parts. This also increases the inventory costs for those available parts. If the product is a component for the downstream manufacturing process, the delay for shipping this product will affect the consequent stages, and in turn, influence the whole network. Therefore, the first issue in managing a SCN is how to control the ripple effect of lead-time so that the variability of a SCN can be mitigated. How to coordinate the policies of up and down stream entities in facilitating such variability reduction is the main concern. Demand forecasting is used to estimate demand for each stage, and the inventory between stages of the network is used for protecting against fluctuations in supply and demand across the network such as machine breakdown, extra large demand, etc. Due to the shortening of product life cycles, such protection seems unwise and actually reduces flexibility.

4.4

Because of the decentralized control properties of the SCN, control of the ripple effect requires coordination between entities in performing their tasks. The management of interdependencies is the key to smooth material flow within the SCN. The interdependencies between entities of the SCN can be described in the following situations:

1. Producer/consumer dependence can be used to describe the supplier/manufacturer relationship in the SCN. This requires cooperation between suppliers and manufacturers in an efficient and effective way. Efficiency means to reduce material lead times, and effectiveness means to supply only the needed materials. This dependence also implies a constraint satisfaction problem, and through the network it is a constraint propagation issue too.
2. Material flows within the SCN implies a synchronization problem, where related materials for a product are delivered to the manufacturer at a coherent speed which incurs minimal inventory and delay.

4.5

Inventory is an unwise approach to dealing with highly changing market demand and short life cycle products. What would be the substitution for inventory? Information can do. The material lead-time information from different suppliers can be used for planning the material arrival, instead of
building up inventory. The demand information can be transmitted to the manufacturers on a timely basis, so that orders can be fulfilled with less inventory costs. The second main issue is how to manage the information flow within a SCN so that decisions made by business entities can take more global factors into consideration. In this way, we can increase SCN visibility.

4.6
These issues are brought up because of the essential concern: how to make the network respond effectively and efficiently to satisfy customer demand, which leads to the motivation for managing SCNs to support the OFP.

4.7
In (Lin, 1996), Lin identified three main types of SCNs, Type I, II and III, based on such attributes as manufacturing process, primary business objective, product differentiation, range of product variation, assembly stages, product life cycle, and main inventory type as shown in Table 2.

Table 2: The Properties of Type I, II, and III SCNs

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Type I SCN</th>
<th>Type II SCN</th>
<th>Type III SCN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing process</td>
<td>Convergent Assembly</td>
<td>Divergent Assembly</td>
<td>Divergent Differentiation</td>
</tr>
<tr>
<td>Primary business objectives</td>
<td>Lean production</td>
<td>Customization</td>
<td>Responsiveness</td>
</tr>
<tr>
<td>Product differentiation</td>
<td>Early</td>
<td>Late</td>
<td>Late</td>
</tr>
<tr>
<td>Range of product variations</td>
<td>Small</td>
<td>Medium</td>
<td>Large</td>
</tr>
<tr>
<td>Assembly process</td>
<td>Concentrating at the manufacturing stage</td>
<td>Distributed to the distribution stage</td>
<td>Concentrating at the manufacturing stage</td>
</tr>
<tr>
<td>Product life cycle</td>
<td>Years</td>
<td>Months to years</td>
<td>Weeks to months</td>
</tr>
<tr>
<td>Main inventory type</td>
<td>End products</td>
<td>Semi-products</td>
<td>Raw materials</td>
</tr>
<tr>
<td>Example industries</td>
<td>Automobile and aerospace</td>
<td>Appliance, electronics and computers</td>
<td>Apparel/fashion</td>
</tr>
</tbody>
</table>

4.8
The automobile and aerospace industries are associated with Type I SCNs, where how to efficiently meet customer demand without carrying excessive inventory, and how to coordinate suppliers and assemblers to smooth material flow, are two main issues and challenges. Structurally, there are many suppliers. The wide range of materials and subcomponents that come from these suppliers converges through a series of manufacturing stages until the final product is assembled at one
location. The final product is then shipped to several distributors and ultimately to a large number of retailers. The appliance, electronics, and computer industries can be classified as Type II SCNs, where reducing the lead-time of the assembly-to-order process, and managing the inventory and purchasing for the assembly, are two main issues and challenges. In these SCNs, a relatively small number of suppliers provide materials and subcomponents that are used to produce a number of generic product models. Complex assembly processes for generic models (semi-products) are executed at factory sites, and simple assembly processes for customized models are executed at distribution sites. A number of distribution points may be needed to quickly respond to customized orders. The apparel/fashion industry is a Type III SCN, where acquiring market information to respond to demand, and deferring product differentiation to maintain flexibility to handle constantly changing markets, are two main issues and challenges. In these SCNs, the number of end items is larger than the number of raw materials. There are a small number of suppliers and manufacturers, but a larger number of distributors and retailers. These three types of SCNs serve as the foundation to understand the issues and challenges for improving the OFP in SCNs.

**The Implementation Of Swarm For Simulating Order Fulfillment In SCNs**

4.9

Figure 1 describes the SCN implementation on the Swarm platform. The topmost swarm, the OFP Batch Swarm, is designed to control the whole simulation. It creates two swarms, the OFP Model Swarm and the Statistics Swarm, creates actions, and then activates the simulation process. The OFP Model Swarm is composed of an array of SCN Entities created while building objects. The SCN configuration with each entity's properties and product information are fed in during the entity's creation. The OFP model actions are composed of each SCN entity's actions, and are activated when the OFP Model Swarm is activated. A SCN entity is composed of several agents, such as an order management agent, an inventory management agent, and a SCN management agent. An entity with manufacturing capability includes a production planning agent, a capacity planning agent, a materials planning agent, a shop floor control agent, and manufacturing systems agent. A SCN Entity Swarm holds entity level information such as suppliers, customers, order transfer delay time, and product delivery time, which are accessible by internal agents and other entities. The encapsulated agents perform certain functions in enabling the movement of information and material within the entity and between entities. The Statistics Swarm is used to compute the statistics data gathered through the simulation for analysis purposes.
4.10

The following scenario describes the interactions among these agents, and Figure 2 summarizes them. For example, an entity $\text{ScnE}_\text{Swarm} A$ receives an order from its customer $\text{ScnE}_\text{Swarm} C$. The order flows to the order management agent ($\text{OrdM}$). According to the customer lead times, the inventory availability information (from $\text{InvM}$), the production plan (from $\text{PrdP}$), and the manufacturing capacity ($\text{CapP}$), the order management agent assigns a due date to the order. If the products are in stock, the order is filled by shipping the products from inventory. If the products are in receiving, the due date is set according to the delivery date of the products.

4.11

For an entity with manufacturing capability, the order is forwarded to the production-planning agent ($\text{PrdP}$) where the schedule for making the products is planned. The capacity-planning agent ($\text{CapP}$) and the material-planning agent ($\text{MatP}$) are partner agents in generating achievable build plans. The material planning obtains build plans from the production-planning agent to allocate materials for manufacturing. It also contributes information about material availability to production planning for scheduling. The capacity planning agent ($\text{CapP}$) plans capacity by taking the build plan from $\text{PrdP}$ and sends capacity usage information to $\text{PrdP}$ for scheduling the build plan. The SCN management agent ($\text{ScnM}$) takes the order information to choose suppliers in allocating material sources. The outgoing orders are transferred through its SCN Entity ($\text{ScnE}_\text{Swarm} A$) to be transferred to other entities (i.e. $\text{ScnE}_\text{Swarm} B$). This describes the information within an entity.

4.12

If the entity is a distribution center or a retailer without manufacturing capability, the ordered products are delivered from suppliers as end products to ship to its customers. For an entity with manufacturing capability, the ordered end products are supplied from the shop floor ($\text{ManuS}$) to its customers. The input materials are components for the end products. This represents the material
flow with an entity. The interaction of these agents enables the flow of materials and information within an entity, and, through the SCN Entity Swarm (ScnESwarm), the information and materials flow across the supply chain network.

![ScnESwarm Diagram]

**Figure 2** SCN Agent Interactions in the Swarm Implementation

### 4.13

In this section we described the components of our SCN simulation model. The specific business environments that we simulate are described in the next section.

**Impact Of Information Sharing On Divergent Assembly (Type II) Supply Chains**

### 4.14

We implemented a supply chain designed to simulate order fulfillment in a Type II SCN. The model and Swarm system both include the major components (as shown in Table 1) of a divergent assembly SCN. The Swarm code is available for verification purposes. Suppliers, manufacturers/assemblers, and distributors are included as entities (actors) in the system. Entities are composed of agents (activities) that represent the agents shown in Figure 1. These agents incorporate the decision making, and information and material processing. (Goals) are incorporated into the decision-making rules of the agents. Message passing between agents (as shown in Figure 2) represents information and material transfer (interdependencies). Modeling of a divergent assembly supply chain is done by structuring the entity interactions to match a generic supply chain structure (as shown in Figure 3), and product structure, seen in the computer or electronics industry (i.e. Hewlett-Packard, Motorola). We verified that the entities, agents, activities, and interdependencies included in the system are those that are typically described in the supply chain management literature. Performance (overall objective) is based on cycle time and inventory levels resulting from the implementation of the other model components. The system performed as expected with positive impacts resulting from increased information sharing. Our Swarm-based divergent assembly supply chain model is valid because it encompasses all of the major components of a real-world supply chain, and it involves a detailed view of the inner-workings that is not seen in
high level analytical models. Validity beyond this level is difficult and would require implementation of one specific real-world divergent assembly supply chain. This is a potential topic for future research.

4.15
"Scn-II" in Figure 3 represents a Type II SCN consisting of 15 business entities aligned into five tiers. Entities in tiers 1, 2 and 3 perform complicated manufacturing and assembly processes, entities in tier 4 execute simple assembly processes, and those at tier 5 do not have manufacturing capability. Scn-II shares some features with a Type II SCN such as divergent assembly, late product differentiation, and distributing assembly to the distribution stage.

4.16 We conducted experiments to evaluate OFP performance using various information-sharing strategies. Information sharing between business entities considers three issues: (1) the information contents, (2) the depth of information penetration (the number of tiers for which information is accessible), and (3) the information acquisition direction (upward or downward sharing). Agent decision-making processes are held constant to isolate the impact of information sharing. The experiments were designed to test two hypotheses related to the importance of different information types, and the importance of different demand management policies. The hypotheses are identified later in this section.

4.17 In the design of the simulation platform, the information acquired by downstream entities is mainly material and capacity availability information from their suppliers. The information acquired by an upstream entity is information about customer demand and orders. The depth of information penetration can be specified in various degrees, e.g., isolated, upward one tier, upward two tiers, downward one tier, downward two tiers, and so forth.

4.18
The obtained capacity and material information from suppliers is used to estimate the due dates of incoming orders, which are the basis for generating build plans or re-ordering schedules. The obtained customer demand information is used to estimate the demand for the next period, so that the production or re-ordering schedules can adapt to external demand.

4.19

Demand management policies, such as make-to-order (MTO), make-to-stock (MTS), and assembly-to-order (ATO) have their characteristics and application situations described in Table 3 (Lin, 1996; McCutcheon, Amitabh and Meredith, 1994).

<table>
<thead>
<tr>
<th>Policies</th>
<th>Characteristics</th>
<th>Application Situations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make-To-Order (MTO)</td>
<td>Production is triggered by customer orders.</td>
<td>High customization pressure but low responsiveness.</td>
</tr>
<tr>
<td>Assembly-To-Order (ATO)</td>
<td>Final assembly is order-driven, but the component parts are forecast-driven and built to stock.</td>
<td>High customization pressure, high responsiveness, and products with late differentiation.</td>
</tr>
<tr>
<td>Make-to-Stock (MTS)</td>
<td>Production is triggered by inventory replenishment points.</td>
<td>Low customization pressure.</td>
</tr>
</tbody>
</table>

4.20

If the amount of customization is low, the firm can usually employ a make-to-stock approach and then use inventories of finished goods to provide short lead times. For products with high customization, the make-to-stock strategy cannot efficiently and effectively match customer preferences. If customers are willing to wait for customized products after submitting orders, the make-to-order strategy can be applied to high-customization firms. When the product design allows the product differentiation stage to occur late enough in the production process, the firm can employ an assembly-to-order approach.

4.21

The experiments were designed to test two hypotheses. The first hypothesis (H1) relates to identifying the best demand management policy for divergent assembly supply chains. An ATO demand management policy should result in the best supply chain performance because divergent assembly supply chains are associated with late product differentiation in an environment where product variations are not small and efficient matching of assembly to demand is essential given the short length of product life cycles.

H1.

An ATO demand management policy results in the best divergent assembly supply chain performance when compared to MTO and MTS.

4.22

The second hypothesis (H2) relates to the importance of demand information sharing. Demand information should be critical because divergent assembly supply chains have a primary business
objective of product customization to fulfill customer orders in an environment where product variations are not small.

H2.

Demand information sharing is critical to divergent assembly supply chain performance.

4.23

The results from evaluating various information-sharing strategies under these three types of demand management policies in the Type II SCN are shown in Figures 4 and 5. The three information sharing strategies are (1) no information sharing, (2) supply information sharing, and (3) supply and demand information sharing. The three demand management policies are listed were listed above.

4.24

From Figure 4 we see that cycle time is stable for MTO and ATO policies as more information is shared. From Figure 5 we see that the same is true for inventory costs for MTO policies. ATO policies result in lower inventory levels when supply and demand information is shared. The addition of demand information is critical. This supports H2. Cycle time and inventory costs are stable for MTS policies when supply information is shared, but when demand information is added, cycle time increases, but inventory costs decline. From the figures we clearly see the tradeoff between cycle time and inventory costs in Type II SCNs. In a Type II SCN, the number of shared components and the range of product variations are higher than in Type I SCNs. Based on our findings, we feel that the best demand management policy is ATO. This supports H1. It results in reasonable cycle times and lower inventory levels. Information can substitute for inventory when a SCN faces a market with high product variations. Indeed, we have seen this ATO strategy implemented in some typical Type II SCNs, such as those in the PC industry.

![Figure 4 OFP Improvement in Order Cycle Time Reduction Using Various Information Sharing Strategies in a Type II SCN](http://jasss.soc.surrey.ac.uk/1/2/5.html)
This study provides two sets of conclusions related to both the feasibility of multi-agent systems as a decision support tool for supply chain managers as well as supply chain performance enhancements arising from information sharing. It is apparent that computational modeling can be feasibly used to simulate order fulfillment in supply chains. It incorporates the major components of the supply chain including its actors, activities, interdependencies and goals. It also enables supply chain managers to identify the impact of various decision-making scenarios on performance measures such as cycle time and inventory levels to accomplish their overall objective. This is a first try at decision support for supply chain managers, but it is apparent that it has many potential applications. This model provides a basis for modeling more complex supply chain issues such as negotiation between supply chain partners (the market mechanism), and power differentials between supply chain partners.

We can also draw conclusions from our simulation results. In Type II (divergent assembly) supply chains, supply chain management is most effective when using an assembly-to-order (ATO) demand management policy coupled with sharing of both supply and demand (forecast and order) information. This supports both \( H_1 \) and \( H_2 \). Inventory costs are reduced while cycle times remain relatively stable. These specific findings produce some interesting overall conclusions. The findings from these experiments enhance the assertion that information technology is important for supporting the order fulfillment process in supply chain networks. We can draw a common conclusion that information can substitute for inventory.

Figure 5 OFP Improvement in Inventory Cost Reduction Using Various Information Sharing Strategies in a Type II SCN

Conclusions

5.1
This study provides two sets of conclusions related to both the feasibility of multi-agent systems as a decision support tool for supply chain managers as well as supply chain performance enhancements arising from information sharing. It is apparent that computational modeling can be feasibly used to simulate order fulfillment in supply chains. It incorporates the major components of the supply chain including its actors, activities, interdependencies and goals. It also enables supply chain managers to identify the impact of various decision-making scenarios on performance measures such as cycle time and inventory levels to accomplish their overall objective. This is a first try at decision support for supply chain managers, but it is apparent that it has many potential applications. This model provides a basis for modeling more complex supply chain issues such as negotiation between supply chain partners (the market mechanism), and power differentials between supply chain partners.

5.2
We can also draw conclusions from our simulation results. In Type II (divergent assembly) supply chains, supply chain management is most effective when using an assembly-to-order (ATO) demand management policy coupled with sharing of both supply and demand (forecast and order) information. This supports both \( H_1 \) and \( H_2 \). Inventory costs are reduced while cycle times remain relatively stable. These specific findings produce some interesting overall conclusions. The findings from these experiments enhance the assertion that information technology is important for supporting the order fulfillment process in supply chain networks. We can draw a common conclusion that information can substitute for inventory.

5.3
Finally, supply chain management involves a fundamental tradeoff between cycle time, inventory and information. In many cases information can replace inventory while maintaining acceptable cycle times. In the past, when information costs were high, inventory was held to manage uncertainty. Today, when information technology continues to reduce information costs, uncertainty can be reduced resulting in lower inventory requirements. Our results illustrate some of the potential impacts of the electronic integration effect (Malone, Yates and Benjamin, 1987). The benefits that we illustrate related to this effect are that supply chain managers may reduce cycle time or inventory costs (or possibly both) because of reduced uncertainty in decision making. This is possible because IT (incorporated into electronic hierarchies) reduces coordination costs. The development of an analytical model to describe this tradeoff is an issue that should be addressed by future research.

References


