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MULTI-AGENT ENABLED MODELING AND SIMULATION TOWARDS COLLABORATIVE INVENTORY MANAGEMENT IN SUPPLY CHAINS

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ABSTRACT

This paper is framed to address the preliminary approach towards process-oriented collaborative inventory management in supply chains, taking advantage of multi-agent technology in terms of modeling and simulation. Initially, a SCM support model is proposed as a foundation to combine the supply chain processes with the multi-agent system. In succession, a simple PC assembling case is investigated and simulated mainly to validate the SCM support model. As a result, the combination has the potential to make possible a real strategic competitive advantage for the entire supply chain and will enable new forms of business, namely, collaborative inventory management. Accordingly, a theoretical framework of collaborative inventory management is highlighted to refine and extend the SCM support model with the purpose to synchronize decisions as well as actions.

1 INTRODUCTION

Accompanying the globalization of business, the competition has transformed from company versus company to supply chain versus supply chain. Accordingly, the supply chain management (SCM) should ensure the objectives to deliver the right product, at the appropriate time, at the competitive cost, and with customer satisfaction in order to keep the competitive advantages. To realize the objectives, SCM might involve very complex decision making. However, the effective management of supply chain inventories is perhaps the most fundamental objective of supply chain management. And, it has become increasingly apparent that limits in achieving the objectives mainly lie in the ability to effectively collaborate on both decisions and actions. At present, almost no such collaboration is really available and applicable. Nevertheless, multi-agent technology could be a favorite alternative to model and simulate the collaboration mechanisms and processes. Accordingly, this paper initially proposes a multi-agent enabled SCM support model to map the basic supply chain processes. After that, a framework of collaborative inventory management is highlighted to refine and extend the SCM support model. In other words, the efforts involved in this paper are to address the preliminary approach towards the collaborative inventory management.

Therefore, the rest of this paper is organized as follows. Section 2 briefly reviews the relevant literature on the application of multi-agent technology in supply chain management. Meanwhile, some opportunities in this research area are identified as well. Then, the SCM support model is initially proposed in Section 3 to model the basic supply chain processes. Section 4 investigates and simulates a simple PC assembling case mainly to validate the SCM support model. Furthermore, Section 5 highlights the framework of collaborative inventory management. Finally, Section 6 addresses some conclusions as well as the future work.

2 LITERATURE REVIEW

The Center for Research in Electronic Commerce in Austin, Texas, concentrates on the real-time supply chain information system involving the use of an organization of software agents and electronic brokerages, and real time optimization technique (Hinkkanen et al. 1997, Kalakota et al. 1996). The structure of this software system closely resembles the structure of a human organization. However, the hierarchical coordination structure may require vast amounts of message passing, and the impacts of supply chain processes on the multi-agent system should be further investigated.

The Enterprise Integration Laboratory (EIL) in University of Toronto, Canada, models enterprise and supply chain integration and addresses coordination problems at the tactical and operational levels (Fox et al. 1993, Beck and Fox 1994, Barbuceanu and Fox 1996). They organize the supply chain as a network of intelligent agents, each performing one or more supply chain functions and each coordinating their actions with other agents. However, further approaches towards the collaborative decision making across the supply chain network are still needed.

The Intelligent Coordination and Logistics Laboratory (ICL) of Carnegie Mellon University has proposed a multi-agent supply chain coordination tool (MASCOT) for supply chain management (Sadeh et al. 1999, Hildum et al. 1997). MASCOT is a re-configurable, multi-level, agent-based architecture for coordinated supply chain. Each coordination agent supports event-driven coordination and mixed-initiative planning and scheduling decision support functions across the supply chain. However, higher level collaboration is still necessary.

The Centre for Electronic Commerce (CEC) in The Environmental Research Institute of Michigan (ERIM), USA, specializes in helping supply chains develop best practice guidelines for electronic commerce technology adoption involving multi-agent technology (Parunak 1998). Accordingly, the CEC has worked with industry to implement common business practices on a pilot basis. However, the solutions involved in their work are somewhat special and more generic approach is needed as well.

Swaminathan et al. (1998) present a multi-agent framework to model supply chain dynamics by means of simulation. A library of software components, which consists of structural and control elements, has been developed. This framework allows the development of models to address issues related to configuration, coordination and contracts. However, detailed coordination mechanisms are not seen in the paper.

As such, some other researchers have also explored the multi-agent enabled modeling and simulation with particular application to supply chain management (Lin et al. 1999, Yung and Yang 1999). However, the major opportunities for collaborative supply chain management in the research arise from two facts regarding the literature reviewed. *First, fewer efforts have been put to clearly map the supply chain processes into the multi-agent system*, even though the concept of process-oriented supply chain integration has been widely accepted. *Second, more work needs to be done to investigate the processes as well as mechanisms involved in collaborative supply chain management especially at the strategic and tactical levels with respect to multi-agent technology.*

3 MULTI-AGENT SCM SUPPORT MODEL

A supply chain can be regarded as a network of autonomous or semiautonomous business entities that performs all processes associated with the flow and transformation of goods and services from the raw material stage, through to the end user, as well as the associated information flows. Material and information flows both up and down the supply chain. However, there are two challenges involved to achieve a successful supply chain management. One is to redefine the supply chain activities in process oriented terms that result in innovative process-integrated business solutions not only internally but also across organizations. The other is to deploy a more sophisticated and advanced infrastructure that support enterprise wide and inter-enterprise distributed information-processing activities and decision making to realize the integrated supply chain management. Therefore, the combination of supply chain process definitions with an advanced infrastructure in terms of multi-agent systems have the potential to make possible a real strategic competitive advantage for the entire supply chain and will enable new forms of business and work (Papazoglou et al. 1999). As a result, the so-called SCM support model is proposed in this section to address this kind of combination.

3.1 Supply Chain Processes

Concurrent with the increased importance of the supply chain to a company's competitiveness has been a shift from traditional function-based (vertical) management to process-based (horizontal) management. As a result, the tight integration of management processes is increasingly important, and complex operation processes must be clearly defined and effectively implemented. Supply-Chain Council (SCC) took the reference model and helped to develop, test and finally release it, calling it the supply-chain operations reference model (SCOR). SCOR has been positioned by the SCC to become the industry standard for describing and improving operational process effectiveness (Stewart 1997).

In fact, SCOR is a process reference model developed specifically for supply chain management. SCOR provides a broad definition of the plan, source, make, and deliver process types, and is the point at which a company establishes its supply chain competitive objectives. The plan, source, make, and deliver framework defines a more strategic view of this critical management function, rather than just a set of independent tactics. The four basic supply chain processes are shown in Figure 1 (Supply-Chain Council 1999).

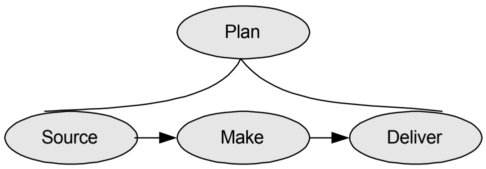

Figure 1: Four Basic SCOR Processes

But, SCOR is not a substitute for developing a comprehensive strategy for supply chain management. In this paper, SCOR is mainly adopted as a foundation to develop the multi-agent enabled SCM support model.

3.2 Modeling Approach for SCM Support Model

The modeling approach is normally crucial to initiating a model especially for studying a large-scale system. The unsuitable or even wrong modeling approach is deemed to mislead the managerial activities, make no sense or even generate wrong management results. Under this circumstance, the proposed modeling approach for SCM support model features four levels (Fu et al. 2000):

3.2.1 Level 1: Physical Supply Chain Identification

The concrete supply chain network is depicted here with respect to the factors as locations, product set and organization. The major material flows are also indicated from point to point. Normally, due to the product complexity and diversity, a physical supply chain is identified by product families, as different product families may involve very different supply chain structures. Furthermore, selecting the correct business entities to depict the physical supply chain will have great benefit to the modeling approach for SCM support model.

3.2.2 Level 2: Process Determination

After the physical supply chain is identified, the processes involved in each supply chain entity are determined in this level based on the SCOR model. In other words, this level configures the appropriate source, make, deliver and plan processes across the entire supply chain that is identified in level one. In addition, the material flows are described in more detail by tying together the set of Source-Make-Deliver supply chain processes that a given product family flows through. And, the information flows are identified to address the plan process and the relationship between different processes. In fact, it is the material flows and information flows that put the supply chain processes in motion.

3.2.3 Level 3: Process Agent Development

This level is designed to model supply chain processes that are generally consistent with the SCOR model. Therefore, the process agents in the SCM support model include at most seven agents, i.e., plan supply chain agent (PSCA), plan source agent (PSA), plan make agent (PMA), plan delivery agent (PDA), source agent (SA), make agent (MA) and delivery agent (DA). In fact, these agents can be classified into two categories: execution agents and planning agents. Execution agents include source agents, make agents and delivery agents, and planning agents include the other four of the seven agents. However, the detailed processes performed by different business entities are normally distinctive among them. For example, the manufacturer may involve seven processes, so we can use all the seven agents to model the processes owned by manufacturer. But for the retailer, we may only need to use three agents (i.e., source agent, delivery agent and plan delivery agent) as far as the processes are considered. Therefore, this can be a flexible and dynamic modeling approach.

3.2.4 Level 4: Process Element Framework

It has become evident that there are significant groups of process elements that are common within a particular process for different supply chain entities. Such consideration gives rise to the concept of process element framework, which is a set of related classes representing business activities that capture a reusable design for the process agents and integrate to implement it. In other words, the process element framework is a set of classes that users can customize or extend to address particular needs. Therefore, the framework emphasizes providing reusable design guidance rather than just code reuse, for developing supply chain process agents based on SCOR model. Frameworks are quite different from class libraries as they include dynamic aspects that are totally missing from class libraries (Papazoglou et al. 1999). The process element framework embodies business activities, architectural elements of a particular supply chain process and include information I/O and process logic built in this framework. For example, a plan delivery agent in manufacturing entity can be developed to model the plan delivery process based on a process element framework that involves four primary classes.

As shown in Figure 2, the requirement-aggregating class is responsible for identifying, prioritizing, and aggregating delivery requirement. The resource-aggregating class is responsible for identifying, assessing and aggregating delivery resources. Furthermore, the balancing class balances resources with requirement. Finally, plan-generating class will generate detailed delivery plan. Above all, Different manufacturers can fine-tune the framework to model their plan delivery processes.

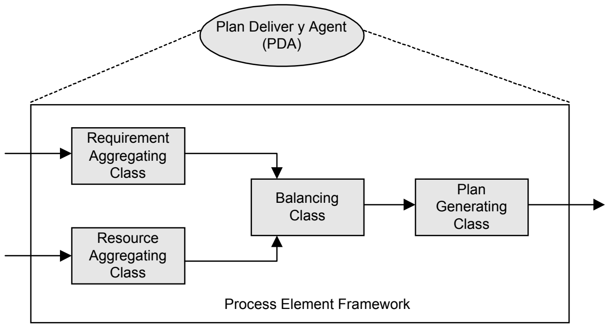

Figure 2: An Example of Process Element Framework

3.3 A Generic Agent Architecture

As described above, there are seven kinds of agents involved in the SCM support model. Every agent in the SCM support model owns its knowledge, interests, status information, message handlers, process element executors and policies. Even so, this research has defined a generic agent which is then specialized to represent different agents, perform different processes and conduct collaboration within a supply chain. For example, a source agent can be specialized from the generic agent to deal with those processes associated with obtaining, receiving, inspecting, holding and issuing materials and providing information for other agents. Moreover, different agents in this model communicate with each other through messages. Figure 3 shows the architecture of a generic agent in SCM support model combining with process element framework.

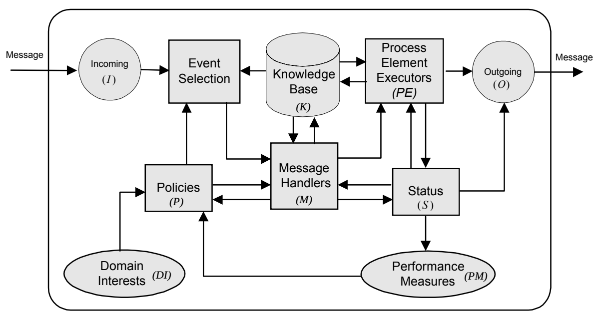

Figure 3: A Generic Agent Architecture

Incoming messages can be dealt with by each agent according to the event selection mechanism that is subject to some pre-determined policies such as first in first out (FIFO). All the messages are based on Knowledge Query and Manipulation Language (KQML) which is a language and protocol for exchanging information and knowledge (Finin et al. 1997). Then the selected message is passed to the message handlers to determine how to process the message and which process element executors are to be executed. Meanwhile, the policies such as inventory control, the knowledge and the status information will be applied and retrieved. At the same time, if the outgoing messages are generated, they are sent to the designated agents. Of course, the local performance of each agent may need to be measured and the policies may be revised according to the new performance information. It should be mentioned that the process element executors, which are derived from the process element framework, are the kernels as the agents are designed to be process-focused.

3.4 Flow Representations

As we know, it is the flows involved in supply chain that put the processes in motion. Actually, three kinds of flows are normally concerned in supply chain management. They are material flows, information flows and financial flows. Financial flows are more special and it will be neglected temporarily in this paper. However, material flows and information flows are clearly defined and represented with respect to the SCM support model.

Accordingly, the message-transferring paradigm is adopted considering the communications among agents and KQML is applied to regularize the message format and protocol as indicated earlier. In fact, the KQML based message-transferring mechanism has well understood semantics and offers a more abstract means of communication. It also provides greater comprehensibility, reliability and control over access rights. Moreover, it makes fewer assumptions about the multi-agent system architecture. Therefore, two scenarios of message transferring---information sharing and task sharing---are presented here with application to the representations of corresponding material and information flows (Jennings 1994).

Information sharing in Figure 4 can be regarded as the fundamental scenario of collaboration. Agents assist one another by spontaneously volunteering partial results which are based on different perspectives of the global problem. However, task sharing, which is shown in Figure 4, has much more interaction than information sharing. In this form of message transferring, one agent asks the others to perform some tasks for it more than just provide information. As a result, material flows and information

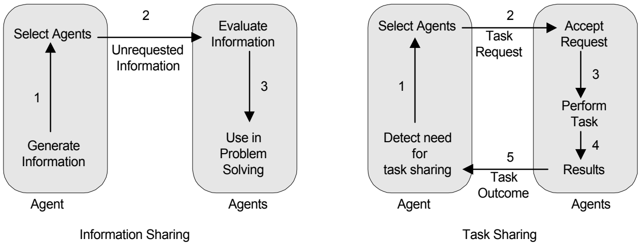

Figure 4: Two Scenarios of Message Transferring

flows in supply chain can be handled by combining these two message-transferring scenarios:

- *Material Flows*. Message transferring with respect to material flows mostly relates to the delivery of goods from one agent to another. In the SCM support model, an execution agent generates the messages directly relating to material flows. For example, when a delivery agent of a manufacturer delivers some products to a source agent of a distribution center, a message is sent from the delivery agent to the source agent. In other words, the processes associated with material flow messages mainly involve the update of inventory records of both message-sending and message-receiving agents. And most of the material flow messages are realized through information sharing process as depicted above.
- *Information flows*. Message transferring with respect to information flows models the exchange of information and contributes to the collaborating processes between supply chain agents. Either execution agents or planning agents in the SCM support model can generate this kind of messages. Most of information flow messages generated by execution agents may be triggered by a material flow message or based on a time phased checking activity. For instance, a material flow message received by a delivery agent may trigger the corresponding plan delivery agent to re-plan the delivery plan considering the existing inventory level. However, Information flow messages generated by planning agents are the common results. Anyway, both task sharing and information sharing scenarios have significant contribution to information flows. Especially, the task-sharing scenario will have great dedication to the collaborative processes introduced later.

4 VALIDATION OF SCM SUPPORT MODEL

After the SCM support model is briefly introduced, a fictitious PC assembling case will be investigated in this section. Though the case study herein is fictitious, the results found and experience acquired are also very useful for the successive research. Thus, the purposes of case study are outlined as follows:

- *Validate SCM support model (major purpose).*
- *Become familiar with multi-agent modeling*
- *Identify some needs for collaborative inventory management.*

4.1 Overview of PC Assembling Case

The case assumes that only one kind of product is manufactured and the capacity for the product is always adequate. There are three inventories in the manufacturing site: raw product inventory (RPI), work-in-process inventory (WIP), and finished goods inventory (FGI). PRI, which includes monitor, PC box, keyboard, mouse, and software, is sourced from different outside suppliers. The corresponding material flows are shown in Figure 5.

Safety stock at FGI is adopted in this model to cover the uncertainties that comprise demand uncertainty, supply uncertainty, and process uncertainty. And the calculation of safety stock is based on the common methods introduced by Chopra and Meindl (2000). In the meantime, the replenishment policy of FGI is assumed to be a continuous review, reorder point, order quantity (s,Q) control system (Silver et al. 1998).

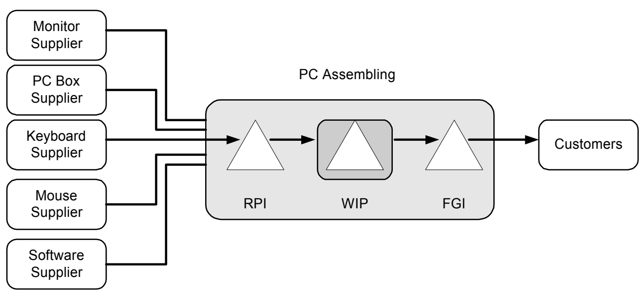

Figure 5: Material Flows of PC Assembling Case

4.2 Multi-Agent Simulation Model

The scenario described above is simulated with the software EXTEND™ developed by Imagine That , Inc. Therefore, the case based on the SCM support model is transformed to a simulation model. The built in, compiled C-like programming language, the message passing mechanism as well as other characteristics of EXTEND™ make it suitable as a tool to validate the multi-agent based SCM support model. As a result, the main interface of the discrete simulation is shown in Figure 6.

Meanwhile, a forecast agent is brought in the simulation to generate a demand forecast. At the same time, suppliers are modeled as the special delivery agents with adequate materials (that is, the non-availability of materials from suppliers is transformed to the changes of lead time). Table 1 briefly shows the agents involved in this model and their corresponding processes.

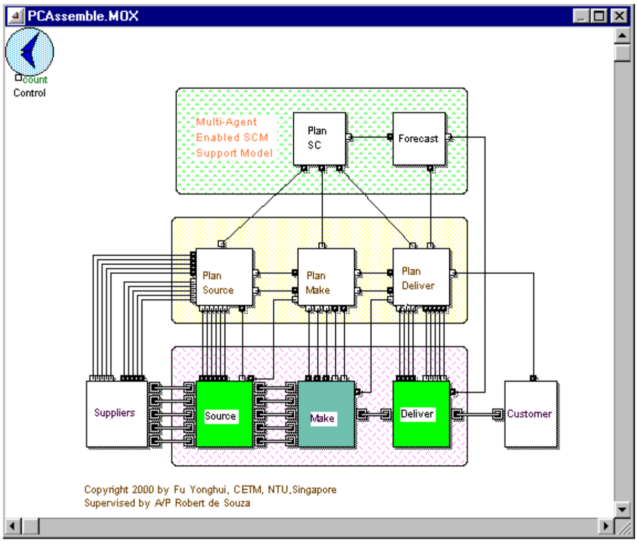

Figure 6: Main Interface of Simulation Model

Table 1: Agents and Their Corresponding Processes

Agents	Corresponding Processes
Delivery Agent	Enter and maintain orders; Fill orders; Deliver products to customers; Provide FGI status
Make Agent	Production; Provide WIP Status
Source Agent	Order Materials; Provide RPI Status
Plan Delivery Agent	Determine Inventory Replenishment Policy; Generate delivery plan
Plan Make Agent	Generate Make Plan
Plan Source Agent	Generate Source Plan
Plan SC Agent	Determine Service Level; Plan Safety Stock
Forecast Agent	Generate a demand forecast (This report assumes that the forecast is obtained based on POS data)
Suppliers' Delivery Agent	Fill orders; Deliver materials to the manufacturer

4.3 Partial Simulation Results

4.3.1 Simulation with Demand Uncertainty

As shown in Figure 7, the normally distributed demand is plotted on the left half. The results of FGI information on the right half of this figure indicate that the FGI undergoes some stockout even though the safety stock has been applied. And, the cycle service level is about 77 percent. As such, the replenishment lead time varies from one replenishment cycle to another replenishment cycle. However, the multi-agent based simulation model works reasonably, as the results got from the simulation is consistent with the expected results from those well-known mathematical models as introduced by Chopra and Meindl (2000).

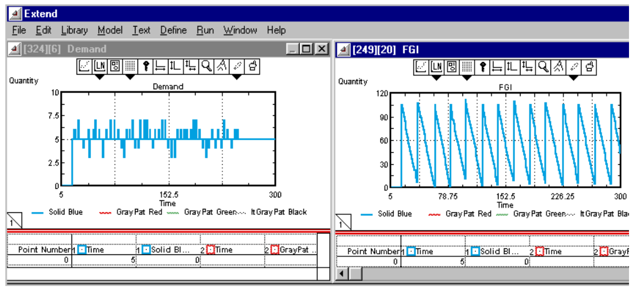

Figure 7: FGI Results with Demand Uncertainty

4.3.2 Simulation with Both Demand and Lead Time Uncertainty

For simplification, the simulation now considers the source lead time uncertainty of PC box. As it can be seen on the right half of Figure 8, the FGI undergoes more stockout comparing with the situation in Figure 7 when the safety stock is same. The cycle service level here is rather lower with only 62 percent. Moreover, the replenishment lead time varies more from one cycle to another. Even so, the simulation results are still reasonable comparing with the analytical results from some mathematical models.

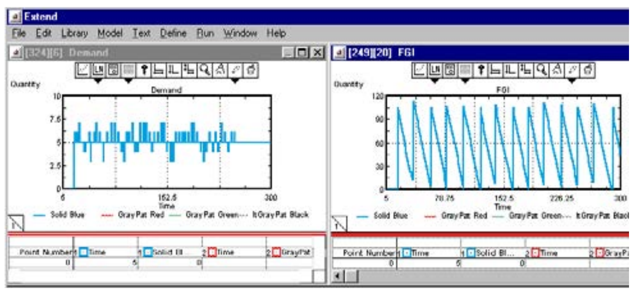

Figure 8: FGI Results with Both Demand and LT Uncertainty

4.4 Simulation Implications and Opportunities

The simple simulations have been conducted so far. However, the simulation implications as well as some opportunities should be accentuated:

- It is testified that the multi-agent based simulation model works properly. The modeling methodology of SCM support model is validated based on the case.

- Demand uncertainty has impacts on inventory, especially on safety stock. However, in this case the calculation of safety stock uses the same value of variance during the simulation time. It is appropriate when the expected demand is a stationary such as this case. However, when the demand has some trends, it might cause big problems. For instance, when the demand is decreasing or even approaches the end of product's life cycle, many inventory excesses can be resulted. Therefore, more demand information should be incorporated into the decisions on inventories.
- Lead time uncertainty also has impacts on safety stock. The situation will be even worse when lead time uncertainties interact with demand uncertainty. However, source lead time is affected by the availability of products on supplier's site. In other words, source lead time is the function of supplier's service level. In addition, the supplier's service level itself is the function of its safety stock. Therefore, safety stock on one site of supply chain cannot be determined separately. The intuition is to determine safety stocks simultaneously across the supply chain. However, detailed models and solutions are necessary. Considering the ability of multi-agent system, through collaboration to solve this problem is appropriate. In other words, this calls for the collaborative inventory management to synchronize the decisions and actions.

5 A FRAMEWORK OF COLLABORATIVE INVENTORY MANAGEMENT

So far, the process oriented multi-agent SCM support model has been briefly introduced and validated. However, the limits in achieving the objective of effective inventory management across the supply chain might lie in the ability to collaborate on both decisions and actions as indicated before. And the needs for collaborative inventory management have been investigated during the simulation. As a result, a theoretical framework of collaborative inventory management is addressed in this section to refine and extend the SCM support model. The ultimate goals are to synchronize the consumer trend or ordering information and synchronize the inventory decisions across the supply chain network. The framework is shown in Figure 9.

As we can see, this framework involves three stages. Stage one is collaborative demand forecasting, the objectives of which are to obtain a synchronized demand forecast and identify the modes of product movements. This synchronized and shared demand forecast as well as the modes of production movements can then become the foundation for inventory planning and replenishment. Accordingly, collaborative inventory planning in stage two contributes to positioning inventories across the supply chain network with respect to the results got in collaborative demand forecasting. However, this stage at present mainly places the safety stocks across the supply chain network considering the uncertainties involved. Even so, different policies of each entity in terms of make-to-order or make-to-stock are concerned in general. Finally, stage three, namely collaborative replenishment, facilitates the collaborative inventory management in operations.

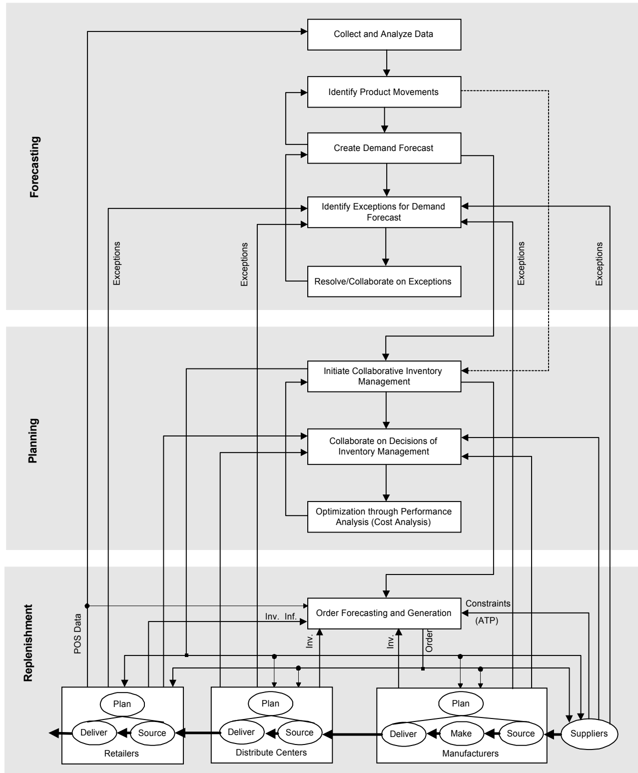

Figure 9: The Framework of Collaborative Inventory Management

Even though the framework of collaborative inventory management has provided some distinctive processes for synchronization among supply chain partners, more detailed mathematical models as well as algorithms and solutions are still necessary to support those processes especially in the stage of collaborative inventory planning. Consequently, the on-going research proposes an idea to map the issues of collaborative inventory planning into a distributed constraint satisfaction problem (DCSP) (Yokoo et al. 1998). At present, we have developed a basic mathematical model that is used to form and solve the DCSP, and thus reach the objectives of collaborative inventory planning. The basic mathematical model supposes that safety stock for a entity of supply chain can not be determined by solving a single-entity material flow problem independently because the replenishment lead time at a entity is a function of the service levels at upstream entities where stock the required items. As a result, the safety stocks for all entities can be obtained simultaneously by collaborating through agents to solve a distributed problem in which the objective is to minimize supply chain network-sized inventory costs subject to service-level constraints on the end-products. However, detailed mathematical models will not be discussed in this paper. Besides, two additional agents are proposed according to the framework. One is the marketing agent, which is in charge of the processes involved in collaborative demand forecasting. The other is supply chain inventory planning agent. This agent initiates and conducts the collaborative inventory planning. Both agents should communicate and collaborate with those agents in the SCM support model. Simulation of this framework introduced in the section will be another episode towards the collaborative inventory management.

6 CONCLUSIONS AND FUTURE WORK

The paper addresses the preliminary approach towards the collaborative inventory management in supply chains, taking advantage of multi-agent technology in terms of modeling and simulation. The conceptual and theoretical results of this paper are crucial to reach the objectives of collaborative inventory management.

However, further approach should be concerned in the future work. It includes:

- Refining the framework of collaborative inventory management as well as the SCM support model in theory.
- Further evaluating the framework of collaborative inventory management using multi-agent based simulation with EXTEND™. A case could be detailedly studied.
- Programming a prototype for collaborative inventory management. At present, the prototype is being designed on the agent platform JATLite which is developed and provided by Stanford University `<http://java.stanford.edu>`.

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