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USING AGENT TECHNOLOGY TO SUPPORT SUPPLY CHAIN MANAGEMENT: POTENTIALS AND CHALLENGES

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Using Agent Technology to Support Supply Chain Management: Potentials and Challenges

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Abstract

The focus of supply chain management has been shifted from production efficiency to customer-driven and partnership synchronization approaches. To implement this strategic shift requires high-level collaboration between supply chain partners. Software agent technology will have great potential in supporting collaboration in supply chain management. In this paper, we review the trend of supply chain management and analyze how agent technology can be applied to support collaboration in information sharing, operation cooperation, and dynamic chain configuration. We also review existing agent systems that support supply chain management at operational and strategic levels. Finally, we analyze the limitations of the agent approach and suggest future research directions.

Key words: Intelligent agent, supply chain management, agent collaboration, agent negotiation, multi-agent system

1. Introduction

Today, business competition is no longer company vs. company but supply chain vs. supply chain. A supply chain is a network of suppliers, factories, warehouses, distribution centers and retailers, through which raw materials are acquired, transformed, produced and delivered to the customer. A supply chain is a dynamic process and involves the constant flow of information, materials, and funds across multiple functional areas both within and between chain members (Umeda and Jones, 1998; Chopra and Meindl, 2001). Member enterprises in the chain need to cooperate with their business partners in order to meet customers' needs and to maximize their profit. Managing multiparty collaboration in a supply chain, however, is a very difficult task because there are so many parties involved in the supply chain operation, each with its own resources and objectives. There is no single authority over all the chain members. Cooperation is through negotiation rather than central management and control. The interdependence of multistage processes also requires real-time cooperation in operation and decision-making across different tasks, functional areas, and organizational boundaries in order to deal with problems and uncertainties. The strategic shift of focus for mass customization, quick response, and high quality service cannot be achieved without more sophisticated cooperation and dynamic formation of supply chains.

Many information systems have been developed for supply chain management (SCM) from EDI and ERP, to newly developed SCM systems and e-Business solutions. Recently, the use of intelligent agents for supply chain management has received great attention in academic research. Agent technology is the preferable technology for enabling a flexible and dynamic coordination of spatially distributed entities in supply chains. This technology changes the metaphor for human-computer interaction from direct manipulation by the user to indirect management of background agent processes because intelligent agents can autonomously perform a lot of coordination and everyday tasks on behalf of their users (Fischer et al. 1996). Although many research papers have been published and many promises have been made, we do not have a framework to understand what is the right role that the agent technology could play in SCM and what are the major problems and issues we have to solve for the success of applying agent technology in the real world of SCM.

The objective of this paper is to identify the potentials and challenges of using agent technology to support supply chain management. The remaining paper is organized as follows. The new trend of SCM and the importance of collaboration are highlighted in section 2. The niche of agent technology is identified based on the analysis of existing information technologies for SCM in section 3. The rationale of using agent systems to support SCM is discussed in section 4. The types of agent support for collaboration in SCM are investigated in section 5. The proposed agent systems for SCM at different levels are reviewed in section 6. The limitations of agent approach and issues for further research are analyzed in section 7. Finally, the conclusion is made in the last section.

2. The new trend in supply chain management

A few years ago, supply chain management was understood as "logistics" management. But logistics is just one important function in the development of an effective supply chain management program. Supply chain management, as we have come to know, emphasizes the important linkages between the manufacturer and the distributors as well as the customers. Supply chain management encompasses the management of material, information, and funds from the initial raw material supplier to the ultimate end user. The key to genuine business growth is to emphasize the creation of an effective supply chain with trading partners, while at the same time maintaining a focus on the consumer. Today, instead of simply focusing on reducing cost and improving operational efficiency, more efforts are put on customer satisfaction and the enhancement of relationships between supply chain partners. This trend is discussed in detail in the following sections.

2.1 Customers are now in charge: Converting Supply Chains into Demand Chains

It is important to recognized that supply chain power has shifted from manufacturer to retailer, and finally to consumer (Blackwell and Blackwell 2001). In the 1980s and early 1990s, the focus of many companies was to reengineer the supply chain for cost saving. As we enter the 2000s, customers have become increasingly demanding. They expect greater customization, higher quality not just in the product itself, but also in delivery and packaged services (Anderson and Lee, 1999). The most pressing issue facing modern business is about delivering value to the customer – what they want, when and where they want it, and at the lowest possible price (Kalakota and Robinson, 2001). Consumers will be in charge of supply chains and will dictate how business is done in the future.

Blackwell and Blackwell (2001) use the name of "demand chain" to emphasize the customer-driven nature of supply chains. A demand chain represents a circular process that flows from the mind of the consumer to the market. It goes beyond the physical distribution boundaries of supply chain management. Demand chains seeks to unite channel members with the common goal of "delighting" customers and solving consumer problems by:

- Gathering and analyzing knowledge about consumers, their problems, and their unmet needs.
- Identifying partners to perform the functions needed in the demand chain.
- Moving the functions that need to be done to the channel member that can perform them most effectively and efficiently.
- Sharing with the other chain members knowledge about consumers and customers, available technology, and logistics challenges and opportunities.
- Developing products and services that solve customers' problems.
- Developing and executing the best logistics, transportation, and distribution methods to deliver products and services to consumers in the desired format.

2.2 Developing synchronized relationships among supply chain partners

As pointed out by Anderson and Lee (1999), the supply chain as a concept and a reality is moving far beyond the confines of an individual organization. It has become a dynamic process that involves the simultaneous acquisition and continuous reevaluation of partners, technologies, and organizational structures. The key concept of a Synchronized Supply Chain strategy is helping people adapt to the new operating realities of cross-supply chain partner collaboration. A Synchronized Supply Chain strategy, with its inherent focus on web-enabled collaboration among supply chain partners, is emerging as a major driver of long-term competitive advantage for pioneering globally aligned companies.

The overall objective of synchronized supply chain initiatives is to make it more profitable for all the parties involved. This is not a "zero-sum game." Supply chain partners need to evaluate their relative strengths and capabilities openly and critically. An implicit requirement is to "open the books" of a firm to managers outside the corporate boundaries so that cross-company and cross-functional teams can analyze cost structures and performance metrics. Trust is the key component if supply-chain partners want to collaborate strategically, rather than only at a tactical level.

A Synchronized Supply Chain strategy requires collaborative planning and execution. Collaborative demand planning is accomplished by allowing order and market information to flow upstream continuously from the point of sale, while information on product availability and inventory levels flow downstream. Collaborative order fulfillment transfers inventory ownership from the customer to the supplier, allowing customer demand data to directly drive orders. Joint capacity planning involves joint coordination on medium to long-term material and capacity issues. Joint venture allows the sharing of risks and rewards among partners. Synchronized supply chain strategies require coordinated cross-functional decision-making throughout the entire supply chain.

All of these initiatives require various types of cooperative relationships among the supply chain partners, ranging from transactional to interactive and interdependent. Transactional relationships do not require much shared information or decision making. Interactive relationship requires shared information, some joint planning and some shared decision-making. Interdependent relationships require deeper cooperation, the willingness and capacity to learn new skills, and varying degrees of trust. In this case, the boundaries between companies become blurred; information (proprietary or otherwise) is shared extensively, as are decisions, investments, and assets. In fact, most companies that are not near this level of cooperation today would require radical transformation to achieve a successful relationship with multiple partners (Anderson and Lee 1999).

3. The evolution of information technology for supply chain management

Information is the key to the success of a supply chain because it enables management to make decisions over a broad scope that crosses both functions and companies (Chopra and Meindl 2001). There are different information systems to support SCM from early less-sophisticated legacy systems to more advanced SCM systems (see Table 1 for summery).

Table 1: Summary of Information Systems for SCM

Systems	Objectives and functions	Limitations
Legacy systems	Transaction process for isolated functions such as order entry, inventory control, or accounting	Lack of integration between functional areas
Electronic Data Interchange (EDI)	Electronic data interchange between trading partners	Only exchange transaction data with pre-arranged partners
Enterprise Resource Planning (ERP)	Integrate functional areas within enterprise at the operational level	Intra-enterprise focus, weak analytical capabilities
Supply Chain Management (SCM) systems	Analytical tools for advanced planning and strategic decisions in SCM	Lack of integration with ERP system
Business-to-Business (B2B) and Business-to-Consumer (B2C) electronic commerce	Electronic marketplace that enables business transaction with customers and suppliers through Internet	Lack of intelligent support for business collaboration through Internet
Multi-Agent System	Support and automate collaboration in SCM	Only in the research stage

In the past, mainframe-based legacy systems were used to support transactional processes within a department such as order entry, inventory control, and accounting.

These transaction processing systems were isolated and implemented using incompatible hardware and software. There was lack of integration across functional areas even within a single company.

Electronic Data Interchange (EDI) helped to link computer applications across organizational boundaries at the transaction level by electronically exchanging transaction data without the need for human intervention. It reduced transaction cost, increased accuracy, and increased responsiveness. It made new ideas such as just-in-time delivery and vendor managed inventory possible. Traditionally, EDI was implemented through value-added networks (VAN) or private wide-area networks that were too expensive for small or medium-size enterprises to implement. Recently, Internet-based EDI makes it possible to link all the suppliers and to gain the benefit of 100% EDI compliance for all the supply chain members (Johnston and Mak, 2000). EDI, however, does not readily provide high-level information and knowledge exchange for high-level business collaboration.

Enterprise Resource Planning (ERP) systems monitor material, orders, schedules, finished good inventory, and other information throughout the entire organization. They help to integrate all the functional areas within an enterprise. They also help companies in their effort of business process reengineering (Evans et al. 1995). Since the information processes across functional areas within the enterprise are now integrated, it provides a much better base for inter-enterprise cooperation. However, since the main focus of ERP is limited to intra-enterprise operation, there is lack of support for inter-enterprise collaboration in SCM. It is difficult to directly connect different ERPs made by different vendors.

Recently, Supply Chain Management Systems (or Analytical Application Systems) have been developed by vendors such as i2 (http://www.i2.com) and Manugistics (http://www.manugistics.com). They provide analytical applications for production scheduling, manufacturing planning, transportation planning, demand planning, and revenue management in order to optimize the use of supply, manufacturing, distribution, and transportation resources to meet the demand. They use sophisticated algorithms and rely on the inputs of transactional data collected from legacy or ERP systems (Chopra and Meindl, 2001). Since their main focus is on analysis, there is still a need to have a system to put the analysis into action through multiparty collaboration.

The rapid growth of Internet and web technology promoted electronic commerce and provided great potential for networking and interaction between business and consumer (B2C) and between business partners (B2B). The main focus of electronic commerce is on creating an electronic marketplace between buyers and sellers. It can allow customer self-service for information searches, product selection and ordering, online delivery of digital products and services, and mass customization. It can enable information sharing and coordination among suppliers, manufacturers, distributors, and consumers through the Internet or extranets (Gaines et al. 1995). It can also be used to create electronic marketplaces for online biding and auctions for business competition

(Emiliani 2000). Electronic commerce or what is more recently termed e-business can enable strategic change in SCM with new business models such as customer driven, virtual enterprise, des-intermediary, and new electronic market. Since the World Wide Web was originally designed for manual access, business coordination through Web access or email is labor intensive. It is clear that we need support for high-level knowledge sharing (not just transaction data) and more robust business collaboration (not just simple buy and sell models) through the Internet.

Recently, intelligent multi-agent systems have shown great promise for supporting supply chain management in today's Internet environment. However, they are still in the early stage of research. We will discuss them in detail in the next two sections in order to have a better understanding on why they are suitable for supply chain management and what roles they can play.

4. The rationale of adopting agent technology for supply chain management

Agents are automated software entities operating through autonomous actions on behalf of the user – machines and humans. They are able to interact with other agents reactively or proactively without constant human intervention. The central idea underlying agents is that of delegation. The owner or user of an agent delegates a task to the agent and the agent autonomously performs the task in behalf of the user. Alternatively, a business agent may decompose the task and delegate parts of it to other agents, which perform the subtasks and report back to the agent. The agent must be able to communicate with the user or other agents to receive its instructions and to provide results of its activities (Papazoglou 2001).

Agents can communicate and interact with each other through communication networks. Mobile agents may also travel from one place to another place to collect and process information and send the results back. These mobile agents provide an innovative concept for creating distributed systems -- they bring the computation to the data rather than the data to the computation. They can reduce network load, overcome network latency, encapsulate protocols, work autonomously and asynchronously, and adapt dynamically. They are also robust and fault-tolerant to changing environments (Schoder and Eymann, 2000).

Agents can exhibit some degree of artificial intelligence. They can autonomously perform tasks in an open environment. Intelligence is the amount of learned behavior and possible reasoning capacity that an agent may possess. At the most basic level, the agent may follow a set of rules that are predefined by the user. The agent can then apply these rules to respond to the environment. The most intelligent agents will be able to learn, and will be able to adapt to their environment, in terms of user requests and the resources available to the agent (Papazoglou, 2001). The key aspects of intelligent agents are their autonomy, their ability to perceive, reason, and act in their surrounding environments, as well as the capability to cooperate with other agents to solve complex problems (Jennings and Wooldridge, 1998).

A multi-agent system consists of a group of agents that can take specific roles within an organizational structure. Different types of agents may represent different objects, with different authority and capability, and perform different functions or tasks. They can be dynamically organized based on a control or connection structure. A multi-agent system can be defined as a loosely coupled network of problem solvers that interact to solve problems that are beyond the individual capabilities or knowledge of each problem solver (Durfee and Lesser 1989). Important characteristics of a multi-agent system are that:

1) each agent has incomplete information or capabilities for solving the problem and thus has a limited viewpoint;
2) there is no system global control;
3) data are decentralized; and
4) computation is asynchronous (Sycara, 1998).

Most research on multi-agent systems focus on the coordinative intelligent behavior among a collection of autonomous intelligent agents. The step from isolated single-agent scenario to open multi-agent systems offers the new quality of emergent behavior: the group of agents is more than the sum of the capabilities of its members (Fischer et al. 1996).

Three important domain characteristics are often cited as a rationale for adopting agent technology (Bond and Gasser, 1988):

1) Data, control, expertise, or resources are inherently distributed
2) The system is naturally regarded as society of autonomous cooperating components, or
3) The system contains legacy components, which must be made to interact with other, possibly new software components.

Supply chain management by its very nature has all the above domain characteristics. A supply chain consists of suppliers, factories, warehouses, distribution centers and retailers, working together to convert raw materials to products and delivered to the customers. Parties involved in the supply chain have their own resources, capabilities, tasks, and objectives. They cooperate with each other autonomously to serve common goals but also have their own interests. A supply chain is dynamic and involves the constant flows of information, materials, and funds across multiple functional areas both within and between chain members. There are already a variety of information systems and networks working within and between chain members to facilitate the flows of materials, information and funds. However, there is lack of coordination and integration between these systems. Agent technology therefore is very suitable to support collaboration in supply chain management.

Intelligent agent systems can be used to model or actually perform tasks in supply chain management due to the similarities of the nature of these two systems shown in Table 2.

Table 2. Similarities between SCM and Multi-Agent System

Nature of Supply Chain Management	Nature of Multi-Agent Systems
A Supply Chain consists of multiple parties working on multi-stage tasks.	A multi-agents system consists of different types of agents with different roles and functions.
Each entity in a supply chain has its own objectives, capabilities, performs certain tasks, and follows certain business rules.	Agents have their own objectives, resources, tasks, and decision rules specified by the user they represent.
There is a need to coordinate material, information, and financial flows between and among all the participating entities.	Agents coordinate with each other through communication and interaction with each other in a network.
Information is distributed. Each entity has incomplete information. Information need to be shared across organizational, functional and system boundaries.	Agents can communicate with human, with other information system, and with other agents. They can share information and knowledge through message exchange between agents.
There is no single authority. Knowledge is distributed among members in supply chain. Decision making in Supply Chain is through multiparty negotiation and coordination.	Agents are autonomous. They are responsive to monitor changing environment, proactive to take self-initiated action, and social to interact with human and other agents.
Learning and reasoning is needed for supply chain members to make individual or joint decisions for operation and planning.	Intelligent agents are capable of reasoning based on the rules given by the user or knowledge learned from an open environment.
The structure of the supply chain is flexible. It can be organized differently to implement different strategies.	Agent system is flexible. Agents can be organized according to different control and connection structures.
Tasks in supply chain can be decomposed to subtasks or multiple tasks can be composed to a large function.	Agent can delegate its task to other agent or coordinate other agents' tasks to form a higher level system.
Supply chain is dynamic. Entities may join or leave a supply chain.	Agents can be created or discarded from a multi-agent system.

5. Using agent technology to support collaboration

Collaboration is a key success factor for supply chain competitiveness. A supply chain may involve hundreds or thousands of parties working through multiple stages from order taking, manufacturing, to delivery goods and services. It requires that parties at all stages of the chain take actions that together increase total supply chain profits. A lack of coordination occurs either because different stages of supply chain have objectives that conflict or because information moving between different stages becomes distorted (Lee et al. 1997). The fundamental challenge today is for supply chains to achieve coordination in spite of multiple ownership and increased product variety (Chopra and

Meindl, 2001). Collaboration in supply chains may work at different levels ranging from collaborative information sharing, collaborative operation, to collaborative configuration. We summarize how agent technology can be used to support different levels of collaboration in Table 3 and discuss the details in the following subsections.

Table 3. Agent support for collaboration

Collaboration Requirement	**Supporting Agent**
Collaborative Information Sharing • Posting • Searching • Cross boundary communication • Access control	 • Yellow page agent • Searching agent • Interface agent • Authorization agent
Collaborative Operation • Monitoring • Exception handling • Synchronization • Optimization	 • Supervision agent • Diagnosis agent • Scheduling agent • Optimization agent
Collaborative Configuration • Searching partners • Matching buyers with suppliers • Biding and auction • Contract negotiation	 • Searching agent • Matchmaker agent • Bidding and auction agent • Negotiation agent

5.1 **Collaborative information sharing**

Information sharing is the first requirement for collaboration. In a supply chain, information is often distributed and controlled by different entities. There is no single information source available for every one in a supply chain. Information sharing in a distributed environment requires for parties to determine what information should be shared, where the information is located, and how to access it across system and organizational boundaries. Information sharing between partners in a supply chain may take place at different levels from transaction processing to operation, planning and decision-making. Varying levels of information sharing may have different impact on improving operational efficiency, reducing inventory cost, and change the competitive position and bargaining power between suppliers and buyers (Seidmann and Sundararajan 1998).

Routine transactional information can be exchanged automatically through EDI and public reference information can be published through the web. However, the high-level information and knowledge sharing required for business coordination may be a candidate for support from agent technologies. For instance, if, for some reason, a supplier cannot deliver specific parts on time or meet the quality standard, this information should be shared by the assembly line to change the production schedule and by other affected part suppliers to adjust their delivery time or provide alternative parts. This type of exception information sharing now is predominantly done manually through human interaction. An intelligent agent may automatically discover the situation and deliver the information to the right parties according to its knowledge for a quicker reaction. As another example, in airline customer service, an agent can be set to automatically notify affected passengers if a flight will be delayed. More advanced agents may search for available alternative connections from other collaborative airline companies for each affected passenger. For consumer's convenience, the messages sent to passengers may be customized based on passenger's preferred language and sent though the communication channel they pre-specified.

Agent technologies can be used to facilitate and control the scope, the time, and the frequency of information sharing based on specific arrangement and possible impact on each partners. Yellow page directory agents provide information on what agent can be contacted for information. Information for sharing may be posted on a blackboard agent or delivered to relevant entities through a broadcasting agent. Searching agents can proactively search various information sources according to user's needs, to monitor theses sources for new changes, and integrate information from various sources into a consistent set of results to be reported to the user. Information sharing can also be automated through communication and interaction between a requesting agent and a responding agent after appropriate arrangements have been made for authorization, security and privacy protection. Since agents can communicate with humans, with legacy systems, or with other agents, they can be used as a communication interface across a variety of boundaries. For instance, translation agents can be used to overcome language boundaries, authorization agents can be used to overcome functional and organizational boundaries, interface agents can be used to overcome system boundaries, and the use of high-level agent communication languages such as KQML (Knowledge Query and Manipulation Language) (Finin and Labrou 1997) can be used to cope with knowledge communication problems. Since agents are used for knowledge sharing and not just data sharing, how to make sure agents understand each other is a big challenge. This will be discussed later as the ontology problem.

5.2 **Collaborative operation**

Due to a variety of uncertainties, the smooth operation of a supply chain requires real-time collaboration between chain members in an ever-changing environment. Partners in a supply chain cooperate with each other often based on contract or agreement with underling short or long-term relationships. Contracts only provide some basic guidelines for business cooperation, their execution needs to be monitored and reinforced. Supervision or monitoring agents can be set up to interpret and reinforce the agreement specified in contract and to monitor the performance of the execution such as the promptness of delivery or the compliance to a quality standard. For a Fortune 1000 company that is managing anywhere between 20,000 and 40,000 contracts, using agents to monitor contract execution would be a great savings.

Since the supply chain operation is very complex, there are always uncertainties, exceptions, or problems. Exception handling agents should be able to detect the problem, collect the necessary information, and deliver the warning information to the affected entities for appropriate action. To make coordinative action such as synchronizing the production schedule, agents should be able to negotiate with other agent to resolve conflict and to make appropriate adjustment through real time scheduling. In order to improve competitiveness not from individual company perspective but from the entire supply chain perspective, long-term profit sharing may need to be arranged and global optimization and cooperative planning can be introduced by integrating agents that dynamically collect data from individual agents, analyze the situation, forecast the long term impact and suggest the course of action to all related agents. Due to the complexity of optimization, agents may invoke analytical systems to do the job rather than do it by itself. Agents that perform cost and profit sharing analysis may also provide incentives for coordination. An example of cooperation in a fresh food supply chain can be the management of "cold chain" in which temperature is monitored for freshness from the day the produce is picked, distributed, put on the retail shelf, until it is brought home by consumers (Anderson and Lee 1999). In each stage the risk and cost of maintaining the temperature range will be calculated to maximize the performance of the "cold chain".

5.3 Collaborative configuration

In order to quickly respond to customer demand and effectively utilize resources, it is important to support the online formation of supply chains or "virtual enterprises". The process of supply chain configuration should be viewed as a cross-enterprise exercise. The key outcomes should be twofold: identifying the best options to deliver product to consumers cost effectively and determination of which corporate entities are most capable of taking ownership of specific processes and activities (Anderson and Lee 1999). Search agents can help to search potential partners through electronic markets. Matchmaker agents (Gil and Ramachandran 2001) can help to match buyers with suppliers based on mutual interests and capabilities. Auction agents can help to select partners through biding or auction. Negotiations are often needed to set up contracts or agreements that guide the collaboration between parties involved, such as liabilities, terms of payments, delivery instructions, return policies, and dispute resolution methods. Negotiation agents may negotiate with each other through a series of message exchanges following formalized negotiation protocols such as "request proposal", "proposal", "accept-proposal", "reject-proposal", etc. The negotiation decision may be made based on pre-specified rules and negotiation strategies (Faratin et al. 1997). An agent may offload some of its tasks to other agents when the tasks cannot be perform by the agent itself, or may be performed more efficiently by other agents (Sandholm, 1999). A self-motivated agent may convince another self-motivated agent to help it with its task, by promises of rewards, even if the agents are not assumed to be benevolent (Kraus 1996). More advanced persuasive negotiation agents may have their beliefs, desires, intentions, and goals. Through argumentation, negotiation agents persuade each other and bring about a change in intentions and achieve cooperation and agreements (Kraus et al. 1998).

Agents may also use multiple negotiation tactics and adapt their negotiation behavior through reinforced learning (Cardoso et al. 1998). At this point, we should be aware that negotiation agents are still in the early stage of research, they are not practical in the real world yet.

In this section we discussed individual tasks that agents may be able to do to support collaboration. In the next section, we review the agent systems that support SCM at different levels.

6. Agent Systems that support supply chain management at different levels

Agent technology has much to offer with respect to the operation of a supply chain. Agents can provide automated and customized services to customers from ordering to delivery through the entire supply chain. Through information sharing, agents can help ensure accurate configuration, check the progress of production, schedule delivery, and respond to customer change requests. The support of complex operational functions by autonomous agents (e.g., production planning) enables direct horizontal coordination of operational functions that are geographically distributed along a supply chain. It also supports the handling of exception workflow, i.e. unexpected events such as machine breakdown, delays, or expedited orders. Thus, local exceptions can often be treated locally without global re-planning, and the necessary coordination processes can be implemented by direct interactions among the agents representing the involved operational functions. Other than supporting the operation of supply chains, agent-based systems are also utilized as a modeling tool to study the impact of different SCM strategies and policies. In the following Table 4, we review several proposed multi-agent systems for supply chain management. They may have different focuses but the basic underling principles are similar.

Table 4. Groups of proposed agent systems for SCM

General framework for Integration and Cooperation	
• Integrated Supply Chain Management (ISCM)	• Fox et al. (1993)
• Mediator Agent for Enterprise integration (MetaMorph II)	• Shen and Norrie (1998)
• Collaborative Agent System Architecture (CASA)	• Shen et al. (1999)
Agent Systems with specific focus	
• Virtual Manufacturing-based Sales Agent	• Choi et al. (2000)
• Mobile Agents for Supervision	• Rabelo and Spinosa (1997), Brugali et al. (1998)
• Dynamic Scheduling	• Sousa and Ramos (1999), Caridi and Sianesi (2000)

Supply Chain Formation • Forming a supply chain through task subcontract auction • Forming a virtual chain as distributed constraint satisfaction problem	• Walsh and Wellman (1999) • Chen et al. (2000)
Agent-based modeling and simulation • Modeling Supply Chain Dynamics • Modeling Order Fulfillment Process	• Swaminathan et al (1998) • Lin and Shaw (1998)

6.1 General framework for Integration and Cooperation

Three general frameworks have been proposed to build multi-agent systems for SCM integration and cooperation. They provide different organizational and functional structures.

Integrated Supply Chain Management. Fox et al (1993) may be the first to propose organizing the supply chain as a network of cooperative intelligent agents. In the integrated supply chain management project (ISCM), each agent performs one or more supply chain functions and coordinates its decisions with other relevant agents. There are two types of agents: functional agents and information agents. Functional agents (including order acquisition agent, logistics agent, scheduling agent, resource agent, dispatching agent and transportation agent) plan and/or control activities in the supply chain. Information agents support other agents by providing information and communication services. The ISCM project addresses coordination problems at the tactical and operational levels. The agent view provides a level of abstraction at which we construct computational systems (agents) that inter-operate globally across networks linking people, organizations, and systems on a single virtual platform (Fox et al. 1993).

Mediator Agent for Enterprise Integration. The MetaMorph II project (Shen and Norrie 1998) developed at the University of Calgary uses a hybrid agent-based mediator-centric architecture to integrate the manufacturing enterprise activities such as design, planning, scheduling, simulation, execution and product distribution with those of its suppliers, customers and partners into an open, distributed environment. In MetaMorph II, agents can be used to represent manufacturing resources (machines, tools, parts, etc.), to encapsulate existing software systems, to function as system/subsystem coordinators, and to perform one or more supply chain functions. They are dynamically connected via the Internet and/or intranets through their respective mediators. Mediators are also agents that provide message services and promote cooperation among intelligent agents. There are four types of mediators. The Enterprise Mediator serves as the administration center of the manufacturing enterprise. The Design Mediator is used to integrate a feature-based intelligent design system. The Resource Mediator is used to coordinate an agent-based dynamic manufacturing scheduling subsystem. The Marketing

Mediator is used to integrate the customer services into the system. A prototype has been developed on a PC network in the form of a simulation.

Collaborative Agent System Architecture. Recently, Shen et al. (1999) propose a Collaborative Agent System Architecture (CASA) in a complex supply chain network. The system is composed of collaborative elements classified as agents, local area coordinators, yellow pages, and cooperation domain servers. The objective of the CASA work is to support collaborative software agents by providing easy-to-use domain independent communication and cooperation services over the Internet. These services include conversation messaging services, lookup and search services, and remote call services. The provision of these services should significantly reduce the complexity of developing systems of collaborative agents.

6.2 Agent Systems with specific focus

In addition to agent systems for general usage, other agent systems have been proposed for specific purposes such as sales, supervision, and scheduling.

Virtual Manufacturing-based Sales Agent. Choi et al (2000) propose a virtual manufacturing-based sales agent (VMSA) with multi-agent architecture to support the sales activity for parts manufacturers in an Internet environment. The sales activity of most parts manufacturing companies is originated from orders of buyers. On deciding whether to accept an order or not, as well as negotiating with buyers, sales persons need information such as load and schedule of production lines, and manufacturability of the order. Manufacturability analysis, process planning, and scheduling are therefore key features in developing an agent of sales activity for the parts manufacturing business. The process of promotion, receipt, and selection of orders of the parts manufacturers is closely coupled with the load status of the production lines.

Mobile Agents for Supervision. Rabelo and Spinosa (1997) propose to implement a virtual enterprise by allowing a coordinating mobile agent to supervise at each supplier side. The mobile agent would be connected to the supplier's internal legacy system and would perform tasks such as monitoring a machine, getting some information from the local database, triggering some local reasoning process, inquiring or negotiating with a user or subsystem, or remotely communicating with the enterprise. Brugali et al. (1998) also propose applying mobile agent technology to implement supply chain networks. This work primarily addresses coordination problems at the tactical and operation levels.

Dynamic Scheduling. Sousa and Ramos (1999) propose using a multi-agent system for dynamic scheduling of a manufacturing system. It dynamically assigns the resources of the manufacturing system to the required tasks. Whenever exceptions appear, renegotiations between agents are involved to handle temporal constraints and scheduling conflicts. The approach assumes that deadlines are the most important constraints to consider. Thus, the acceptance or refusal of a resource of a specific task depends on the capability of executing the operation within the specified deadline. Caridi and Sianesi (2000) also apply a multi-agent system for the scheduling of mixed-model assembly lines. By leveling the load of the workstations, production smoothing allows a more regular material flow, shorter manufacturing lead times, and lower work in process inventories. The experimental results show that this innovative approach has good performance compared to traditional approaches.

6.3 Supply Chain Formation

Most proposed agent systems are oriented towards maintaining pre-existing relationships in the supply chain. However, it is important to support the vision of dynamically forming and dissolving business interactions (e.g. "virtual corporations"). We review two systems that both use agent negotiations to dynamically form a supply chain but with different approaches and criteria.

Forming a supply chain through task subcontract auction. Walsh and Wellman (1999) propose using negotiation agents to form a supply chain in a task dependency network. Agents have specialized capabilities and can perform only certain combinations of tasks or produce certain resources. In order to complete a complex task, an agent may delegate subtasks to other agents, which may in turn delegate further subtasks. Resource contention is used to constrain the set of feasible supply chain allocations and the optimal allocation is one of the feasible allocations that maximize the value of the supply chain such as the sum of total consumer value minus the total supplier cost. Agents negotiate through simultaneous, ascending auctions for each good or task to form a supply chain in the task dependency network. However, due to the computational complexity and the nature of distributed decision-making, the solution generated through agent negotiation may not necessarily be optimal.

Forming a virtual chain as distributed constraint satisfaction problem. Chen et al. (2000) propose a negotiation-based multi-agent system for supply chain formation. In their framework, functional agents are used to represent companies with their own interests and may join in, stay, or leave the system according to their own judgment. When an order arrives, a virtual supply chain may emerge from the system through automated or semi-automated negotiation processes between agents. The negotiation process is modeled by using Colored Petri Nets (CPN) and the virtual chain can be established by solving a distributed constraint satisfaction problem.

6.3 Agent-based modeling and simulation

Simulation provides an effective pragmatic approach to detailed analysis and evaluation of supply chain design and management alternatives. However, building a supply chain model is a very difficult and time-consuming task. Multi-agent systems can be used as a very natural and powerful tool to model supply chain management. Through simulation, the model can be used to study the dynamic behavior of a supply chain with different structures and management strategies.

Modeling Supply Chain Dynamics. Swaminathan et al (1998) propose a multi-agent framework for modeling supply chain dynamics. Supply chain models are composed from software components that represent types of supply chain agents (such as suppliers, manufacturers, transporters, retailers, and customers), their constituent control elements (such as inventory control policy, demand control policy, supply control policy, and information control policy), and their interaction protocols (such as order messages, request for goods messages, and goods delivered messages). The underling library of supply chain modeling components provides a reusable base of domain-specific primitives that enables rapid development of customized decision support tools. This approach was used to model IBM's supply chain for improved inventory management.

Modeling the Order Fulfillment Process. Lin and Shaw (1998) used a multi-agent simulation called Swarm to model the reengineering of the order fulfillment process (OFP) in supply chain networks. Simulation was conducted to identify useful strategies for improving the OFP. Three types of supply chain networks were investigated: convergent assembly for lean production, divergent assembly for mass-customization, and divergent differentiation for quick response. The strategies evaluated included: coordinating demand management policies, information sharing, synchronizing material and capacity availability, dynamic resource allocation, and combinations of various strategies. The performance of OFP was measured by the order cycle time, the order fulfillment rate, the inventory cost, and tardiness on committed due dates. The results of the comprehensive study identified the main effects of various strategies on OFP performance.

7. Limitations of an agent-based approach for supply chain management

As we have observed, a variety of agent systems have been proposed to support supply chain management at all the levels. However, as pointed out by Jennings and Wooldridge (1998), there are a number of problems or limitations associated with the agent approach:

1) No overall system controller. An agent-based solution may not be appropriate for domains in which global constraints have to be maintained, in domains where a real-time response must be guaranteed, or in domains in which dead-locks or live-locks must be avoided.
2) No global perspective. Decision-making based on local knowledge by individual agents may lead to globally sub-optimal decisions.
3) Trust and delegation. For individuals to be comfortable with the idea of delegating tasks to agents, they must first trust them. Both individuals and organizations need to become more accustomed and confident with the notion of autonomous software components, if they are to become widely used.

These problems also exist when agent technology is applied to supply chain management.

No overall system controller. In general, a supply chain does not have an overall system controller. However, in some cases, one company may have dominant influence in supply chain coordination. For instance, Dell dominates its PC manufacturing supply chain, and mass-customization and fast delivery are crucial for its success. In this case coordination through Dell's extended ERP may be more effective. However, agent approach can still be used to coordinate under a central control. In other cases, such as in a traveling service supply chain, no one has a dominant power and coordination through distributed agent will be more appropriate.

No global perspective. It is difficult to reach global optimization through agent negotiation based on their local knowledge. However, if some profit sharing can be arranged among partners based on some overall objective, optimization algorithms can be used for planning and agents will be used to coordinate the execution based on the optimal solution with minor adjustments if necessary. If there is no profit sharing or other common goals, the sub-optimal decision is not avoidable.

Trust and delegation. Trust is probably the most difficult obstacle to overcome. However, the degree of trust also depends on the nature of the task delegated, the uncertainty and risk involved, and the degree of autonomy granted. For instance, people may trust a software agent to buy or sell a specified stock based on a set of well-specified criteria, but are less likely to trust a software agent to select and buy an unspecified stock without human approval. We should delegate suitable tasks to software agent the same way as asking an assistant to do what he or she can do for you. The trust problem exists not only between humans and agents but also between agents. A trusted certificate mechanism is needed for establishing and communicating agent trust.

While many of us are enthusiastic about the potentials of intelligent agents, we should not expect more than they are capable of delivering. There is still a long way to go to implement a truly intelligent agent application (Allen 2000). Nwana and Ndumu (1999) outline several issues, including the information discovery problem, the communication and ontology problem, the legacy software integration problem, and the reasoning and coordination problem. These issues also need to be solved before any meaningful application of agent technology in supply chain management.

Information discovery problem. Agents need to discover information in an open environment. If we ask an agent to search for a suitable supplier for a particular part or material, where is the source of the information? Although facilitator agents such as yellow page agents or directory agents may help to identify what information other agents may have, it is limited within a closed system and not for discovering external information. If we want an agent (not ourselves) to discover information on the Internet from Yahoo, then, will Yahoo provide an agent interface service ready for use? So far, most web pages are designed for manual access. It will be an important step to make Web agent-accessible through the use of Extensible Markup Language (XML) (Glushko et al. 1999) and to share the ontology with agents in important business domains (Smith and Poulter 1999).

Communication and Ontology problem. Agents need to communicate with each other at the knowledge level rather than solely at the transaction level. Suppose a supplier agent needed to tell the manufacturer agent that there is some problem associated with delivery and needed the production schedule to be adjusted. What terms should be used to make them understand each other? This is the so-called ontology problem. The ontology (or concept definition) specifies the terms each party must understand and use during communication (Nwana and Ndumu 1999). We may need to specify words to describe a delivery problem such as "delay", "cancel", "reschedule", "change amount", "change package size", as well as their true meanings. Great effort needs to be done to specify and standardize the syntax or semantics of the messages for different application domains. Progress is being made by Knowledge Sharing Effort (KSE) and the Foundation for Intelligent Physical Agents (FIPA) to address above problems. The ARPA-sponsored KSE project (http://www.cs.umbc.edu/kse/) is developing methodologies and software for the sharing and reuse of knowledge. Much of this is very relevant for building agent-based systems, such as Knowledge Query and Manipulation Language (KQML) and Knowledge Interchange Format (KIF). KQML is both a message format and a message-handling protocol to support run-time knowledge sharing among agents. KQML can be used as a language for an application program to interact with an intelligent system or for two or more intelligent systems to share knowledge in support of cooperative problem solving. KIF is a computer-oriented language for the interchange of knowledge among disparate programs. FIPA (http://www.fipa.org) was established as a not-for-profit organization in 1996 for the purpose of standardizing agent technology. FIPA's normative specification addresses such areas as agent management, agent communication languages, agent-software integration, mobility, ontology, human interaction, nomadic application, and architecture. FIPA has also produced informative specifications that illustrate how the technology can be applied to certain application domains (Núñez-Suárez et al. 2000).

Legacy software integration problem. Agents will not replace existing information system but do need to be integrated with a diverse range of information systems. Even the most recently developed ERP or supply chain management systems were not designed to communicate with agents. Progress has been made by software vendors to interconnect legacy systems over the Internet using EDI or XML. However, agent communication language usage is still not common within the mainstream software development industry (Núñez-Suárez et al 2000). Furthermore, creating agent connection interfaces for each application system could be very expensive. Since agents can also be implemented by using object-oriented programming, making agent access through Object oriented methodologies such as UML maybe a way to go. We expect agent-based approach will be getting popular for building complex software systems (Jennings 2001).

Reasoning and coordination problem. We have assumed agents are intelligent, that they can reason and negotiate, for example. However, so far, the intelligence we can give to agents is very limited, and is based on existing AI technology or some mathematical models. They may do a reasonable job for relatively simple, well-structured problems. However, they are not smart enough to respond to uncertain, complex environments. Use of agents requires varying degrees of human intervention depending on the uncertainties and risks involved. Another limitation is that agents are also not creative. For example, when two agents negotiate with each other, they will fail to reach any agreement if there is no overlapping between their acceptable solution spaces. But human negotiators can be innovative to find an alternative solution beyond the existing solution space. When we use the intelligence of agents, we need to understand what is their true "IQ".

8. Conclusion

In this paper, we have reviewed the recent trends of supply chain management including the strategic shift towards customer-driven and relationship synchronization approaches. We have suggested that agent technology can be used to support the collaboration required to support these strategies. Agent technology can be viewed as a glue to enhance the connection of the major building blocks in the supply chain. We may view an agent as an assistant rather than a manager in supply chain management. An assistant can help the manager to do some coordination work, but cannot replace the manager.

Most research on agent systems for supply chain management is still in the early stage of theoretical framework or demonstrative prototyping. There is a long way to go. While we still have many theoretical problems to discuss, real word applications, even simple ones, will be very valuable to provide more in depth insight. We are pleased to see the recent progress of the EU-sponsored collaborative project aimed to test the use of FIPA (Foundation for Intelligent Physical Agents) agent technology for the development of the Personal Travel Market. In this electronic marketplace, three types of agents (personal travel agents, travel broker agents, and travel service agents) collaborate to resolve the travel requirements for a human user. The results are very encouraging (Núñez-Suárez et al 2000).

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