A Framework for Multi-Agent System-Based Dynamic Supply Chain Coordination

Li Zhengping, Malcolm Yoke Hean Low
zpli@simtech.a-star.edu.sg, yhlow@simetech.a-star.sg
Production and Logistics Planning Group
Singapore Institute of Manufacturing Technology
71 Nanyang Drive, Singapore 638075

Arun Kumar
mjiao@ntu.edu.sg
Center for Supply Chain Management
School of Mechanical and Production Engineering
Nanyang Technological University
Singapore 639798

Abstract

Coordination is defined as the management of interdependencies of activities. Due to the complexities of supply chain, the coordination of activities among all the parties involved in the supply chain is quite challenging. This paper proposes a framework for supply chain coordination and optimization by applying agent technology. The research aims to automate the coordination and optimize the decision-making tasks of a supply chain. A prototype based on the proposed framework and the process flow in a typical supply chain is also presented in the paper.

Keywords: supply chain, agent, coordination, 4PL.

1. Introduction

Supply chain management (SCM) aims to produce and distribute merchandise to customers in the right quantities, to the right locations, and at the right time, with minimized system-wide costs, while satisfying service level requirements. However, the complexities of supply chain make it difficult to achieve the objective. Coordination of the activities among supply chain partners is one of the critical challenges in the management of supply chain network that is composed of organizations with different and even conflicting organizational objectives.

It is futile to optimize the operations within a single party involved where the overall system performance will still be poor. The coordination must be efficient and effective such that the best combination of decisions is made. These decisions include selecting the right manufacturer, transporter and supplier, purchasing the right amounts of material, and producing the right finished goods. The task in establishing the global optimized solution involves a tremendous amount of decision making, and in many cases decisions have to be made based on insufficient and dynamic information. This causes the coordination and decision-making processes to be difficult, iterative and time consuming.

An agent is a computer system situated in a certain kind of environment, and that is capable of autonomous action in the environment in order to meet its designed objectives (Jennings and Wooldridge, 1998). A multi-agent system (MAS) is a loosely coupled network of software agents that interact to solve problems that are beyond the individual capacities or knowledge of each problem solver. Agent-based systems technology has been hailed as a new paradigm for conceptualizing, designing, and implementing software systems. Such systems may be used for distributed control, distributed resource management, optimization, and electronic marketplaces. MAS enhances overall system performance, specifically along the dimensions of computational efficiency, reliability, extensibility, responsiveness, reuse, maintainability, and flexibility. Multi-agent based system is capable of solving (faster and closer to life) the problem of matching supply to demand and allocating resources dynamically in real time, by recognizing opportunities, trends and potential problems, as well as carrying out negotiations and coordination.

This paper puts forth the viewpoint of applying agent technology to automate and optimize the coordination and decision-making processes in a typical supply chain. An agent-based supply chain coordination prototype and the related process flow are also described.

2. Application of Agent Technology in SCM

Agents act autonomously on behalf of their users across open and distributed environments. In recent years, many researchers have used multi-agent technology in supply chain modelling and management. In agent-based modelling, organization units and processes are designed as agents that have their particular objectives, behaviours and interfaces. Agents exchange messages for communication and coordination purposes. Intelligent decision and learning rules are defined in agents. Supply chain performance is supposed to be improved by the coordination and collaboration between agents.

Enterprise Integration Laboratory (EIL) at the University of Toronto explored the modelling of enterprise and supply chain (Beck and Fox, 1994; *Barbuceanu, M. and Fox, M.S., 1995*). They organize a supply chain as a network of cooperative intelligent agents, and address coordination at the tactical and operational levels. Their work tries to support the construction of supply chain intelligent agent systems in a manner that guarantees that agents use the better communication, coordination and problem solving mechanisms available with minimal program effort. Fu, Gek and Michael (1999) proposed a multi-agent enterprise modelling method for extended enterprise modelling. They studied the dynamics of business processes and interactions between business units in an enterprise, and developed a framework for enterprise modelling using process hierarchy approach. Swaminathan et al. (1996, 1998) described a simulation-based framework for developing customised supply chain models from a library of software components. These components capture generic supply chain processes and concepts, thereby promoting modular construction and reuse of models for a wide range of applications. In addition, many other investigations have studied the application of multi-agent technology in supply chain modelling and management (Lin et al 1998, 1999; Strader, 1998; Yung and Yang, 1999; Parunak et al., 1998; Moore et al., 1997).

Due to the complexities in supply chain, the representation of the coordination of activities, inter-organization interdependency, and the synergy of supply chain are challenging issues. The application of agent technology in SCM is appropriate and it is still in research. However, despite the potential advantages, agent technology remains relatively immature, and we have yet to establish, test and verify good design principles and techniques (Wooldridge, Jennings and Kinny, 1999), especially for the complex and dynamic supply chain environment. It is not enough to just use the agent concept to model the entities and processes in a supply chain. There is a need to provide method to describe complexities of supply chain interdependencies and coordination mechanism, and also implement and test the concepts and design. The combination of coordination technology and optimization technology is a way to improve performance in an agent-based supply chain coordination system.

In this paper, coordination theory, optimization technology and agent technology is employed to model and automate the coordination process and to converge at a “global best solution”. A framework and a set of techniques for agent-based supply chain coordination and optimization in distributed environment are proposed.

3. Framework for Agent-based Supply Chain Coordination

The research interest of the project is originally from industry. For example we meet the CD-ROM manufacturing and distribution scenario (Figure 1) in computer industry. In this scenario, a computer manufacturer may wish to focus on its core business. It receives the customers’ demand and outsource its CD-ROM logistics solution to a Fourth Party Logistics (4PL), which is responsible for finding the right manufacturer, printing plant and packing and labelling service provider and also the transporters. The 4PL acts as a supply chain integrator that assembles and manages the resources, capabilities, and technology of its own organization with those of complementary service providers to deliver a comprehensive supply chain solution to the client. This paper applies 4PL concept and addresses the coordination and decision-making process in supply chain. The 4PL is actually the logistics coordinator and integrator that links to all the relevant companies and it consolidates the global information and plays an important role in the coordination and allocation of resources.

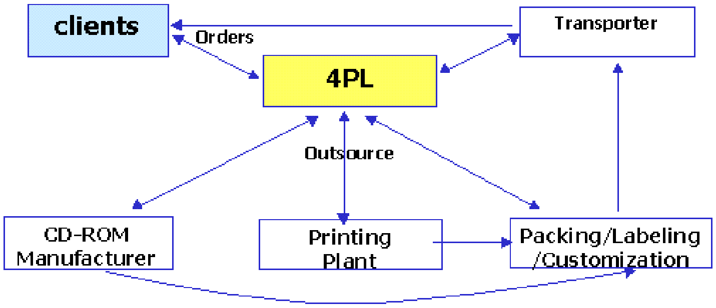


Figure 1: Industry context - CD-ROM 4PL model

The actors in a supply chain could be defined as agents that do not exist in isolation. They relate to or depend upon one another, either through the interactions of their activities or the relations of their common goals. The ability to coordinate their behaviours and manage their interdependencies is crucial for supply chain systems. Following Wexler's (2000) saying "Today, the mission of one institution can be accomplished only by recognizing that it lives in an interdependent world with conflicts and overlapping interests", we argue that the missions of supply chain system can be achieved only by recognizing that individual enterprises are living in an interdependent environment with conflicts, overlapping interest, and mutual dependencies. This motivates our research in constructing a framework that deals with agent-based supply chain coordination and performance improvement based on interdependencies management in volume, inventory, time, and price, etc.

Supply chain coordination is analyzed in the context of a typical logistics scenario. The scenario consists of a variety of manufacturers, suppliers, and logistics service providers. A case study in the PC industry is used in this research. Computer Co. is a leading PC manufacturer and distributor. As a worldwide leader in computing, Computer Co. offers the best in integrated solutions. It has regional headquarter (coordination center) and a manufacturing site in Singapore to make Storage Processing Unit (SPU). It outsources components from Taiwan, and China for various models. The packed home PCs are distributed to the Asia Pacific region through two distribution centers in Singapore and Australia. In the problem domain, the studied scenario includes one distribution center, two logistics coordinators (4PL), two transporters and two manufacturers (Figure 2).

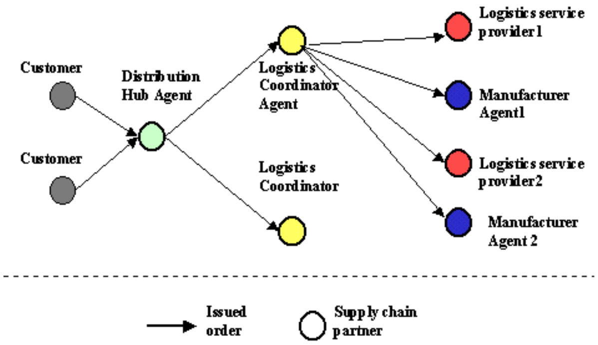


Figure 2: Order network in a supply chain

The coordination structure of a supply chain consists of basic coordination structures – product hierarchy, decentralized market and function broker (Li, Kumar and Lim, 2001). The 4PL model shown in Figure 2 complies with the function broker coordination structure. The links between the organizations represent the issued orders and suborders resulting from one or more customer orders. The distribution hub consolidates customer demand and produces orders for logistics coordinators (4PL). The logistics coordinator acts as a function broker that is linked to multiple manufacturers and transporters who provide the manufacturing and logistics services. The scenario could be more complex. For example, the manufacturer could further outsource components and services to other suppliers and logistics service providers.

Coordination agents are designed to accomplish order coordination tasks in organizations. These agents are Distribution Hub Agent, Logistics Coordinator Agent, Manufacturer Agent and Transporter Agent. These four types of agents represent the generic role in a typical supply chain. They may also link to other agents such as inventory management agent and planning application to get necessary information. The sequence of task flow is depicted in Figure 3 below. The Distribution Center will send its distribution requirement (DRP) to a Logistics Coordinator who will transform the DRP into transport and manufacturing requirements. These requirements will be broadcast to the available transporters and manufacturers so that they could work on their bids. After the bids are received, the logistics coordinator will work on a global optimized solution before committing the distribution centers.

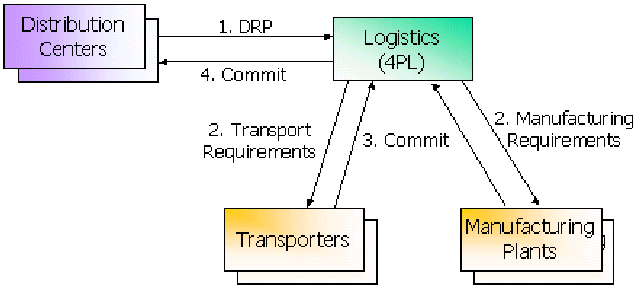


Figure 3: Framework for agent-based supply chain coordination

The agent-based supply chain coordination system outlined here is based on Foundation for Intelligent Physical Agents (FIPA, 2003) standards. These standards define basic technical applications and services needed in a multi-agent environment. An architecture for agent-based distributed logistics coordination has been designed (Figure 4) based on JADE agent platform (Bellifemine et al. 1999; JADE, 2003). Each participant of a supply chain provides the agent platform with a set of agent instances. The agent platforms are linked via Internet connections. This platform includes basic management agents and application agents. Basic management agents include Registration Agent, Communication Agent, and Directory Agent to facilitate the creation and management of application agents. The logistics management agent is actually an instance of the application agent, which is used to coordinate and produce the optimized logistics decision. The application agent includes interface, activation controller, optimization/planning modules, and knowledge base. Different supply chain planning/optimization modules such as demand forecasting, transportation/manufacturing planning could be incorporated into the platform.

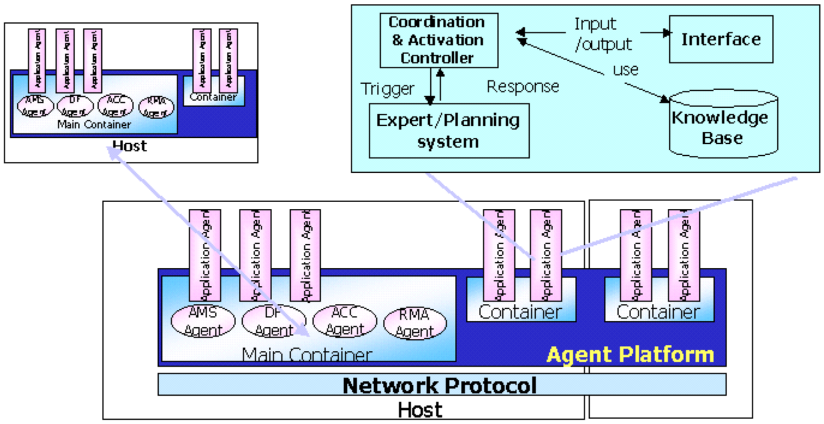


Figure 4: Platform of agent-based distributed logistics coordination

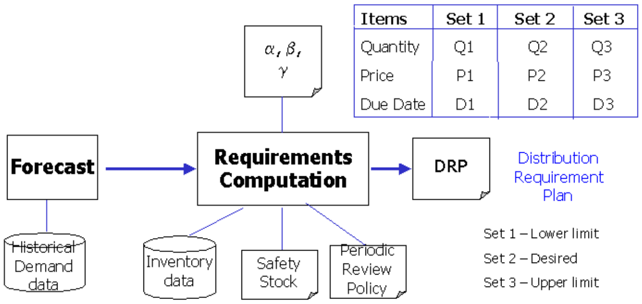
4. Agents in a Supply Chain Coordination System

Based on the above framework, four types of coordination agents have been designed in a developed prototype system. These agents are coordination agents in the corresponding supply chain organizations. There could also be other agents such as Information Agent and Planning Agent in the same organizations. The function, coordination process and interface of the coordination agents are introduced in this section.

4.1 Distribution Hub Agent

To establish the DRP, the Distribution Hub Agent will perform distribution requirement computation using inventory data, safety stock information, periodic review policy, and forecasted demand produced by an external forecasting application (see Figure 5). Each DRP requirement consists of 3 sets of data points. Each set is composed of 3 parameters, namely quantity, price and due date. The "Price" is the summation of all the prices for both manufacturing and transportation, and the "Due Date" refers to the final date when the Distribution Center can receive the product. While set 2 denotes the desired quantity, set 1 and 3 denote the upper and lower limits of the values.

In addition, a set of weighting factors will be established to determine the relative importance of the 3 parameters. If quantity is critical for the order, then it will carry heavier weighting as compared to price and due date. These weightings are important when the logistics provider attempts to search for the global best solution.



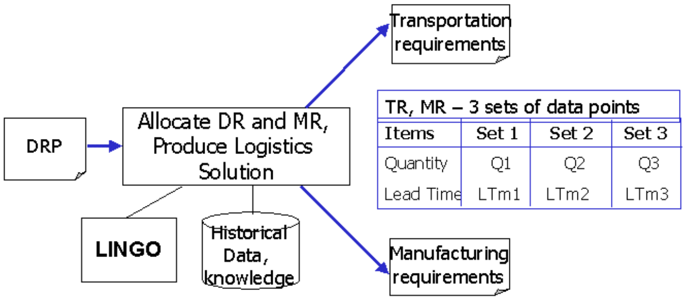
Items	Set 1	Set 2	Set 3
Quantity	Q1	Q2	Q3
Price	P1	P2	P3
Due Date	D1	D2	D3

Figure 5: Distribution Hub Agent

4.2 Logistics Coordinator Agent

On receiving the Distribution Requirement, the Logistics Coordinator Agent understands the needs of the Distribution Hub Agent. The requirement includes three sets of parameters. Each set includes three items named "Quantity", "Due Date" and "Price". The Logistics Coordination Agent shown in Figure 6 transfers the "Due Date" into total "Lead Time". The Logistics divides the total Lead Time into "Lead Time for Manufacturer (LT_M)" and "Lead Time for Transporters (LT_T)".

In accordance with the different sets of parameters given by the Distribution Hub, the requirements given to the Manufacturing Plants and the Transporters are three sets of data represented as (Q_1, LT_{M1}), (Q_2, LT_{M2}), (Q_3, LT_{M3}) and (Q_1, LT_{T1}), (Q_2, LT_{T2}), (Q_3, LT_{T3}). Here the "Price" afforded by the Distribution Center is not given to the Manufacturer and the Transporters because it could be a confidential parameter. The Transporter and Manufacturer Agents will bid for the task with prices. The Logistics Coordinator Agent will also coordinate with the Transporters and Manufacturers to reach a feasible and optimized global logistics solution, which will be introduced later.



TR, MR – 3 sets of data points			
Items	Set 1	Set 2	Set 3
Quantity	Q1	Q2	Q3
Lead Time	LTm1	LTm2	LTm3

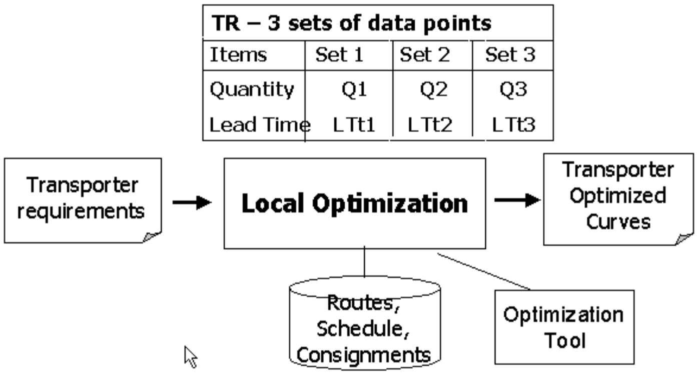
Figure 6: Logistics Coordinator Agent

4.3 Transporter Agent

Transporters provide pickup and delivery services from the source to the destination terminals. The operation decisions facing a Transporter Agent include:

- Select the right mode(s) of transportation based on costs and lead time,
- Consolidate consignments for economies of scale,
- Calculate and reserve freight space with the long haul providers,
- Produce the commitments with different quantities, lead time and price information.

The transporter agent receives the transportation requirement and conducts local optimization to produce candidate transportation commitments. It will perform local optimization using its data on routes, schedule and consignments (see Figure 7).



TR – 3 sets of data points			
Items	Set 1	Set 2	Set 3
Quantity	Q1	Q2	Q3
Lead Time	LTt1	LTt2	LTt3

Figure 7: Transporter Agent

The coordination and optimization will produce candidate points with quantity, price and lead time. These points are obtained based on minimizing price as the objective function and varying the lead time over a small range. The solution to this routing-cum-load distribution problem could be approached using the Transshipment Model we studied. The transportation task refers to the consignment order. Each consignment order is defined by its identity number *i*, pickup and delivery points, and source and destination terminals. The consignment is broken up into a number of individually transportable pallets for flexibility in transportation, denoted by *m*. Along each route there may be a varying number of modes based on the services available. Handling and warehousing charges at intermediary nodes have also been considered. The objective function for the Transportation Decision Model is defined as:

$$Min\left\{\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{k_{ij}}(((\sum_{l=1}^{L}\sum_{m=1}^{m_l} P_{lm}\lambda_{ijklm})*C_{ijk})+\sum_{l=1}^{L}\sum_{m=1}^{m_l}P_{lm}\lambda_{ijklm}*(Cw_i*WT_{ilm}+Cl_i))\right\}$$

λ_{ijklm} : A binary decision variable indicating whether the l^{th} consignment's m^{th} pallet will travel from node i to j using mode k.

P_{lm} : Indicates the size of l^{th} consignment's m^{th} pallet.

WT_{ilm} : Waiting time at node i for the l^{th} consignment's m^{th} pallet.

C_{ijk} : Unit transportation cost.

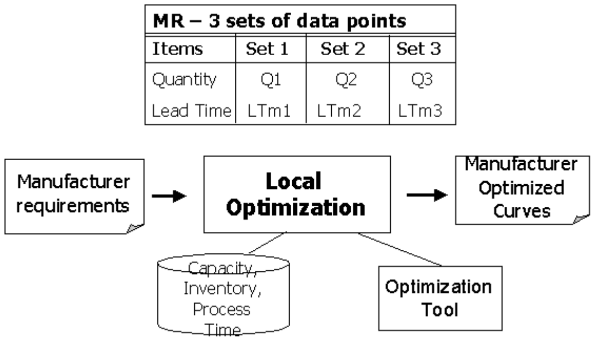
Cw_i : Unit loading cost at node i.

Cl_i : Unit waiting cost at node i.

4.4 Manufacturer Agent

Similarly, the Manufacturer Agent receives the manufacturing requirements from the logistics coordinator and conducts local optimization to find feasible manufacturing solutions. The solutions actually are solution points (specified with quantity, lead time and price information) and are provided to the logistics coordinator agent for selection.

The function of the Manufacturer Agent is to produce the required products within required order lead time with minimized cost (Figure 8). So the objective function is defined as *[Min (Cost = Fixed Cost + Variable cost)], w*here, *Variable cost = material cost + process cost+ storage cost+ inventory holding cost; Fixed cost = setup cost + tooling cost+ overhead cost.* The local optimization uses the information of material requirement plan, capacity, inventory, manufacturing process and lead time. The minimizing of the total cost is subject to a set of constraints, such as quantity constraints, capacity constraints, customer service level and lead time.



MR – 3 sets of data points			
Items	Set 1	Set 2	Set 3
Quantity	Q1	Q2	Q3
Lead Time	LTm1	LTm2	LTm3

Figure 8: Manufacturer Agent

5. Supply Chain Coordination and Optimization Model

In this section, supply chain coordination and optimization will be introduced based on our prototype system. In the distribution requirement from Distribution Hub Agent, a software Forecast Pro is used for forecasting. Based on forecasted demand established, the Distribution Hub Agent calculates the distribution requirements. Thereafter the Distribution Hub Agent can pass the DRP to the Logistics Coordinator Agent by pre-defined data interface.

The logistics coordinator splits the requirement into manufacturing and transportation requirements. Because the demand information may have been consolidated, the Manufacturing Plant would not care about the due date to deliver the goods to the Distribution Center. Instead, they must know when the product should be ready for the Transporters.

Order from Distribution Center

Items	Set 1	Set 2	Set 3	Weight
Quantity	Q_1	Q_2	Q_3	α
Due Date	D_1	D_2	D_3	β
Price	P_1	P_2	P_3	γ

Order to Manufacturing Plants

Items	Set1	Set2	Set3
Quantity	Q_1	Q_2	Q_3
Lead Time	LT_{M1}	LT_{M2}	LT_{M3}

Order to Transporters

Items	Set1	Set2	Set3
Quantity	Q_1	Q_2	Q_3
Lead Time	LT_{T1}	LT_{T2}	LT_{T3}

Table 1: Dividing the Distribution Requirement

The Logistics Coordinator Agent divides the distribution requirements based on a historical knowledge base. In this database, the records show for a product, how long it will take for the Manufacturing Plants to produce a specific quantity, and how long it will take for the Transporters to deliver as shown in Table 1.

In the first round of coordination, the "Price" afforded by the Distribution Center is not given to the Manufacturing Plants and the Transporters. Instead, the Logistics Coordinator waits for the service providers to bid with price. The Transporter Agents perform local optimization using their own data on routes, schedules and consignments. The Manufacturer Agents will perform local optimization using data on inventory, capacity and processing times. The results of the optimization will be transferred to the Logistics Coordinator Agent for global optimization.

5.1 Global optimization by Logistics Coordinator Agent

After the Manufacturer and Transporter Agents finish local optimization process, they will commit the orders back to the Logistics Coordinator Agent. The Logistics Coordinator Agent will attempt to combine the respective commitments to produce joint commitments by summing up price and lead times (for Q1, Q2 and Q3 respectively). A Manufacturer Agent will summit three different sets of parameters, namely the preferred, upper limit, lower limit Lead Time, and their corresponding prices for each quantity. Once the Logistics Coordinator Agent receives these local optimization commitments, it combines them accordingly. For the two sets of data (with the same quantity) coming from the Manufacturers and the Transporters, the total price can be achieved by adding the price of the Manufacturer (P_M) to the price of the Transporter (P_T). To calculate the Due Date, the Logistics Coordinator Agent will combine the lead time of the Manufacturer (LT_M) and the lead time of the Transporter (LT_T) to get the total lead time of the product. Based on this total lead time, the Due Date of the product can be easily obtained. Table 2 shows examples of commitment of Manufacturers and Transporters and corresponding combined commitments. The combination of the commitments from the Transporters and Manufacturers can create multiple sets of candidate points as shown in Table 2.

Using the combined candidate points, the global optimization objective is to minimize the difference between the ask and bid in order quantity, lead time and price, and improve supply chain performance. The optimization function can be defined as:

$$Min(V = \sum_j f_j(X_j) \times w_j)$$

where $f_j(X_j)$ is the difference between the order and the bid and W_j is the importance coefficient.

Items	Set1	Set2
Quantity (K)	8000	8000
Lead Time (Day)	9	12
Price (K$)	260	180

Commitment from the manufacturer

Items	Set1	Set2
Quantity (K)	8000	8000
Lead Time (Day)	7	9
Price (K$)	38	34

Commitment from the transporter

Items	Set1	Set2	Set3	Set4
Quantity (K)	8000	8000	8000	8000
Lead Time (Day)	16	18	19	21
Price (K$)	298	294	218	214
Due Date	Aug 17th	Aug 19th	Aug 20th	Aug 22nd

Combined Commitment

Table 2: Commitments from manufacturers and transporters and their combination

The objective function is used to find and choose the optimal solution - the point with the minimum value of *V*. The optimization searching process is to find the optimal point (see Figure 9) which with acceptable difference with that of the customer requirement (with quantity, price and due date). If the point identified is still not acceptable, a boundary box will be defined around the optimal point to set the lower and upper limits so that a second round of bidding can be done. This process will be repeated until the solution converges.

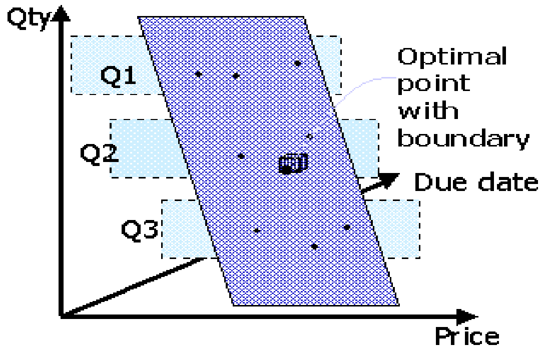


Figure 9: The search for global optimal solution

After the optimal values for the product quantity and lead time are obtained, the Logistics Coordinator Agent then returns these suggested values to the selected manufacturers and transporters to allow them to calculate the corresponding prices, which the Logistics Coordinator Agent will compare the price result with the solution achieved by data matching. The Logistics Coordinator Agent may submit the solution with the lowest price to the Distribution Hub Agent.

5.2 Performance

The performance requirement of a supply chain is to match the supply with demand in volume, time and price with lowest cost. Hence the performance index used here is cost and is based on the matching of demand and supply with a minimum V value. For testing, we have selected 2 closely correlated products (see Table 3), which are manufactured and distributed in the Asia-Pacific region.

	Product A:	**Product B:**
	Zip drive	*CD-ROM drive*
Distributor price	*$175*	*$42*
Retail price	*$250*	*$60*
Mean DC demand	*500 units*	*800 units*
Mean Aggregate demand	*3000 units*	*20000 units*
Physical weight	*0.15kg*	*0.25kg*

Table 3: Product profile for performance testing

From Ballou (1999), the insights gained in the distribution of costs as a percentage of sales helped to establish the guideline on the proportion of manufacturing cost and transportation cost, so as to submit reasonable bids. The following variations are considered in scenario determination:

- Number of orders from distribution center – 2 (quantity 500 and 400) over two consecutive time periods;
- Capacity – 2 levels (High and Low);
- Number of manufacturers and transporters – 2 each;
- Lead time – 2 levels (LT1 and LT2 where LT1: 13 days for manufacturers and 8 days for transporters, and LT2: 17 days for manufacturers and 4 days for transporters).

	Order 1 (500)		**Order 2 (400)**	
Scenario	**Worst**	**Best**	**Worst**	**Best**
1	61.84%	0.00%	54.27%	3.98%
2	56.84%	1.20%	66.86%	9.40%
3	61.84%	0.00%	65.93%	0.00%
4	58.25%	1.20%	63.63%	12.70%
5	61.84%	0.00%	60.52%	3.98%
6	56.84%	1.20%	65.88%	9.40%
7	61.84%	0.00%	65.93%	0.00%
8	58.25%	1.20%	62.23%	0.85%
9	62.26%	0.00%	60.47%	3.95%
10	57.39%	1.19%	66.55%	21.03%
11	62.26%	0.00%	65.85%	0.00%
12	58.76%	1.19%	63.56%	12.60%
13	62.26%	0.00%	60.47%	3.95%
14	57.39%	1.19%	65.79%	9.32%
15	62.26%	0.00%	65.85%	0.00%
16	58.76%	1.19%	63.79%	0.56%
Avg	59.93%	0.60%	63.60%	5.73%

Table 4: Percentage of system-wide cost savings for Order 1 & Order 2

16 scenarios each were tested for order quantities of 500 units and 400 units from the customer for 2 manufacturers and 2 transporters to submit their bids. These 16 scenarios illustrate different combinations of capacity availability (High and Low) for the manufacturers and transporters. Table 4 below gives the percentage system-wide cost savings of the test runs for Order 1 and for Order 2 from the application of our proposed solution against the traditional practice. From the test results, we can see that the proposed solution model can achieve as high as 21% savings as

compared to the best case of traditional practice, and an average of 60% as compared with the worst case (Li et al., 2002).

6. Conclusions

This paper presented an approach of applying agent technology to automate the coordination and decision-making tasks. Its main features, which differentiate it from other approaches, are the following: (1) In the proposed framework, coordination and optimization are combined and built into the supply chain coordination agents which have both cooperation and competition patterns; (2) A prototype system is developed and can be used to testing the agent-based coordination and optimization models; (3) Our approach could be used to produce and verify innovative models for business issues faced by the participants in a supply chain.

The first version of our prototype of multi-agent system-based supply chain coordination has been implemented. Our solution model has achieved high savings from the test results. The improvement and implementation is still in progress. Further research issues include: (1) Improve the optimization and coordination models so that it is more suitable for real-time optimized decision-making; (2) Design supply chain ontology for the knowledge-based coordination in the prototype system.

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