APPLYING MULTI-AGENT TECHNOLOGY TO SUPPLY CHAIN MANAEMENT

Stanley K. Yung
Anderson Consulting, Hong Kong SAR

Christopher C. Yang†
Department of Systems Engineering and Engineering Management
The Chinese University of Hong Kong, Hong Kong SAR
yang@se.cuhk.edu.hk

Adela S. M. Lau
Department of Systems Engineering and Engineering Management
The Chinese University of Hong Kong, Hong Kong SAR

J. Yen
Department of Systems Engineering and Engineering Management
The Chinese University of Hong Kong, Hong Kong SAR
jyen@se.cuhk.edu.hk

ABSTRACT

Supply Chain Management (SCM) is extremely important to the manufacturing and retailing industries. Profitability of enterprises in these two industries depends on the efficiency and effectiveness on they manage their supply chains. Information technology has been a key element in supporting supply chain management. As the access to the Internet becomes easier, managers are able to access real-time data and use decision support tools to support their decision making. In this paper, we investigate how multi-agent technology and constraint network can be integrated together to improve the efficiency and transparency of supply chain management.

A multi-agent based supply chain management system has been developed to support communication, coordination, collaboration, and operation of different entities in supply chains. Which enabled the warehouses and plants to query and share information. A constraint network model has been applied to model the objectives and constraints of each entity in supply chains. Two experiments have been conducted to evaluate the usefulness and performance of the system with participation of a retailing firm. The results indicated that the proposed system has several benefits. For example, improve efficiency by saving time and efforts for decision makers as well as improve the quality and responsiveness of decision making by value-added services, such as, bullwhip detection agent.

1 Introduction

A supply chain is a network of facilities that supports procurement of material, transformation of material to intermediate and finished goods, and distribution of finished products to customers [Lee 1993a]. Basically, there are four components in a supply chain, from down-stream to up-stream: retailers, wholesalers, manufacturers, and suppliers of raw materials or parts. Among various activities in supply chain management, inventory management or control can be the most important one. Lee [Lee 1992] identified fourteen pitfalls exist in the inventory systems that developed with traditional supply chain models, which are mainly operation research or optimization based. Most of such approaches are centralized systems, which provide each facility limited autonomy and information are owned and processed centrally. These pitfalls can be categorized into problems related to information definition, related to operation and control, related to strategic planning, and related to the design of supply chains. Which create the opportunities for multi-agent technology to overcome some of such pitfalls.

One review showed that in 1995, value of enterprise-wide software and services that related to supply chain management was more than US$ 3.5 billion and projected with an annual growth rate of 15 to 20 percent from 1994 to 1999 [Anderson 1996]. Anderson pointed out that many leading-edge systems were able to capture reams of data but were not able to digest and translate them into actionable intelligence [Anderson 1996]. The pulling force from owners of supply chains and the driving force from the new technologies determine how the problems can be solved.

† : corresponding author

Globalization, organizational barrier reduction, rapid growth and changes of product varieties, as well as customer information sharing and analysis are the urgent needs in supply chain management. These demands create the pulling force. Cohen stated that the globalization of supply chain will be widely adopted due to the increased competition, rising customer expectations, growth of product varieties, and the convergence of consumer tastes [Cohen 1989]. Ford has created a Ford 2000 program, in which the automobile manufacturing has been restructured from regional operation to global integration. A global supply chain, however, creates competitive advantages only if the management of the supply chain's geographically dispersed activities have been effectively executed and coordinated. This coordination only happens if the firm has the ability to adjust its value-adding activities throughout the world, at each stage and each location, in response to changes in market situation, which can be defined to be the transparency of supply chains. Naturally, coordination and flexibility are key requirements in design and implementing systems to support global supply chain management.

Lee and Billington stated that there are organizational barriers in adopting supply chain management. Therefore, information flows can be restricted, such that complete and centralized control of the material flows may not be feasible or desirable [Lee 1992].

The variety of products is increasing and changes quickly which creates the demand for faster and more effective information delivery [Fisher 1994]. Traditional supply chain management could not respond to these changes fast enough to understand and meet the demands from the customers. For example, Black and Deck lost millions of dollars in sales in less than one year because of failure in predicting the increased demand from retailers. Power tools industry requires fast delivery and increases product varieties in order to survive in competition [Fisher 1994]].

Sharing point-of-sales (POS) data is now a standard practice to those medium and large retailers [Frantz 1998]. Most consumer goods firms (CGs) finally have access to retailers' point-of-sale data and be able to automatically identify the customer behaviors. The ability to generate insights on consumer behavior and their demands have led to new approaches to support assortment planning and point-of-purchase display. Which make the shopping experience easier and more enjoyable as well as increase the sales through cross-merchandising or cross-selling.

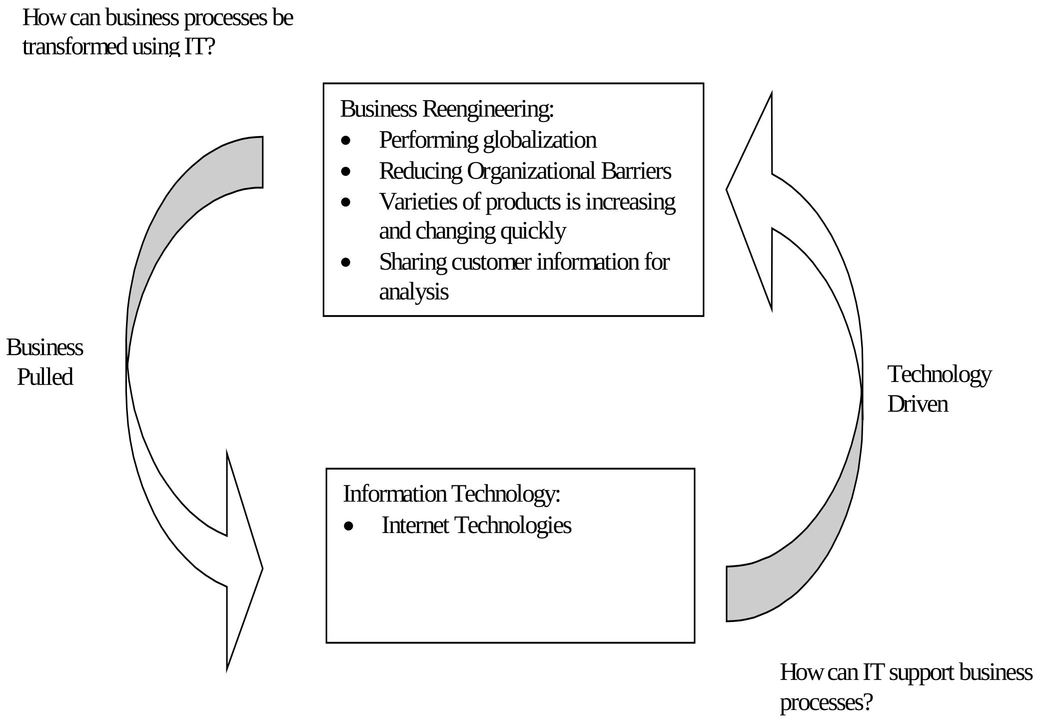

Figure 1. Needs for business process reengineering

As the Internet and its related technologies grow rapidly, more channels, such as, mobile phones and PDA, to transmit and receive information or data along the supply chains have been developed. Recently, most major retailers have developed their web sites. Two thirds have at least one web site and over 90 percent will follow within 18 months. Two thirds of those web sites display product information, and 20 percent are able to receive orders over the Internet [Frantz 1998]. The Internet changes the purchasing or shopping behavior of customers as well as the behavior of managers. While the Internet technologies provide perfect channels to support management of supply chains, software agent and multi-agent technologies are still in the early stage. However, some prototype systems that able to capture and model the behavior of each component in supply chain have been developed.

When managers use different approaches in forecasting, quantitative analysis, qualitative analysis, simulation, etc., communication or sharing of information has become very important. Agent technologies can be used to develop distributed environment to support such decision making process [Swaminathan, 1998], where each facility in supply chain is modeled by an agent. These agents form an agent community and they communicate with each other to jointly or individually make decisions.

Constraint network is able to model the dynamics and constraints of managers' decisions [Beck 1994]. A constraint network is a declarative structure, which expresses relations and tolerances among parameters. It consists of a number of nodes that connected by constraints [Davis 1987]. Multi-agent is one of the approaches that can be used to model and implement constraint networks. For example, Sycara has developed a distributed constrained heuristic search (DCHS problem), where the solution is the result of cooperative multi-agent problem solving [Sycara 1991]0. Therefore, agent technology and constraint network can be integrated together to support coordination and sharing of information among facilities in supply chains.

Once the infrastructure is there, information of supply chain can be shared more efficiently and effectively. Value added applications, such as bullwhip detection agent, can be developed on top of this infrastructure to better utilize the available information or to provide specific functionality to the users.

2 Literature Review

Research in coordination of supply chains can be categorized into the following four areas:

1. Modeling of Supply Chains – the processes and functionality of supply chains must be organized and coordinated efficiently to achieve better performance. Recently, constraint network model have been studied and applied, for example, to solve problems in manufacturing industry [Barbuceanu 1998, Beck 1994, Genesereth 1994, Kalakota 1997b, Swaminathan 1998].
2. Modeling of Information Flows - which provides the communication among facilities within the supply chains, where real-time data are critical in supporting decision making. It enabled quick response and accurate data transmission. Electronic data interchange (EDI) is one of the most popular applications. However, EDI is a closed environment for facilities within the supply chain. Internet provides a channel to support communication for both the facilities within and outside the supply chains [Barbuceanu 1998, Genesereth 1994, Kalakota 1997b].
3. Human Computer Interface (HCI) - the amount of information generated from a supply chain is overwhelming. It is important to have a good interface for users to input and retrieve data or information. Recently, many research have focused on software agents to model the behavior of the users and use the captured behavior to support design of better graphical user interface (GUI) [Barbuceanu 1998, Genesereth 1994, Kalakota 1997b, Swaminathan 1998].
4. Optimization Method – optimization is an important research area to search for better resources allocation in supply chain management. Some mathematical models have been applied to increase the performance of supply chains. But such research can be computational intensive if the number of facilities is large. Heuristic search or problem decomposition methods, random search methods, such as genetic algorithm, and negotiation methods may not guarantee global optimality, but their solutions are quicker to get and the differences from the optimal ones may be acceptable [Barbuceanu 1998, Beck 1994, Genesereth 1994, Kalakota 1997b].

Recently, several researchers have explored the intelligent agent approach to support management of supply chains. Some focused on real-time management of supply chains, while others applied rule-based mechanism and constraint relaxation approaches to model behavior of agents. Hinkkanen proposed a distributed decision support system to support real-time supply chain management [Hinkkanen 1997]. Hinkkanen modeled human decision makers as agents, who are able to adjust behavior according to the changes in the environment. For optimization of resources allocation, an auction market model was used, where resource agents and request agents submit bids and asks simultaneously. However, the optimization only focused on resources allocation within a manufacturing plant and did not consider the efficiency of delivery.

Kalakota designed an agent-based real-time system to coordinate the supply chains by modeling the system as a multi-commodity network flow problem (MCNFP) with side-constraints [Kalakota 1997b]. He employed the Primal (Benders-type) Decomposition approach to decompose the problem into a set of sub-network problems. When all the sub-network problems are solved, the overall problem also solved accordingly. Since the supply chain is very complicated, the sub-problems are also complicated and solving these problems is still not straightforward after decomposition.

Beck and Fox develops the mediated approach to coordinate the supply chains. It consists of a schema for constraint relaxation algorithms on Partial Constraint Satisfaction Problems (PCSPs) [Beck 1994]. An experiment has been conducted and the result showed that the mediated approach has better performance than the negotiation approach. It also showed that the mediated algorithm using heuristic search on the aggregated constraint graph out-performed the human expert.

Barbuceanu and Fox have integrated an agent-based system with rule-based mechanism [Barbuceanu 1995]. To find the best rules that can account for the uncertainty of the environment, an associated probability is assigned to each rule and state.

In a global environment, supply chain management has to deal with globalization, proliferating product variety, organizational barriers, and quick information sharing. In response to these challenges, an appropriate model to support the supply chain management is needed. In this paper, we propose a model that integrates both intelligent agents and constraint network. Functional agents and interface agents were developed to coordinate the operation. In particular, we investigate the communication protocol among agents to support the global supply chain management.

2.1 Supply Chain Model

We propose a supply chain model that is able to adapt to the changes in the environment. Traditionally, mathematical models with optimization are used to solve supply chain management problems. However, such approach is not capable of solving real-time optimization of large-scale problems. Although an optimal solution can be obtained, it is usually delayed and the condition of the environment already changed. Agent descriptions provide an ability to specify both static and dynamic characteristics of various supply chain entities [Swaminathan 1998]. Each agent can be assigned to model a facility and relationships can be defined as links to connect these agents together, as Lee stated, a supply chain is a network of facilities [Lee 1992].

The relationships among facilities pertain to how materials "flow" from suppliers to the plants, undergo transformation or assembly, transported to field warehouses or distribution centers, and finally reach the hands of customers [Kalakota 1997b]. These relations can be represented in quantities of materials or products, in cost or scheduling of deliveries, etc. The finite domains are the limitations that the environment imposes to the supply chains. It is analogous to the constraint optimization problem, with subsystems and components act as constraints on variables [Parunak 1997].

As a result, we have a finite set of variables, each is associated with a finite domain, and a set of constraints that restrict the values of the variables can simultaneously take. Today's business environment requires design to be done by distributed teams of engineers, so the analogy can be extended to distributed constraint optimization (DCOP) [Parunak 1997]. Figure 2 provides an example of how a constraint network models a traditional supply chain and the relations among facilities.

When we zoom into each facility, a process can be decomposed into a set of sub-processes and each sub-process can be modeled by an agent. It is impossible to use one agent to model a large process, but a group, or a society, of agents can be a solution [Kalakota 1997b]. Figure 3 shows a decomposition of a process into several sub-processes, and each sub-process is modeled by an agent.

The above figure shows the sub-processes of a simple warehouse. First, it waits for customer orders (1). After that, it processes the order by checking whether it has the stock or not. If the warehouse has enough stock, it delivers product immediately (10). If it does not have enough stock, it places an order to the manufacturer (2,5) and initializes a stock-monitoring agent (3) to alert (8,9) to start the delivery process when the stock is enough (6,7).

2.2 Roles of Agents

Major task of an agent is to assign a value to each variable that satisfies all the constraints. In addition to finding solutions for the constraint network, agents can be an interface between the manager and the system.

2.2.1 Functional Agents

For functional agents, each handles a specific problem. According to the functions defined by Kalakota [1997a], five different agents can be defined: Production and Cost Management Agent (PCMA), Purchase-Order and Inventory Control Agent (POICA), Accounting Agent (AA), Order Management Agent (OMA), and Labor Management Agent (LMA).

The Production and Cost Management Agent (PCMA) contains the constraints for monitoring the operation cost and the quantity of raw materials. The Purchasing-Ordering and Inventory Control Agent (POICA) contains the constraints for monitoring the inventory levels. In addition, it needs to acquire information from manager or to calculate based on historical data for optimal reorder quantities.

The Accounting Agent (AA) communicates with all the other agents for payment or similar information because all the transactions in a supply chain involve cash flows and transactions among accounts of different facilities. In addition to the bookkeeping and accounting, it also monitors a set of variables, such as, the exchange rates, tax rates, and other financial derivatives that affect the performance, such as, cash flow, of a supply chain. Also a set of cost constraints is needed to support the monitoring of the total costs or costs of sub processes that near or over the limits.

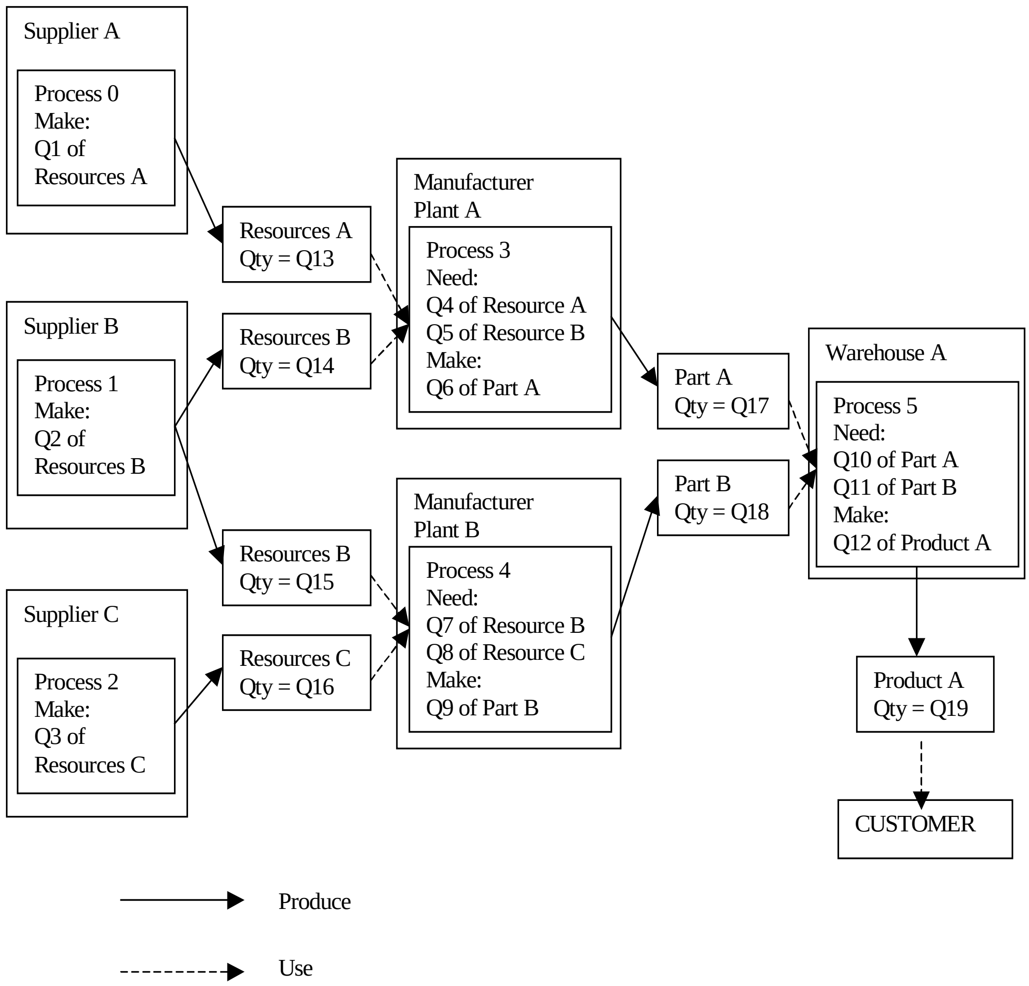

Figure 2. A model of constraint network that model the traditional supply chain and demonstrate the relation between facilities

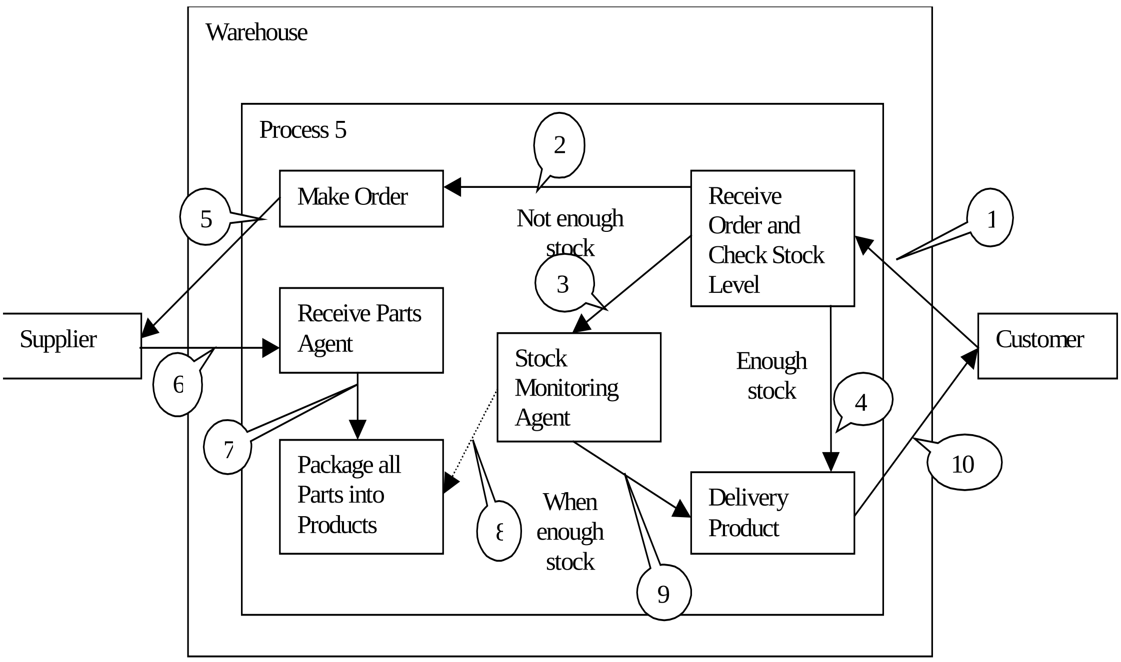

Figure 3. A warehouse with processes linked together and each agent is assigned to each process

The Order Management Agent (OMA) contains the constraints to monitor costs and scheduling of product distribution. In addition, this agent stores data of demands and customer services and shares such information with other agents. Up-to-date demand information is extremely important, especially the manufacturing plants. They need to know the optimal quantity to produce in order to meet demands from down stream [Fisher 1994].

The Labor Management Agent (LMA) contains the constraints to monitor costs of labor. A single agent can be developed to monitor the performance of each employee by using constraints, such as, working hours, utilization, sales quotas, etc.

After defining constraints and role of each agent, an efficient communication mechanism is needed for these agents. There are two major communication methods: direct communication (negotiation approach) and assisted coordination (mediated agent approach). The mediated approach was selected in our research for two reasons: the earlier experiments showed mediated agent approach out-performed the negotiation system [Beck 1994] and if the optimization method needs to be modified, it is very expensive to modify all the warehouse agents when negotiation approach is used. For mediated agent approach, mediation agent is the only component that needs to be modified.

We used a top down approach to design the agent architecture. That is, a complicated process is decomposed into smaller processes and those smaller processes are further decomposed into processes until each can be handled by an agent. As a result, a mediated agent is needed to support communication and control for each layer of process decomposition.

2.2.2 Interface Agent

An agent can be an interface between a manager and the system. For the constraint model described above, managers need to input the constraints and formulate the constraints. In addition, information is stored in the database. Therefore, managers also need to access and extract data and feed them to the constraint system. Also, it is difficult for a manger to create all the constraints from scratch. Therefore, constraints for different inventory systems can be loaded into agents and allow managers to choose or modify according to their needs.

In addition, agents can be linked through the Internet and managers can look for the most suitable set of constraints by sending a searching agent to other facilities in the supply chain. If the format of constraint is the same throughout the supply chain, constraints can be shared. However, a manager may not understand the meaning of the searched result and description of constraints should be added as metadata.

3 Agent Communication

The functionality of different agents has been discussed in previous section. The technologies or languages that used to implement these agents and their communication will be discussed in this section.

Selection of an appropriate technology or language to implement agent is important, because it affects the performance of the system. There are two main approaches of agent communication languages, procedural and declarative. For procedural approach, Telescript is one example [Genesereth 1994] and for declarative approach, Knowledge Query and Management Language (KQML) is the most widely used one [Genesereth 1994].

For Telescript, agents execute in any computer where a Telescript engine has been installed [White 1996]0. However, Telescript does not support cross-platform communication as good as JAVA. Such ability to support operation on different platforms is extremely important for global supply chains.

For KQML, the major disadvantage exists in transmitting objects among agents. For the proposed supply chain model, the variables, constraints, and parameters not only presented in ASCII, but also presented as objects or an array of objects. KQML needs to be installed in every facility in the system and storage of KQML content in facility is helpful for the direct communication approach. But it creates a large overhead for the assisted coordination approach. Furthermore, the actions implemented in KQML are limited.

Due to the limitations discussed above, both languages were not suitable for our target system. The question that we need to answer is that “What is the appropriate language for the proposed system?” Finin has defined some requirements for communication language, which are form, content, semantics, implementation, networking, environment, and reliability [Finin 1997].

For our system, JAVA was selected to implement the communication protocol and the agent system. There are several reasons why we selected JAVA. JAVA provides interface, such as Remote Method Invocation (RMI) interface, that transfers objects through the Internet. It also platforms independently which is suitable for geographically dispersed nature of the supply chains. It is also proven accurate and efficient in general. Finally, JAVA has tremendous libraries in support networking and communication.

3.1 Constraint Network Model

There are three types of independent-demand inventory systems: economic order quantity, continuous review system (Q System), and periodic review system (P System) [Krajewski 1993]. Economic order quantity is based on the lot size, which is the ordered quantity from warehouse to upper stream that minimizes total holding and order cost. Continuous review system reviews the level of stock whenever a withdrawal is made to determine whether an reorder is needed or not. Periodic review system (P System) reviews the inventory position periodically and an order is placed at the end of each review [Krajewski 1993]0.

Our approach aims at supporting real-time operation; inventory position has to be reviewed whenever there is a change. Among the above three models, Q system was selected to convert the optimization model to a constraint network:

IP = OH + SR – BO --- (1)
IP = inventory position of the item (in units)
OH = number of units in on-hand inventory
SR = scheduled receipts (open orders)
BO = number of units either back ordered or allocated

R = D + B --- (2)
R = reorder point
D = average demand during lead time L
B = safety stock

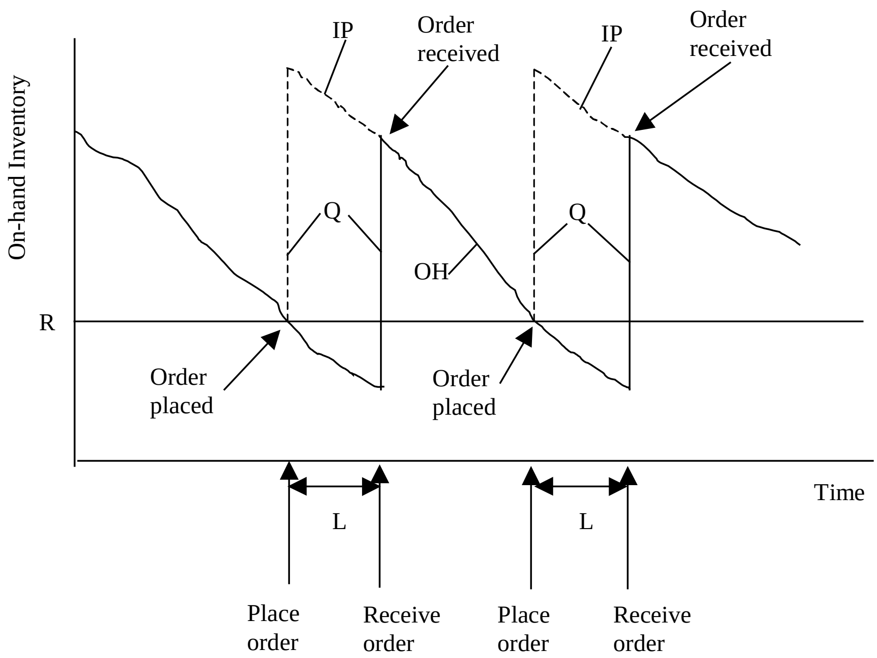

Figure 4. Illustration of Q system in chart form

In equations (1) and (2) as well as Figure 4, whenever IP is smaller than R, an reorder is place automatically. Therefore, IP > R is a constraint and the constraint model can be constructed as the following:

Table 1. Variables and their constraints

Variables	Related constraints and formulas
IP	IP = OH + SR – BO (formulas) IP > R (constraint)
R	R = D + B (formulas) IP > R (constraint)

Figure 5 is the constraint network used to model the operation of warehouses. It combines both constraint networks of IP and R. An additional constraint of order from customers is needed to show the completeness. Figure 6 is the combined constraint network with two warehouses.

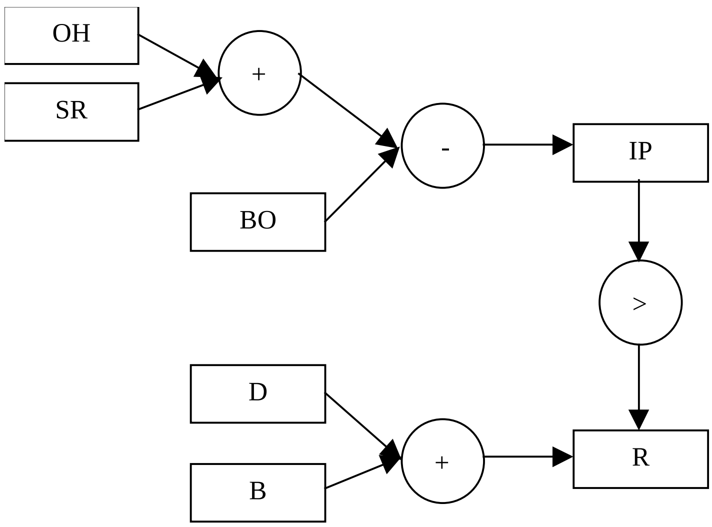

Figure 5. The constraints in chart format

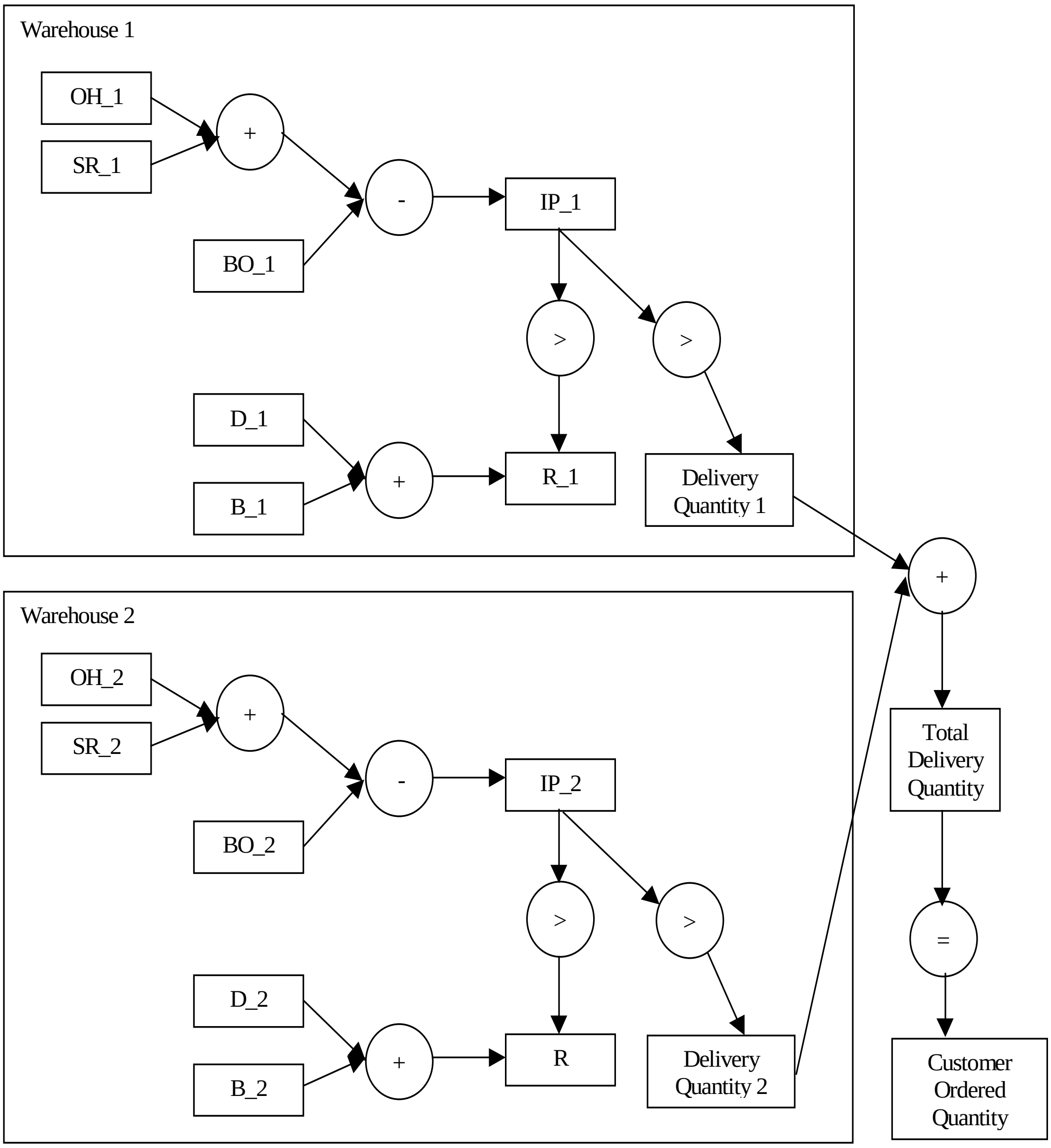

Figure 6. The combined constraint network of two VoChan's warehouse

In a supply chain, at least one warehouse is located in each location. In reality, different warehouses may use different inventory systems. Even same inventory system is used, differences in parameters or tolerances of constraint toughness still exist. For example, D (average demand during lead-time L) can be calculated based on moving average of the historical demand or be forecasted by probability distribution. Therefore, the ability to change according to the dynamics of the environment is important. For our system, managers can add, remove, or edit the constraints whenever needed.

Constraints can be applied to model many problems in supply chains, for example, resources allocation, purchasing, production, and replenishment [Barbuceanu 1995, Kalakota 1997b]. When all activities are modeled by constraints, it creates two opportunities. Firstly, they can be linked together to form a network. Secondly, global optimization becomes possible.

As mentioned earlier, when all constraints are linked together, global optimization becomes possible. In this section, we studied the problem of how warehouses allocated and transported products to customers in order to minimize the costs.

Genetic Algorithm was selected to implement the optimization module and it has four steps in the problem solving process: initialization, crossover, mutation, and selection. When using constraints network, constraint checking has to be inserted into every step, because genetic algorithm generates solutions randomly and some of them are invalid. The invalid ones need to be removed from the candidate solutions.

The candidate solutions (chromosomes) have to be represented as strings of building blocks (genes) [Tsang 1993]. Initialization generates a population of chromosomes that satisfy all constraints. After that, crossover and mutation generate a set of offspring and they have to satisfy all constraints as well. A new population will be selected from old population and new offspring. New offspring are selected depend on the predefined optimization function. Again, crossover, mutation and selection are performed on the new population until it converged or the termination condition is satisfied.

For the delivery distribution problem, the format of a chromosome depends on the number of warehouses, as well as number of and quantities of products in each order. For example, if there are two warehouses, four products in an order, and the quantities are 2, 5, 8, and 10 respectively. These numbers have to be converted to binary numbers and an example in provided in Figure 7.

```
Format:
Warehouse 1                  | Warehouse 2
A     B     C     D          | A     B     C     D
-----------------------------+---------------------------
a1    b1    c1    d1         | a2    b2    c2    d2

Example (Binary):            |
00    011   0001  01010      | 10    010   0111  0000
```

Figure 7. An example of chromosome format

In crossover, parts of the building blocks (genes) of the selected parents (chromosomes) are exchanged to form new offspring. For the format shown in Figure 7, genes are exchanged at each product quantity behind a randomly selected cutoff point. For each product, the cutoff points have to be the same for all warehouses. Figure 8 demonstrates a simple crossover.

```
Crossover:
Parent 1       0|0  01|1  00|01  0101|0    1|0  01|0  01|11  0000|0
Parent 2       1|0  01|0  01|11  0000|0    0|0  01|1  00|01  0101|0
Offspring 1    0|0  01|0  00|11  0101|0    1|0  01|1  01|01  0000|0
Offspring 2    1|0  01|1  01|01  0000|0    0|0  01|0  01|11  0101|0
```

Figure 8. An example of crossover

In mutation, a random building block (gene) of a selected parent (chromosome) is picked and its value changed. Selection method of parents will be discussed later. For the chromosome format above, a gene is selected randomly at each product quantity and its value will be changed. Therefore, if the value of a gene in parent chromosome is 1, then the new value will be 0. Figure 9 demonstrates a simple mutation.

```
Mutation:

Parent          00  011  0001  01010    10  010  0111  00000
Offspring       00  010  0001  01000    10  011  0111  00010
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Figure 9. An example of mutation

The weighted-random selection is used for the selection of parents in crossover and mutation as well as the candidate solutions in generating new population. For product delivery, the cost function considers parameters related to order, products, delivery tools, distance between customer and warehouses, and the order processing cost (including holding costs). When the genetic algorithm stopped, the solution is selected according to the performance function only not the weighted-random selection.

4 Experiments and Data Analysis

In this section, two experiments been conducted to test the usefulness of the system will be discussed. In the first experiment, performance of the original system will be compared with that of the system that developed with constraint network and agents. In the second experiment, the performance of the constraint network and agent system will be compared with that of the same system that uses a different optimization algorithm.

In order to test the usefulness and performance of the system, we tested the system to support the operation of VoChan Import and Export Co. Ltd., which is a leading supplier of provision, cans, sauce, sundries, frozen, and food in Macau. In phase 1, VoChan agreed to provide ordering data of warehouses and customers ordering data to test the system. In second phase, the system was actually used to support the decision making of managers of VoChan.

VoChan has two warehouses in Macau. The larger one has two floors and is located outside of downtown Macau. The smaller one has only one floor and is located inside downtown. Their customers, mainly hotels and restaurants, are located inside Macau as well as inside China that near the border. Most products have been delivered from the large warehouse, which has a fleet of four trucks and two mini vans. They only provided one delivery a day. If a customer missed the order before early morning, they had to wait for the next day. The small warehouse was a retail store and provided no delivery service

VoChan tried to utilize the usage and deliver products from both warehouses. In addition, they tried to provide just-in-time service by delivering products right after an order is received. However, it was difficult to decide what warehouse to deliver the products. In addition, they did not have any system to manage inventories.

In our research, we applied the agent technology and constraint network to support their inventory system reengineering. The experiment for VoChan was focused on the optimization of delivery and inventory control.

Measurements of supply chains can be classified into qualitative and quantitative. Qualitative measures include, for example, customer satisfaction, easiness of integration of information and material flows, and effectiveness of risk management [Swaminathan 1998]0. Quantitative measures include, for example, cost minimization, profit maximization, fill-rate maximization, customer response-time, supplier reliability, and lead-time minimization [Swaminathan 1998]. In the following experiments, both set of measures will be used to identify which system has better performance.

4.1 Experiment One

In the first experiment, we compared the operation cost of the inventory and delivery system of six months operation in VoChan with and without the agent and constraint network. The following are the basic statistics of the original operation in Hong Kong dollars.

Running cost for the small warehouse: $20,000/month.
Running cost for the large warehouse: $109,000/month.
Delivery cost for the small warehouse: $5,100/month.
Delivery cost for the large warehouse: $54,000/month.
Average number of orders processed in the small warehouse: 30 per month.
Average number of orders processed in the large warehouse: 220 per month.

The monthly running cost of the small warehouse is estimated by adding labor cost (3 workers * $5,000 average monthly salary), utilities costs ($3,000 including electricity and water supplies), and other miscellaneous costs ($2,000 including stationary and so on). The monthly running cost of the large warehouse is calculated based on similar approach.

Based on the above data, parameters are calculated for the constraint network and agent system. For the small warehouse, we assume that the processing cost of an order is $20,000 / (30 days * 30 orders), which equals $22.2 per order per day. For the large warehouse, the processing cost will be $109,000 / (30 days * 220 orders), which equals $16.5 per order per day.

As VoChan would like to reengineer the process into a JIT (Just-In-Time) distribution, therefore, using trucks for delivery is impossible and costly inefficient. As a result, eight small vans replace four trucks used in the large warehouse and one small van will add to the small warehouse. By estimation, new average delivery cost for a single order by using one van will drop down to $11. For the small cart, it will be $5 for a single order.

After gathering those parameters, a two-month simulation has been conducted to estimate the costs of the constraint network and agent system. The total cost of the current system is $47,025 per week and the total cost of the constraint network and agent system is $33,151.1 per week, which indicated that the constraint network and agent system saved 29.5 percent of the total operation costs. In the following tables, both qualitative performance measures and quantitative performance measures are shown. The results of qualitative approach were based on the interviews with managers of stores.

Table 2. Qualitative performance measures of the first experiment

Qualitative	Current System	Constraint Network and Agent System
Customer Satisfaction	Not available.	Not available.
Integration of Information and Material Flows	Done manually.	Information stored in database and can be retrieved to support decision making Agents automatically calculate stock levels based on constraints entered by managers.
Risk Management	Done manually.	Real time data are available for managers to use tools to calculate risk levels

Table 3. Quantitative performance measures of the first experiment

Quantitative	Current System	Constraint Network and Agent System
Cost Minimization	It is not a major consideration.	Optimization aims to minimize the delivery costs
Profit Maximization	The marginal profit is the only consideration	Without revenue data profit could not be calculated
Fill-rate Maximization	Done manually by checking stock levels and no optimization performed.	Stock level was automatically checked after each order. System sends notification to fill the stocks when it is lower than the reorder point. However, no optimization was performed.
Customer Response-time Minimization	No minimization was done. Customers had to wait for the manager to provide information or for the delivery on the next day	No minimization is done at this point. In the future, when the information of price and product can be accessed through Internet, minimization can be done.
Supplier Reliability	Pen and papers were used and invoices could be lost easily	Invoices are processed and printed by system. Orders cannot be lost easily.
Lead-time Minimization	Only two deliveries per day and orders had to wait till the next day if customers missed deliveries.	Just-In-Time delivery, which provides immediate delivery to customers after an order is received. It significantly shortens the lead-time.

4.2 Experiment Two

In the second experiment, the constraint network and agent system was tested with two different settings of optimization in order to test whether reorder cost affected the system performance. The first system was as the same as that used in experiment one except the estimation method of the order processing cost. The second system added a parameter - reorder cost, into the optimization function. The cost functions are shown below:

Table 4. Cost functions for the second experiment

Type	Cost (a single order)
Without reorder consideration	((number of cars needed * cost of a car) * a regional distance factor from warehouse to destination) + order processing cost
With reorder consideration	((number of cars needed * cost of a car) * a regional distance factor from warehouse to destination) + order processing cost + reorder cost

Reorder is a purchase order from a warehouse to a manufacturer. When there are more than one warehouses that have the needed products, the costs are lower if delivery is made from a closer warehouse if the delivery cost is the only consideration. However, it increases the frequency and costs of reordering.

In the second experiment, we looked at how effective the system was when reorder cost was considered. The average reorder cost per order was estimated based on the average lead-time of making a purchase order and the average order processing cost (including the holding cost). The following are the numbers of reorders for VoChan.

Estimated Average number of reorders processed for the small warehouse: 120/month
Estimated Average number of reorders processed for the large warehouse: 880/month

For VoChan, the average lead-time of making a purchase order is two days. For the small warehouse, the average number of orders per day is 30 and the number of reorders per month is 120. Therefore, the processing cost per order is $17.5 which equals $20,000 / ((30 days * 30 orders) + (120 reorders * 2 days lead-time)) for the small warehouse. For the large warehouse, the numbers are 220 and 880 respectively. Therefore, the processing cost per order is about $13.0, which equals $109,000 / ((30 days * 220 orders) + (880 reorders * 2 lead-time)). These costs sum up equal the total processing costs, which include order processing and all other miscellaneous costs except the reorder processing costs. The results of the simulation indicated that the total costs per week, if reorder costs were not considered, are 51,634 HKD. If reorder costs considered, the total costs per week equals 46,802.9. Therefore, the reorder cost has impact, about 10.2 percent, on the total processing costs.

Similarly, the total number of reorders per week, if reorder costs were not considered, equals 670. If reorder costs considered, the total number of reorders is 470. Therefore, considering reorder cost has a significant and positive impact, about 42.7 percent, on the total number of reorders.

The costs are close for both cost functions even though the cost for having reorder consideration is smaller than the cost for having no reorder consideration. It is possible that it will cost more on delivery in order to avoid reordering. However, intangible costs of reorders cannot be quantified by the function, which is the introduction of the bullwhip effect. The demand order variability is amplified as they move up the supply chain and this phenomenon is named bullwhip effect [Lee 1997].

In addition, the number of customer orders is the same for both tests, but there are forty percent more reorders when the reorder cost is not considered. Therefore, a larger warehouse is needed to store extra stocks. The maximum capacities of both warehouses are assumed to be equal to the average demand of products for two weeks. Moreover, if the products have short expiry dates, which can be defined as perishable goods, warehouses have to bear the risk of not selling products in time to recover the costs. Finally, managers may need to hire more people to handle the extra stocks of products. Therefore, number of reorders is important and needs to be considered in the cost structure.

4.3 Discussion

The system that we developed for VoChan has been used for over one year. It currently supports five simultaneous users and contains 450Mbytes of data. The company's operation has been improved with the use of the system. The benefits can be seen in many areas. For example, the information is no longer centralized and can be accessed through Internet, which has improved transparency. The system also improved efficiency and effectiveness. Before using such system, a bottleneck existed at writing and keeping invoices. With the system, staff can print or check the invoice whenever it is needed.

It also reduced the total operation costs. Employees can easily retrieve and review the historical data to predict the demand and sales trend. Lastly, the system provided an opportunity for management to reengineer the company. In the past, employees used to be occupied by paper works. With such system, they can focus on higher value-added tasks, such as, identify new business opportunities.

5 Conclusion and Future Work

Combine the pulling force from the owners of supply chain and the pushing force of Internet technologies; some problems in the supply chain management can be solved by multi-agent technologies. One of such problems is that managers in different geographical regions have different perspectives and behavior. Therefore, systems that developed with traditional approaches, which are centralized or passive, were difficult to help them overcome the challenges.

The second problem relates to the variety of products, which increases quickly. Systems that support the management of supply chains have to adapt to these changes automatically and dynamically, which are the issues of scalability and adaptability. The third problem relates to the transmission of real-time information to support decision making at each facility. Design of the protocols to support such efficient and transparent information transmission is extremely important.

In this paper, a system that integrated constraint network model and multi-agent technology to support coordination and management of supply chains has been developed. The constraint network model adapts to the changes of environment dynamically and captures the behavior of managers. In addition, agents communicate through Internet to support dynamic optimization. Genetic algorithm has been applied to support such optimization, which has acceptable performance in the two experiments conducted.

An agent communication protocol as well as a set of agent requirement and specification has also been proposed. Based on the requirements, JAVA was selected to implement the distributed system. In addition, RMI (Remote Method Invocation) provides the needed features for agents to communicate and collaborate.

Specifically, how warehouses allocate and transport products to customers has been tested with experiments in the industry. The results showed that the system has created significant impacts and benefits. In addition, it allows users to insert information or modify parameters while system is in operation. Agents that provide value-added services can be implemented to handle problems that are more specific; for example, bullwhip effect that came from inadequacy of transparency.

There are four directions for future research. First, a standard methodology can be developed to convert the operation models to constraint networks. Currently, many supply chain models are developed in mathematical formats. Some of them are computationally expensive to reach optimal solutions, which are difficult to support operation on the real-time basis. Secondly, the proposed communication protocol is barely enough to support the transfer of constraints, variables, functionality, and parameters. More complete or complicated protocols are needed to support communication and collaboration. For example, when two requests arrive at an agent in the same time, how to determine which request to process first.

Thirdly, the system has been tested with real-world data. However, the firm that participated in the experiment did not have complicated supply chains. If experiments with more complicated supply chains can be conducted, the true performance of such approach can be revealed. Finally, more value-added services can be developed. Currently, bullwhip detection agent has been developed, but more value-added services, such as an information-sharing agent to support constraint building and validation. can also be added. . It visits different facilities to gather information of those constraints and shares them with other managers.

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