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An extended contract net mechanism for dynamic supply chain formation and its application in China petroleum supply chain management

Jiang Tian[a], Richard Foley[a], Xin Yao[b] and Huaglory Tianfield[a,*]
[a]*School of Computing and Mathematical Sciences, Glasgow Caledonian University, Glasgow G4 0BA, UK*
[b]*School of Computer Science, University of Birmingham, Birmingham B15 2TT, UK*

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Abstract. Software agents representing supply chain partners make it possible to automate supply chain management and particularly can address the challenging problem of automating the process of dynamic supply chain formation. This paper puts forward an extended contract net mechanism for dynamic supply chain formation and applies it to China petroleum supply chain management, which is characterized by a semi-monopolized market, where conventional negotiation protocols are limited because they are based on the assumption of a pure market. The proposed multi-agent negotiation mechanism is algorithmized and validated in two scenarios of dynamic supply chain formation, i.e., semi-monopolized market and emergency, respectively.

Keywords: Dynamic supply chain formation, extended contract net mechanism, multi-agent system, supply chain management, multi-agent supply chain management

1. Introduction

Roughly speaking, computerization of enterprise systems has evolved over three levels. At the basic level, departmental business processes and workshop-wide processes in an enterprise, such as design, procurement, production, assembling, and distribution, are automated. For example, Computer Aided Design (CAD) automates the routine activities of design, Materials Requirements Planning (MRP-I) automates material supply scheduling, Computer-Aided Process Planning (CAPP) automates production planning and control, and Customer Relationship Management (CRM) automates the management of customers profiles and the interdependent relationships. At the middle level, enterprise-wide business processes and workflows are automated. For example, Manufacturing Resource Planning (MRP-II) and Enterprise Resource Planning (ERP) automate the planning and monitoring of various interdependent plans and improve the utilization of various resources within an enterprise. The recent trend for computerization of enterprise systems is at the top level, where the automation of inter-enterprise business processes is particularly aimed at. Supply chain management (SCM) is one of the most typical inter-enterprise problems. In today's business environments, enterprises have to focus their own operations in the fields of their core competence. Multiple enterprises in

*Corresponding author: School of Computing and Mathematical Sciences, Glasgow Caledonian University, 70 Cowcaddens Road, Glasgow, G4 0BA, United Kingdom. Tel.: +44 141 331 8025; Fax: +44 141 331 3608; E-mail: h.tianfield@gcal.ac.uk.

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a supply chain have to come together to form a strategic consortium which as a whole provides customers with well-packaged products or services. SCM is basically to form strategic partnerships and achieve cooperation among the multiple enterprises in a supply chain.

How to automate SCM processes has remained a highly challenging problem. While information technologies such as Electronic Data Interchange (EDI) and e-commerce have enhanced the information exchange and workflow interoperation, enterprise cooperation among the multiple enterprises in a supply chain has not been significantly evolved. Two main reasons may be attributable. First, the information infrastructure as required to support the dynamism of SCM [7] is far from flexible, which largely limits the dynamic reconfiguration of a supply chain. Second, SCM still has to rely upon rigid, linear and centralized methods, and thus the cooperation between supply chain partners is not optimized and agile in most cases.

Relationships between supply chain partners can be intricate. Suppliers or customers in a supply chain may have their own suppliers or customers, and different supply chains may overlap when the same partners simultaneously participate in different supply chains. Overlapping of supply chains results in the partners in one supply chain acting as competitors for another supply chain [2,3,13,33]. Most prominently, relationships between supply chain partners are inherently dynamic. In real-world business environments, supply chain partners are independent enterprises, and have their own motivations and goals. Only coming to cooperate with their own interests, supply chain partners may join or leave a supply chain based on their own judgment without the obligation to remain with the supply chain. Therefore, the cooperation in a supply chain is inherently dynamic [4].

For a complex product/service, the number of suppliers involved in a supply chain may reach hundred or even thousand. Multiplied by the number of hundred or even thousand of suppliers, the intricate and dynamic relationships between supply chain partners will very easily entail the complexity of SCM to explode into an unmanageable level.

Today's business environments are fiercely competitive. Changes in a market environment are inherently unpredictable and instantaneous, with an order as short as a week, a day or even a couple of hours. In such circumstances, dynamic supply chain formation is much more crucial and challenging for SCM than any other problems of SCM such as modeling, simulation, and operation, etc.

Supply chain formation is basically a multi-objective decision making and reconfiguration process. There may be two scenarios of supply chain formation, i.e., top-down and bottom-up [31]. In the top-down scenario, there is a principal enterprise in charge of the formation, maintenance, management and dissolution of a supply chain. The principal enterprise selects the partners strictly under one principle, which is whether the partners will increase the profit of the whole supply chain. In the bottom-up scenario, every supply chain partner only uses local knowledge to form a supply chain. There need to be many interactions between partners and the final partners are determined according to their own considerations and consensus on cost and profit. Through these local demand-supply interactions, a supply chain formed in this scenario may not be the best one, and the process may even end up with a fail. While the top-down scenario may simulate planning based economic environments, the bottom-up scenario simulates market or part-market based environments.

Dynamic supply chain formation is to form a supply chain in real time. It is simply unimaginable how manual processes can handle dynamic supply chain formation properly in face of unpredictable and instantaneously changing market environments. For such situations, automation of dynamic supply chain formation is undoubtedly desirable.

In recent years multi-agent system (MAS) has been recognized as a promising technology for the automation of SCM. MAS essentially supports decentralized methods for SCM and can significantly improve the dynamic reconfigurability of supply chains and the agility of SCM. On the one hand, MAS provide natural metaphors for the modeling and simulation of SCM. On the other hand, if each supply chain partner is well equipped with and trustworthily represented by one software agent (normally a powerful one in terms of capabilities, Sadeh etc. [20] presented a type of software agents representing supply chain partners), the SCM can be fully automated in real time as a multi-agent cooperation problem. In particular, the interactions between agents using an agent communication language, enable supply chain partners to be able to negotiate and coordinate with one another effectively in real time in an automated manner for dynamic supply chain formation and supply chain operation. Through the negotiation process performed among the software agents representing supply chain partners over a certain period, different objectives of supply chain partners can be individually accommodated and various constraints can be met [1,4,27,28]. In fact, dynamic supply chain formation via automated negotiation is where software agents make unprecedented difference to SCM.

Automation of dynamic supply chain formation via MAS requires an environment comprised of the following stacks (in a bottom-up order):

1. Inter-enterprise communication infrastructure, including internet, intranet, and/or EDI, etc.
2. E-commerce and workflow interoperation applications, and/or grid computing environment;
3. Agent platform suitable for real-time applications, including software agents, agent management system (authentication, resources, white pages (naming)), directory facilitator (yellow pages), and agent communication system (agent communication language, content language, ontology, and agent communication channel), etc.;
4. Agent interaction mechanism (or protocol) suitable for real-time applications;
5. User interface, e.g., agent-user interface, etc.

This paper is concerned with agent interaction mechanism suitable for real-time applications in SCM.

Negotiation is a kind of decision making where two or more participants jointly search for a space of solutions with the goal of achieving consensus [4,19,27, 28]. Specifically, negotiation is a process by which two or more parties verbalize contradictory demands and move toward an agreement by a series of concession making and search for new alternatives. This process involves exchange of information between participants to reconcile their differences and produce a settlement [17,18,24]. There may be three outcomes for negotiation: win-win, win-lose, and lose-lose. The win-win outcome meets the needs of both parties [5].

For the requirements in real-world supply chains, a negotiation mechanism should consider multiple attributes, uncertainties and particularly concession making upon the original proposals. Only a limited number of multi-agent negotiation protocols are suitable for dynamic supply chain formation, including contract net protocol, third-party negotiation protocol, double bid based protocol, simulated trading algorithm, and multi-attribute negotiation. Strictly speaking, these protocols are not in full sense about negotiation, but only for resource allocation or task assignment, because they involve least concession making upon the original proposals.

The main drawback of conventional negotiation protocols is that only one bidder is selected in the negotiation outcome. To guarantee the existence of dynamic supply chain formation, at least one supplier has to be chosen in any time by the consumers. Otherwise, the supply chain will become nonexistent. Therefore, negotiation mechanism should allow auctioneer to choose a ranked list of several candidates as the winning bidders. Moreover, all the conventional negotiation protocols are based on the assumption that there is a pure market for supply chain partners. In the reality, however, supply chain partners sometimes have to subject themselves to non-market restrictions such as monopolization. The conventional negotiation protocols are unable to effectively tackle the SCM problems in such non-market circumstances.

This paper puts forward an extended contract net mechanism for dynamic supply chain formation. Specifically, concession making is incorporated into the conventional contract net protocol. This study is based on a real-world problem domain, i.e., China petroleum supply chain management (CP-SCM), which is uniquely characterized by a semi-monopolized market.

2. The context and the overall framework of an extended contract net mechanism

Petroleum industry is typical of large-scale, complex supply chains. CP-SCM is constrained by the multi-layered administrations which involve the state, provinces, and national corporations. The distinctive characteristic of CP-SCM is the semi-monopolized market.

There are three national petroleum corporations which monopolize the petroleum supply chains in China, namely China National Petroleum Corporation (CNPC) [36], China Petroleum and Chemical Corporation (Sinopec) [37], and China National Offshore Oil Corporation (CNOOC) [35]. These monopolistic corporations control (or try to control) their complete petroleum supply chains ranging from petroleum exploration and exploitation, transportation, refining and petrochemical processing to distribution. CNPC and Sinopec occupy the upstream and downstream businesses in petroleum supply chains, while CNOOC only occupies exploration and exploitation. The competitions between the three corporations are limited. There is a rough regional division for petroleum supply among the three corporations, i.e., CNPC controls the petroleum supply in North, Northeast, Northwest, and Southwest China, Sinopec controls the petroleum supply in East, Central, and South China, and CNOOC

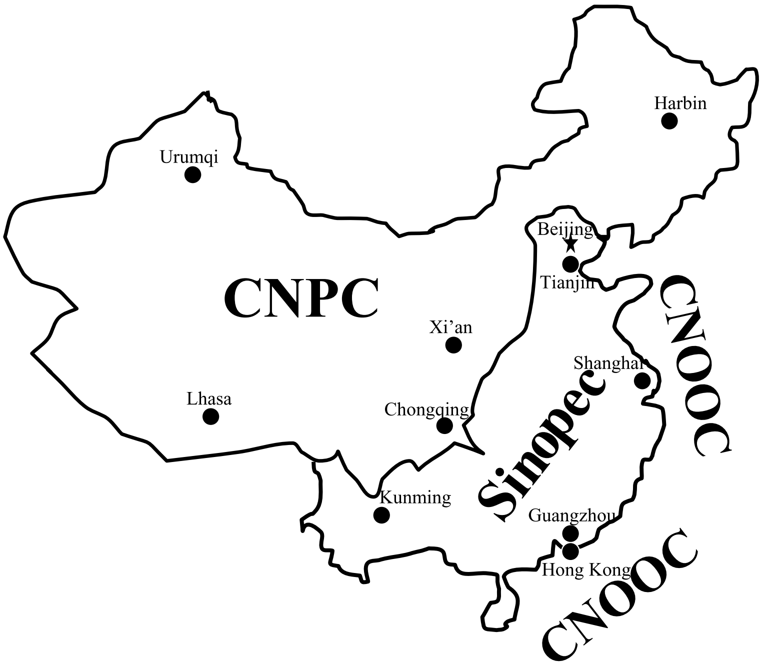

Fig. 1. Regional occupations of the three national corporations.

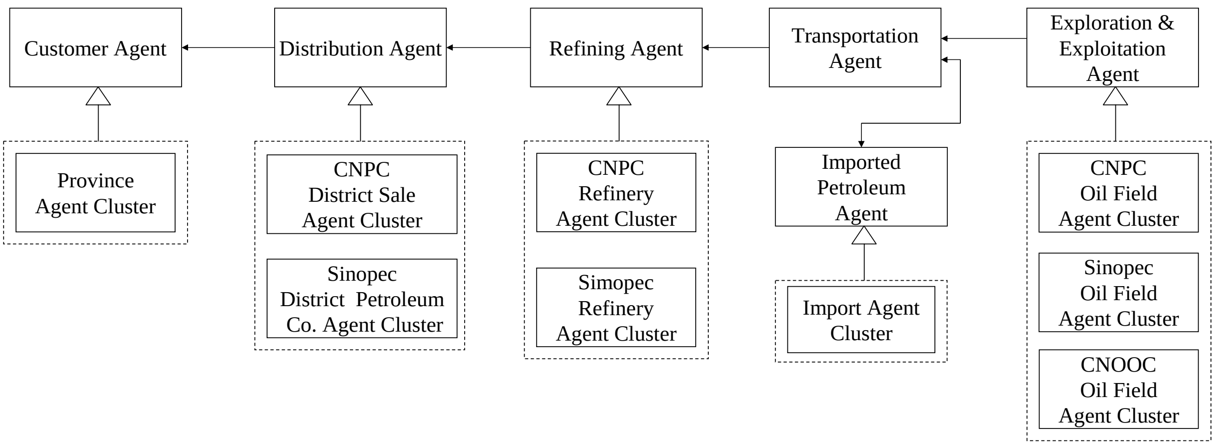

Fig. 2. The multi-agent system of China petroleum supply chains.

controls the exploration and exploitation in the coastal and offshore areas of China, as sketched in Fig. 1.

CP-SCM can be modeled as a MAS where the subsystems of CP-SCM are represented with agents, respectively, as shown in Fig. 2. Since the three corporations (CNPC, Sinopec and CNOOC) monopolize the petroleum supply businesses from exploration and exploitation, transportation, refining, to distributions, each agent of the MAS is further expanded with an instantiation by a cluster of specific agents. Substitute products are not considered in the petroleum supply model, and in fact developing natural gas to substitute petroleum has a similar supply chain to petroleum.

In exploration and exploitation subsystem, the tasks are carried out by a cluster of oil field agents, i.e., the relevant companies of CNPC, Sinopec and/or CNOOC. Exploration and Exploitation Agent allocates subtasks to these oil field agents, and negotiates with them and monitors them to complete the exploration and exploitation tasks. Furthermore, the oil fields can be instantiated into geology tectonics and even into a number of oil wells. This paper confines itself only to the oil

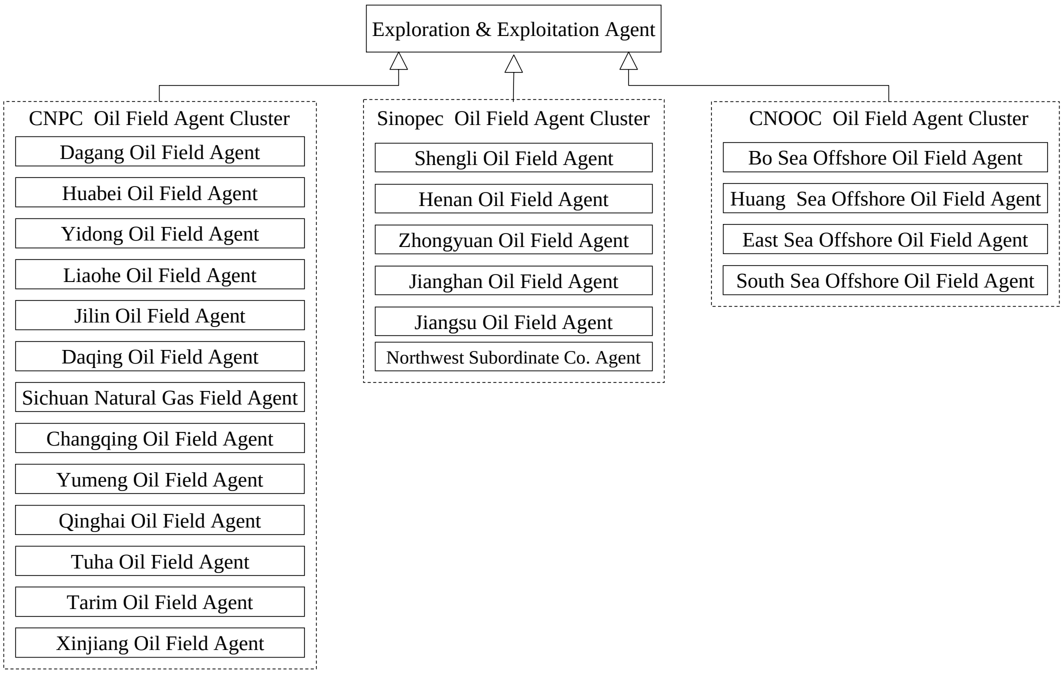

Fig. 3. The instantiation architecture of Exploration and Exploitation Agent.

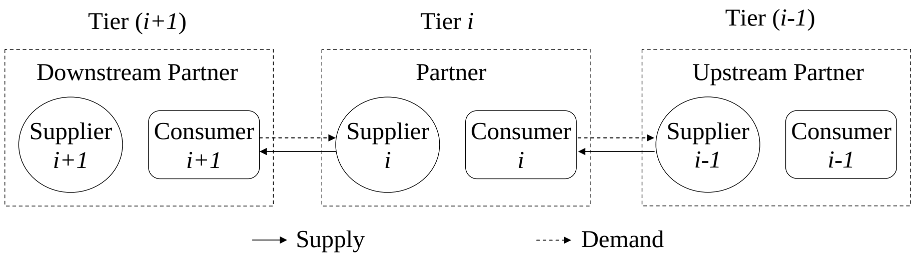

Fig. 4. Consumer-supplier relationships in petroleum supply chains.

field level. Figure 3 depicts the instantiation architecture of Exploration and Exploitation Agent. Similarly, Customer Agent, Distribution Agent, Refining Agent and Imported Petroleum Agent can have their instantiation architectures to carry out their tasks, respectively.

Since a petroleum supply chain is a systems operation problem, it is impossible to analyze an isolated province in China. A partner enterprise in a petroleum supply chain is a consumer to upstream partners and at the same time a supplier to downstream partners. The consumer-supplier relationship, including the notations for tiers, is depicted in Fig. 4. Petroleum supply chains are simultaneously formed depending on both consumers and suppliers in the supply chains. For example, for Beijing, Dalian Petrochemical Ltd. in Liaoning Province is ideal petroleum supplier, but Dalian Petrochemical Ltd. may be selected by Liaoning Province because the geographical proximity in the latter case can make lower supply cost.

Petroleum supply chain formation is achieved via multi-agent negotiation between agents representing supply chain partners. The formation of petroleum supply chains is not a separated process, but a simultaneous process in the negotiations between supply chain partners to obtain or allocate the resource, as shown in Fig. 5. The consumers/suppliers in the same corporation are given the priority to form the petroleum supply chain. The suppliers outside the corporation are considered only if the suppliers within the corporation fail to meet the demands of consumers. Furthermore, if domestic petroleum supply fails to meet the demands for petroleum, imported petroleum will be considered. Imported petroleum will be used to meet different regions' demands according to the shorter transportation

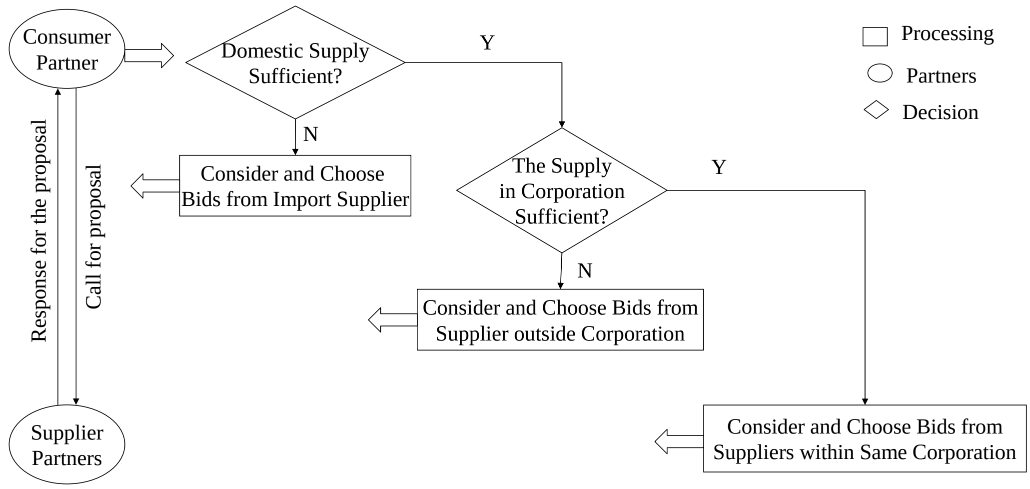

Fig. 5. Dynamic formation of China petroleum supply chains.

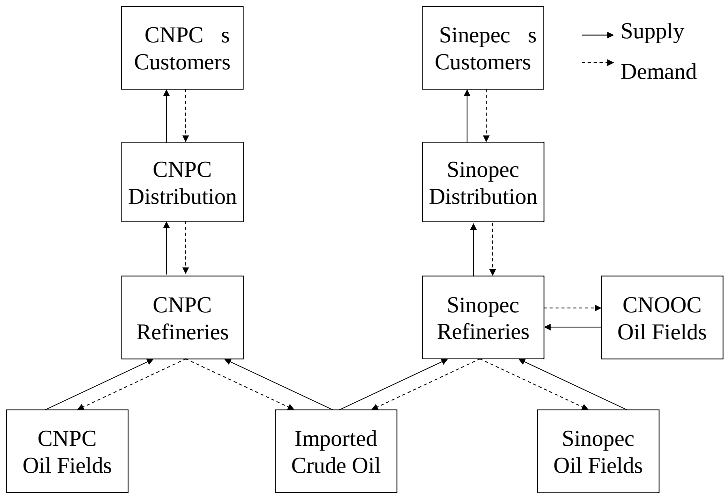

Fig. 6. Priority criterion for semi-monopolized market.

distances and the infrastructure conditions. For example, imported crude oil from Kazakstan and Russia can be used to meet the demands in Northeast and Northwest China because they are shorter transportation distances and there are pipelines and railways in place, while imported petroleum from Middle East and Africa can be used to meet the demands in East and South China, because it is shorter than in North China and there are harbor infrastructures for imported petroleum by tanker fleets.

Basically there are two criteria for multi-agent negotiation in CP-SCM, i.e., priority to meet the demands of the consumers in the same corporation, and then minimum cost to meet the demands of all the consumers. Suppliers in the same corporation are given priority to those outside the corporation. Because Sinopec has a very high level of demand for crude oils, and CNOOC's oil fields are adjacent to Sinopec's refineries, CNOOC becomes an important upstream supplier for Sinopec. The priority criterion for semi-monopolized market is depicted in Fig. 6.

The second negotiation criterion in CP-SCM is to minimize the overall cost in a supply chain. The supply distance is an important factor contributing to the supply chain wide cost. Petroleum companies even in the same corporation are geologically dispersed across China. If supply is excessive to demand, only the adjacent suppliers are selected. On the contrary, if demand is excessive to supply, the distant suppliers may be considered depending on the balance of the cost incurred by distance. For example, Daqing Petrochemical Co. firstly requests Daqing Oil Field to supply crude oil because the crude oil pipeline between is the shortest. If Daqing Oil Field can not meet Daqing Petrochemical Co.'s demands, distant oil fields such as Liaohe Oil Field and Jilin Oil Field can be considered by Daqing Petrochemical Co. Moreover, different petroleum products or crude oils with different properties will also result in different supply costs. For example, the crude oils in different oil fields, which have different properties, can cause different exploitation costs.

A multi-agent negotiation mechanism, based on the conventional contract net protocol, is put forward here. The mechanism takes account of the domain-specific requirements in CP-SCM, and comprises four main steps as follows.

Step 1: Consumers/suppliers calculate their demands or supply-capacities and announce the requests for bids;

Step 2: Considerations in the negotiation are not only the quantitative factors such as supplier's price and delivery date, but also the strategic factor such as collaborative partnership. For example, CNOOC is an important crude oil supplier for Sinopec because they have collaborative partnership in crude oil supply;

Step 3: Both consumers and suppliers have to agree on bids for their own benefits. For example, consumers will select the supplier entailing lower procurement price, while suppliers may agree with the consumers making higher demand quantity. This is a mutual process, which is not used in the conventional contract net protocol.

Step 4: After a negotiation round, consumers/suppliers can revise their negotiation contents so as to settle the bids in the next negotiation round.

The proposed multi-agent negotiation mechanism for dynamic supply chain formation in CP-SCM is further depicted in Fig. 7.

The proposed multi-agent negotiation mechanism are algorithimized and validated below in two scenarios of dynamic supply chain formation, i.e., semi-monopolized market, and emergency of petroleum supply, respectively. Semi-monopolized market is the most distinctive characteristic of CP-SCM, and emergency is a challenging case because existing petroleum supply chain in China is very weak and fragile to deal with emergency events.

3. Algorithmization of multi-agent negotiation mechanism for dynamic supply chain formation in a semi-monopolized market

Semi-monopolized market is a practical problem in CP-SCM. There are several ways to solve this problem. For example, the announcements are only declared to a certain corporation agents; or by defining corporation relationship between agents the negotiation protocol is only allowed to be adopted for this corporation relationship; or the negotiation protocol is only adopted for predetermined agents. In this paper the solution for semi-monopolized market is to restrict the announcement only to certain corporation agents. Consumers and suppliers in the MAS announce their demands/supply-capacities within the corporation, and the suppliers/consumers outside the corporation will not be notified, as depicted in Fig. 8.

The multi-agent negotiation process for dynamic supply chain formation in CP-SCM in a semi-monopolized market is designed as follows.

Step 1: Set i from 5 to 1. For Tier i, repeat steps 2–8.

Step 2: Tier i and Tier $i-1$ agents calculate their demands/supply-capacities, respectively. If the capacity of a Tier $i-1$ supplier is approaching nil, the supplier quits the negotiation, even if it has a competitive supply price.

Sept 3: Tier i consumers announce their demands within the same corporation. A request for bids contains product type, demand date, demand quantity, and demand price, etc.

Step 4: Tier $i-1$ suppliers formulate and submit bids to the requesting Tier i consumers according to the demands. The supply price $p^{i-1}_{\mathrm{supp}ly}$ of a Tier $i-1$ supplier can be calculated by considering its procurement cost $c^{i-1}_{\mathrm{procure}}$, and its processing cost $c^{i-1}_{\mathrm{process}}$ including refining and storing. In the simple case,

$$\left.\begin{aligned} & p^{i-1}_{\mathrm{supp}ly} \Leftarrow \frac{c^{i-1}_{\mathrm{procure}}+c^{i-1}_{\mathrm{process}}}{q^{i-1,i-2}} \\ & = p^{i-1}_{\mathrm{procure}} + \frac{c^{i-1}_{\mathrm{process}}}{q^{i-1,i-2}} \end{aligned}\right\} \tag{1}$$

where $q^{i-1,i-2}$ is the quantity of goods that the Tier $i-1$ agent procures and processes. The cost relationships between adjacent tiers are depicted in Fig. 10. Only Tier $i-1$ suppliers with the required product type submit bids to the requesting consumers. For example, if a refinery requests heavy crude oil, oil fields with light crude oil will not submit bids to this refinery.

If no Tier $i-1$ suppliers submit bids, Go back to Step 3, Tier i consumers re-announce their demands but outside the corporation.

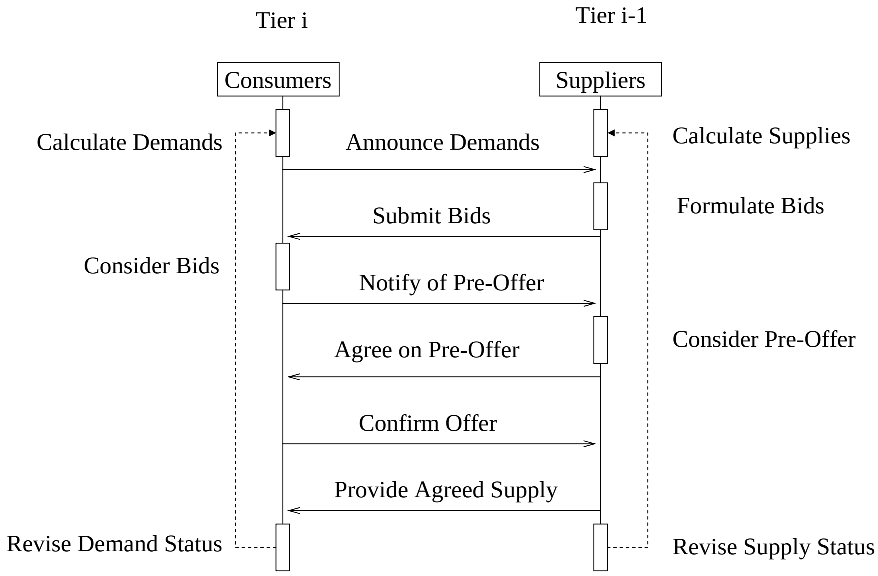

Fig. 7. The multi-agent negotiation mechanism for dynamic supply chain formation.

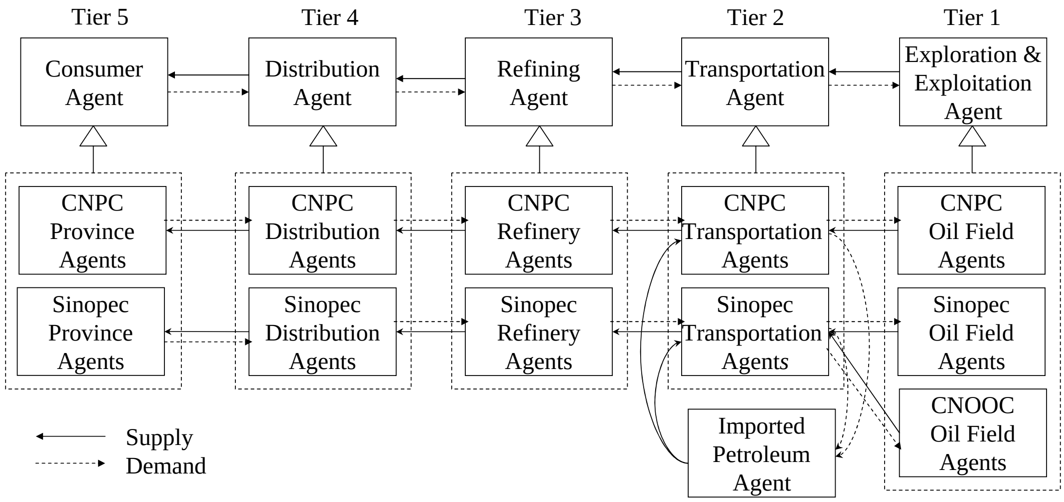

Fig. 8. The multi-agent negotiation in a semi-monopolized market.

Step 5: Tier i consumers consider the bids received from Tier $i-1$ suppliers.

(5.1) Tier i consumer pre-checks the bids received from Tier i-1 suppliers.

(a) If the product type does not match the requirement, reject the bid. Otherwise, proceed with the bid.
(b) If the supply date does not precede the demand date, reject the bid. Otherwise, proceed with the bid.
(c) If the supply quantity is less than the demand quantity, reject the bid or let the human operator decide. Otherwise, proceed with the bid.
(d) If there is collaborative partnership between the consumers and the supplier, let the human operator decide. Otherwise, proceed with the bid.

(5.2) The Tier i procurement price p^{i}_{procure} is calculated by considering the supply price p^{i-1}_{supply} of the Tier $i-1$ supplier, and related costs such as the transportation cost from the Tier $i-1$ suppliers to the Tier i consumer. A transportation price can be calculated as

$$c^{i,i-1}_{\text{transport}} = d^{i,i-1} \times l^{i,i-1} \tag{2}$$

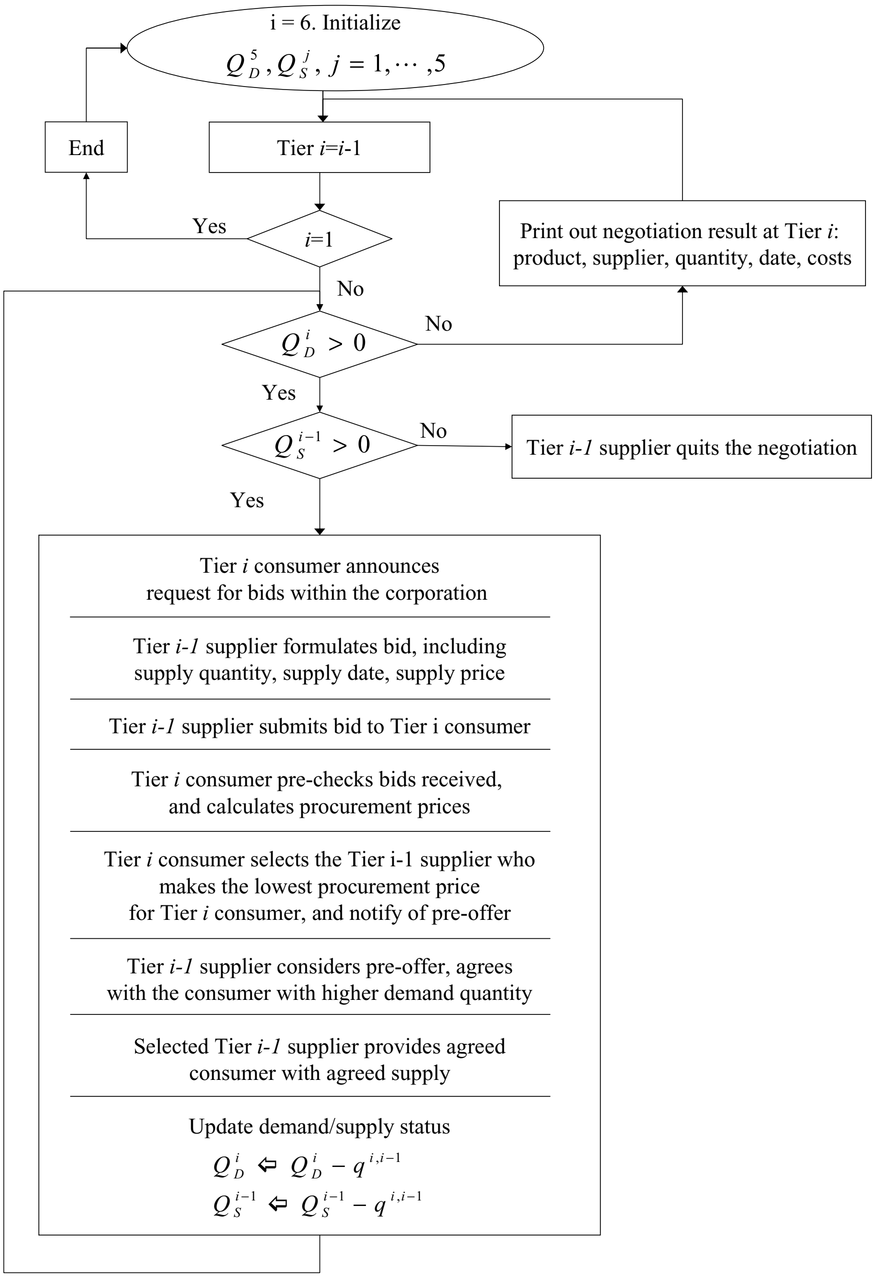

Fig. 9. The negotiation process of dynamic supply chain formation in a semi-monopolized market.

where $d^{i,i-1}$ is the supply distance from Tier $i-1$ supplier to Tier i consumer, and $l^{i,i-1}$ is the transportation price. In the simple case,

$$p^i_{\text{procure}} \Leftarrow p^{i-1}_{\text{supply}} + \frac{c^{i,i-1}_{\text{transport}}}{q^{i,i-1}} \quad (3)$$

By bringing Eq. (1) into Eq. (3), there is

$$p^i_{\text{procure}} \Leftarrow p^{i-1}_{\text{procure}} + \frac{c^{i-1}_{\text{process}}}{q^{i-1,i-2}} + \frac{c^{i,i-1}_{\text{transport}}}{q^{i,i-1}} \quad (4)$$

See Fig. 10 for the cost relationships between tiers.

(5.3) Arrange Tier $i-1$ suppliers in an ascending order according to the Tier i consumer's procurement prices with regard to them. Select the Tier $i-1$ supplier that makes the lowest procurement price for the Tier i consumer.

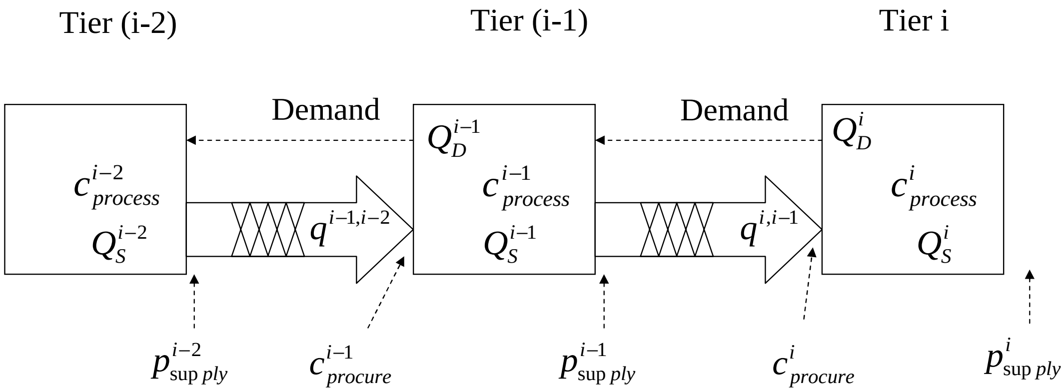

Fig. 10. Cost relationships between tiers.

Then Tier i consumer notifies the selected Tier $i-1$ supplier of the pre-offer.

If there is not a proper Tier $i-1$ supplier for Tier i consumer to select, go back to Step 3, Tier i consumers re-announce their demands but outside the corporation.

Step 6: The selected Tier $i-1$ supplier considers the pre-offers from Tier i consumers.

(6.1) If there is collaborative partnership between the Tier $i-1$ supplier and the Tier i consumer, let the human operator decide. Otherwise, proceed with the pre-offer.

(6.2) If there is more than one Tier i consumer accepting the supply price, the Tier i consumer that has higher demand quantity is to be agreed with so that the supplier can sell more products. Otherwise, proceed with the pre-offer.

(6.3) Agree with the Tier i consumer on the pre-offer.

Step 7: The agreed Tier i consumer confirms the offer to the selected Tier $i-1$ supplier. The procurement cost of the Tier i consumer can be calculated

$$c^i_{\text{procure}} = p^i_{\text{procure}} \times q^{i,i-1} \quad (5)$$

where $q^{i,i-1}$ is the supply quantity from the Tier $i-1$ supplier. Print out the negotiation results.

Then the selected Tier $i-1$ supplier provides the agreed Tier i consumer with the agreed supply at the agreed supply price.

Step 8: Tier i, Tier $i-1$ agents update their demand/supply status after a successful negotiation, or the unselected agents in the negotiation revise their demand/supply status.

The negotiation process can be diagramed as in Fig. 9, and further depicted by state machines of agents in a petroleum supply chain, as in Fig. 11.

The negotiations between supply chain partners simultaneously take place at each tier of a petroleum supply chain. There are many rounds to find out the supplier that makes the lowest procurement price. Once a round is complete, the demand/supply status will be updated, e.g., the reduced demands and supply capacities. The negotiation processes at Tier i will not stop until the demands of all the Tier i consumers are fully met, and the negotiation process in a supply chain will not stop until the demands at all tiers are completely met.

4. Algorithmization of multi-agent negotiation mechanisms for dynamic supply chain formation in emergency

In emergency events, e.g., petroleum pipeline is broken, in order to meet the emergent demands for petroleum and at the same time to provide steady petroleum supplies in normal regions, first, the procurement time instead of the procurement cost becomes the crucial factor for the multi-agent negotiation in a petroleum supply chain; second, the monopolistic restrictions between different corporations should be disregarded, and agents in different corporations are in a pure market, as shown in Fig. 12.

Supply distance is quite influential because the shorter a supply distance, the less the delivery time. First of all, the consumers can be supplied by the suppliers within the same province/city because this is the quick way for supply. As there is no more monopolistic restriction between different corporations, the demands of the consumers will be announced to all agents in a petroleum supply chain, and the agents from different corporations will have the equal opportunity to submit bids. After all, the procurement cost will be considered, especially when two suppliers entail near

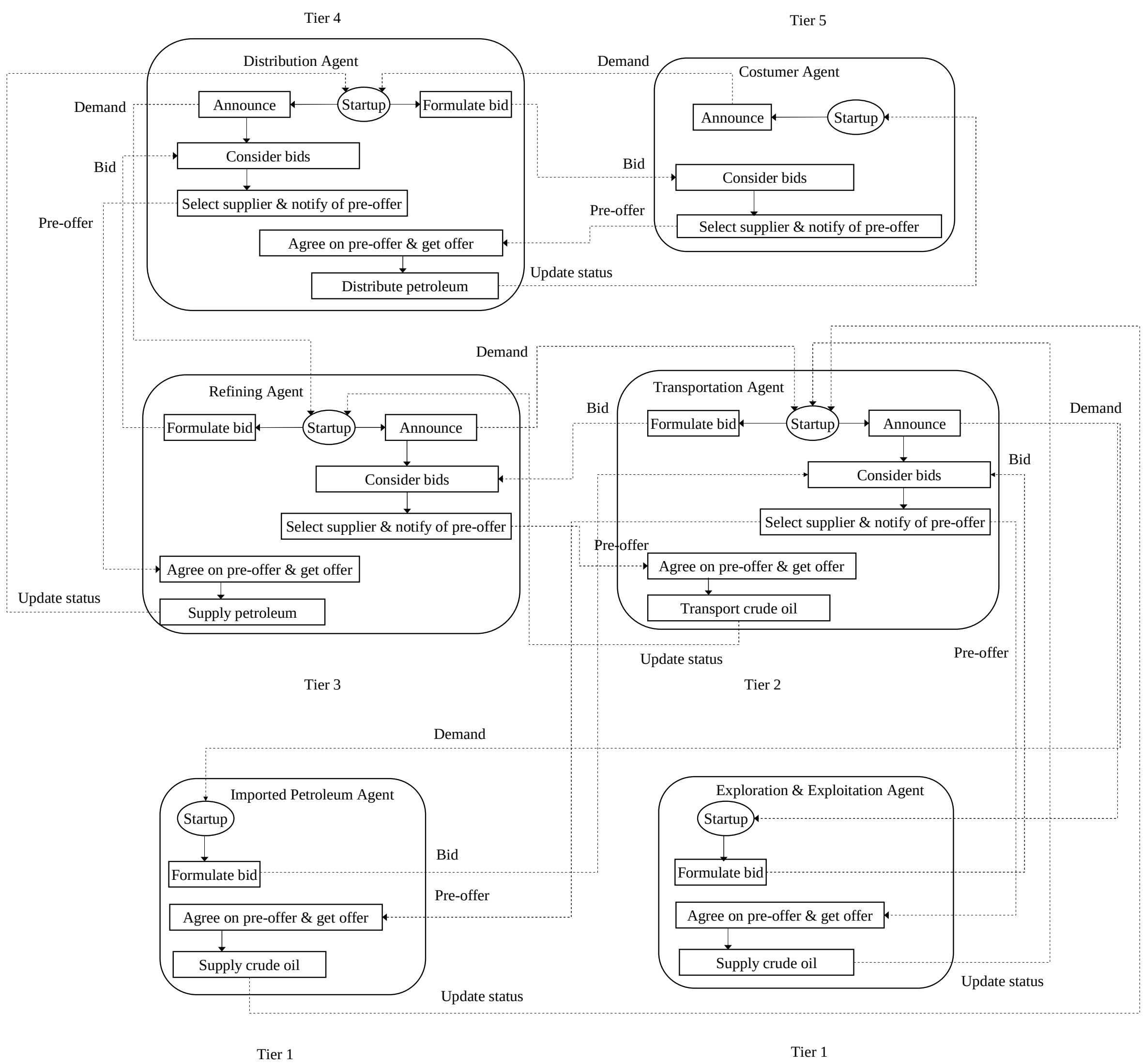

Fig. 11. The state machine graph of the negotiation for dynamic supply chain formation in a semi-monopolized market.

procurement dates for the consumer (e.g., when they are located in the same city). When a supplier considers pre-offers, the consumer that requests a lower quantity can be agreed with because resource is limited in emergency.

In emergency, the procurement date becomes crucial, which is determined by processing time, including storing and wrapping, and the transportation time in a petroleum supply chain. The transportation time depends upon the transportation speed. The transportation speeds by different modes, i.e., pipeline, railway, tanker fleet, and truck, can be calculated as

$$time^{i,i-1}_{\text{transport}} = \frac{d^{i,i-1}}{300/\lambda} \quad (6)$$

where $d^{i,i-1}$ is the supply distance from Tier $i-1$ supplier to Tier i consumer, and λ is the transportation speed coefficient. The standard $(\lambda = 1)$ transportation speed is assumed as 300 km/day by railway, and λ is assumed as 0.8, 1.2, and 1.4 by pipeline, truck and tanker fleet, respectively. Although different transportation modes have their own supply distances, in this paper, supply distances are uniformly approximated using the geographical survey coordinates of supply nodes.

The multi-agent negotiation process for dynamic supply chain formation in emergency is designed as follows.

Step 1: Set i from 5 to 1. For Tier i, repeat steps 2–8.

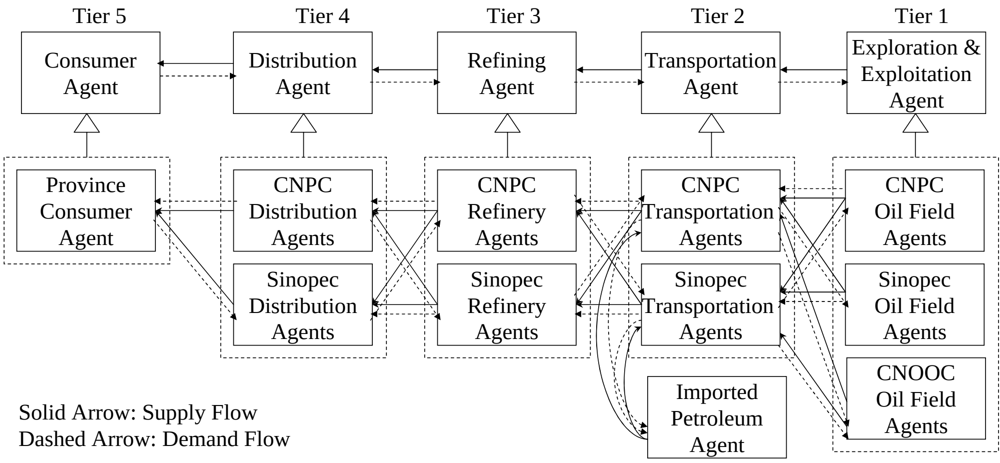

Fig. 12. The multi-agent negotiation in emergency.

Step 2: Tier i and Tier $i-1$ agents calculate their demands/supply-capacities, respectively. The emergency circumstance is taken into consideration, e.g., processing capacity may decrease because of the prolonged repair of a refinery. If the capacity of a Tier $i-1$ supplier is approaching nil, the supplier quits the negotiation, even if it has a desirable supply date and/or a competitive supply price.

Sept 3: Tier i consumers announce their demands to Tier $i-1$ suppliers. A request for bids contains product type, demand date, demand quantity, and demand price, etc.

Step 4: Tier $i-1$ suppliers formulate and submit bids to the requesting Tier i consumers according to the demands. A bid contains product type, quantity, supply date and supply price, etc. The supply price p^{i-1}_{supply} of a Tier $i-1$ supplier can be calculated by considering the procurement cost c^{i-1}_{procure}, and the processing cost c^{i-1}_{process} including refining, storing and wrapping, as in Eq. (1). The supply date $date^{i-1}_{supply}$ reflects the processing time. In the simple case,

$$\begin{aligned} date^{i-1}_{supply} &= date^{i-1}_{\text{procure}} \\ &\quad + time^{i-1}_{\text{proccess/store/wrap}} \end{aligned} \tag{7}$$

Step 5: Tier i consumers consider the bids received from Tier $i-1$ suppliers.

(5.1) Tier i consumer pre-checks the bids received from Tier $i-1$ suppliers.

(a) If the product type does not match the requirement, reject the bid. Otherwise, proceed with the bid.
(b) If the supply quantity is less than the demand one, reject the bid or let the human operator decide. Otherwise, proceed with the bid.

(5.2) The procurement date $date^{i}_{\text{procure}}$ of a Tier i consumer is calculated by considering the supply date $date^{i-1}_{supply}$ of the Tier $i-1$ supplier, and the transportation time from the Tier $i-1$ supplier to the Tier i consumer, $time^{i,i-1}_{\text{transport}}$. In the simple case,

$$date^{i}_{\text{procure}} = date^{i-1}_{supply} + time^{i,i-1}_{\text{transport}} \tag{8}$$

By bringing Eq. (7) into Eq. (8), there is

$$\begin{aligned} date^{i}_{\text{procure}} &= date^{i-1}_{\text{procure}} \\ &\quad + time^{i-1}_{\text{proccess/store/wrap}} \\ &\quad + time^{i,i-1}_{\text{transport}} \end{aligned} \tag{9}$$

(5.3) If there is more than one Tier $i-1$ supplier with near supply date $date^{i-1}_{supply}$, choose the supplier that makes the earliest procurement date $date^{i}_{\text{procure}}$ for the Tier i consumer, which, in terms of Eq. (8), implies the Tier $i-1$ supplier in the quickest transportation. Otherwise, proceed with the bid.

(5.4) The procurement price p^{i}_{procure} of a Tier i consumer is calculated by considering the supply price p^{i-1}_{supply} of the Tier $i-1$ supplier, and the related costs such as transportation costs from the Tier $i-1$ supplier to the Tier i consumer, as shown in Eqs (3) and (4).

(5.5) Arrange Tier $i-1$ suppliers in an ascending order according to the Tier i consumer's procurement dates and prices with regard to them. Select the Tier $i-1$ supplier that makes the earliest procurement date and lower procurement price p^{i}_{procure} for the Tier i consumer.

Then Tier i consumer notifies the selected Tier $i-1$ supplier of the pre-offer.

Step 6: The selected Tier $i-1$ supplier considers the pre-offer.

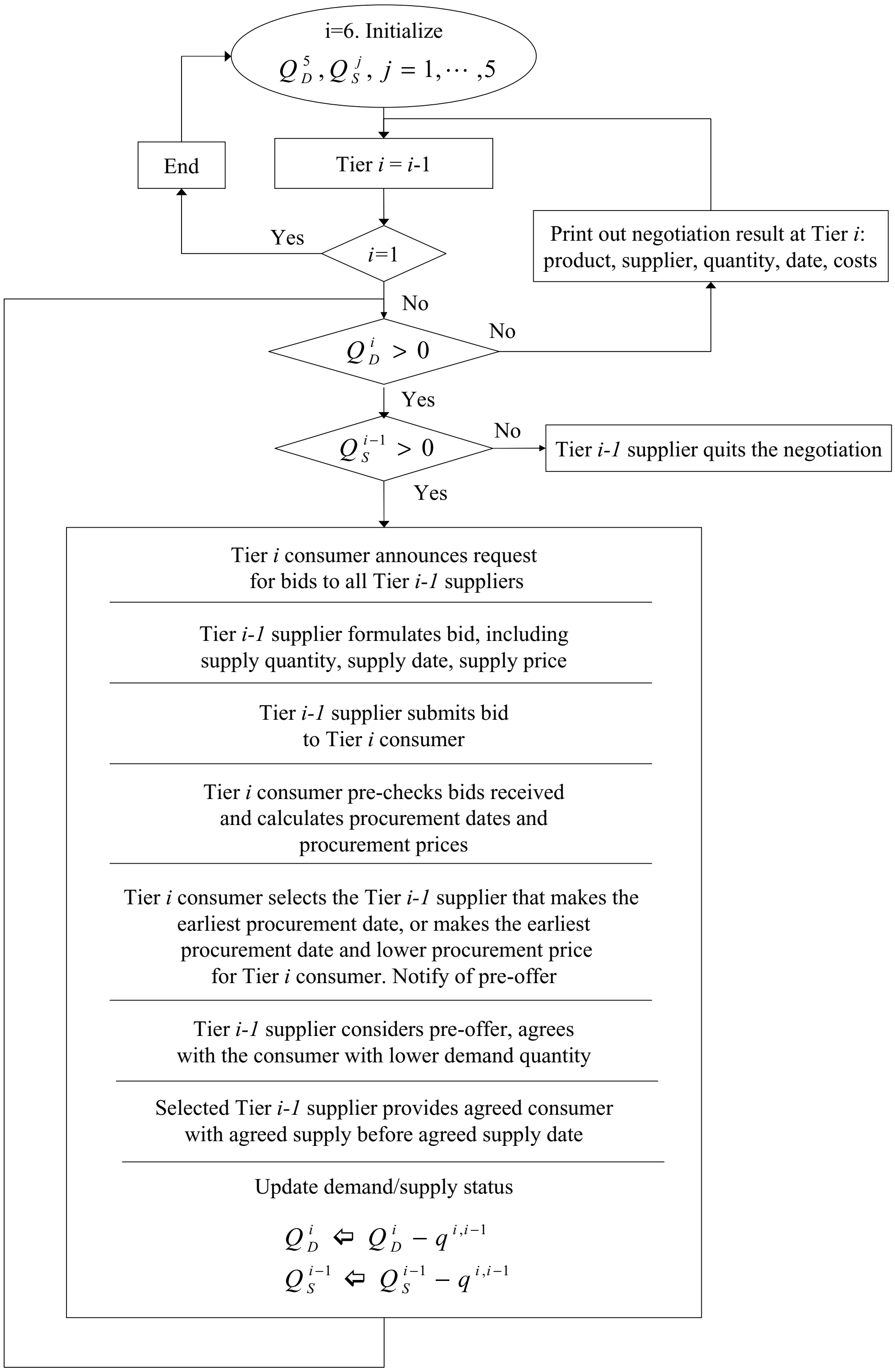

Fig. 13. The negotiation process of dynamic supply chain formation in emergency.

(6.1) If there is more than one Tier i consumer accepting the supply date of the Tier $i-1$ supplier, the Tier i consumer that has lower demand quantity is agreed with because resource is limited in emergency. Otherwise, proceed with the pre-offer.

(6.2) Agree with the Tier i consumer on the pre-offer.

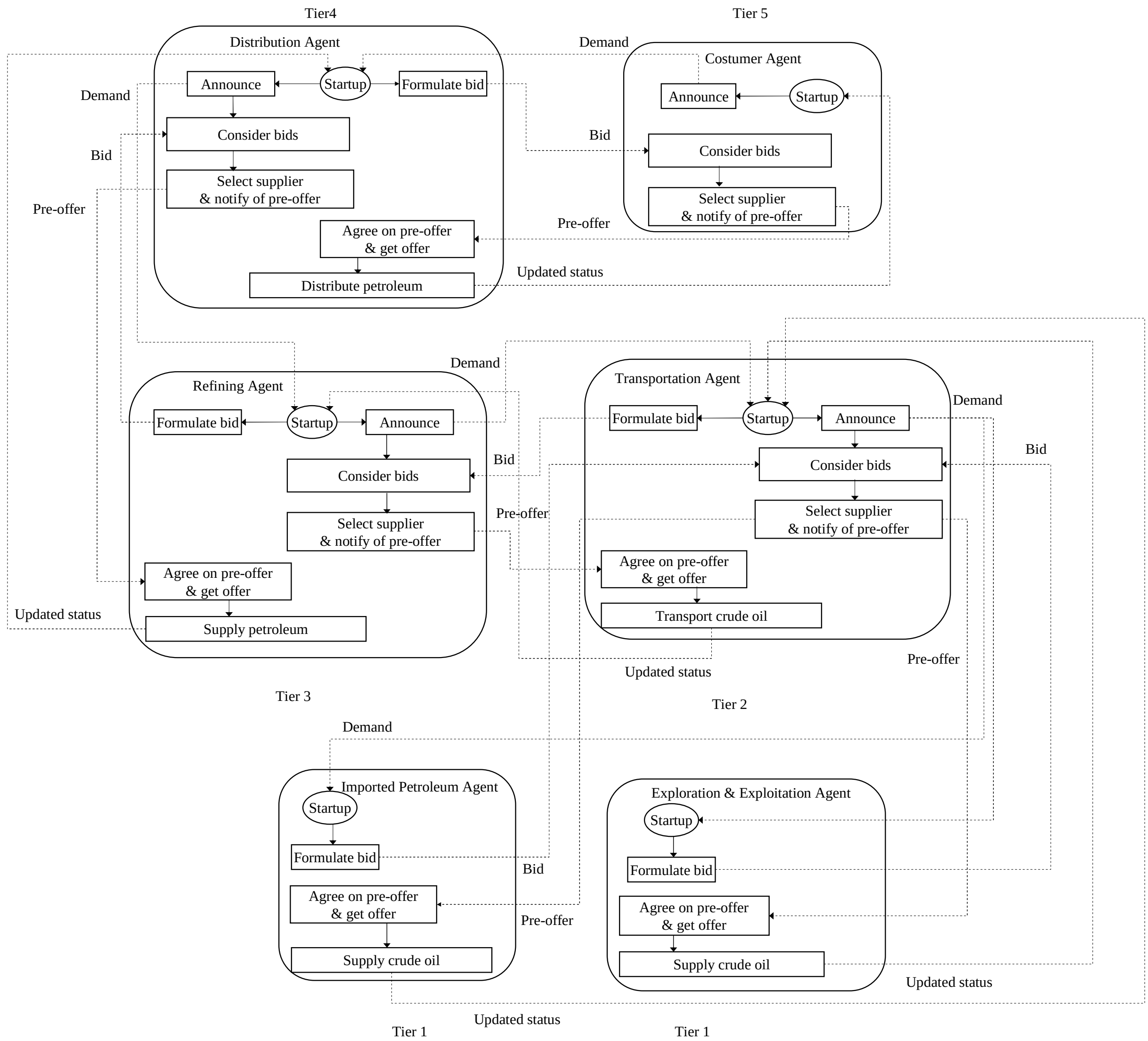

Fig. 14. The state machine graph of the negotiation for dynamic supply chain formation in emergency.

Step 7: The agreed Tier i consumer confirms the offer to the selected Tier $i-1$ supplier. The procurement cost c^i_{procure} of the Tier i consumer can be calculated as in Eq. (5). Print out the negotiation results.

Then the selected Tier $i-1$ supplier provides the agreed Tier i consumer with the agreed supply before the agreed supply date and at the agreed supply price.

Step 8: Tier i, Tier $i-1$ agents update their demand/supply status after a successful negotiation, or the unselected agents in the negotiation revise their demand/supply status.

The negotiation process can be diagramed as in Fig. 13, and further depicted by state machines as in Fig. 14. The negotiation processes at Tier i will not stop until the demands of all the Tier i consumers are fully met, and the negotiation process in a supply chain will not stop until the demands at all tiers are completely met.

5. Case studies

A petroleum supply chain in Northeast China is simulated to demonstrate the proposed negotiation mechanism for dynamic supply chain formation in a semi-monopolized market and an emergency scenario. Northeast China region is one of the main petroleum supply foundations in China. Monopolization and im-

Table 1
Demands/supply-capacities of customer, refinery and oil field agents (10^4 tonnes)

Customer Agent	Petroleum Product Demanded	Refinery Agent	Petroleum Product Supplied	Processing Crude Oil Demanded	Oil Field Agent	Crude Oil Supplied
Heilongjiang Province Agent	660	Daqing Petrochemical Agent	433.96	602.72	Daqing Oil Field Agent	4640
Jilin Province Agent	450	Fushun Petrochemical Agent	666.12	925.17	Liaohe Oil Field Agent	1435.65
Liaoning Province Agent	1170	Liaoyang Petrochemical Agent	540	750	Jilin Oil Field Agent	505.5
		Jinxi Petrochemical Agent	432	600	CNOOC Bo Sea Oil Field	691.51
		Jinzhou Petrochemical Agent	396	550	Russia Imported Agent	1077
		Dalian Petrochemical Agent	511.2	710		
Total	2280		2979.28	4137.89		8349.66

(Source: CNPC: http://www.cnpc.com.cn/, CNOOC: http://www.cnooc.com.cn/).

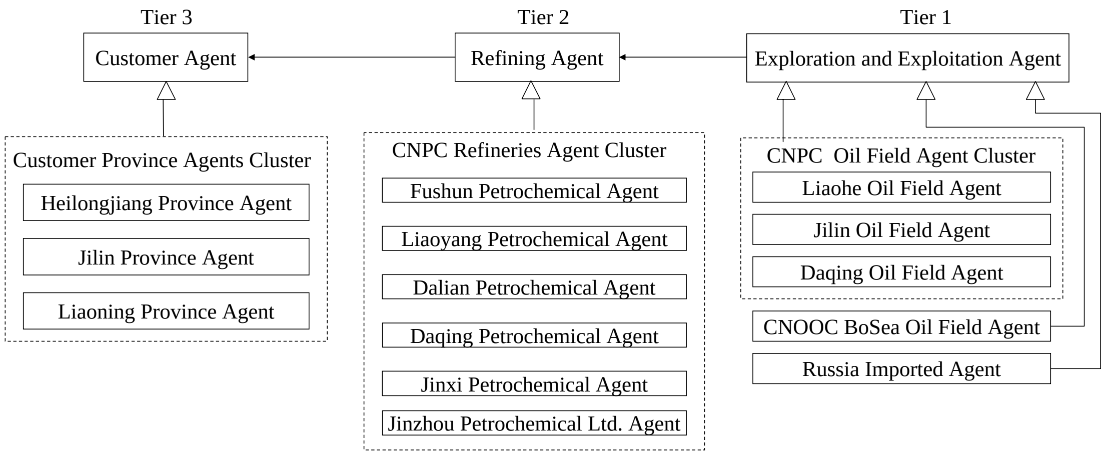

Fig. 15. The multi-agent system of petroleum supply chain in Northeast China.

ported petroleum coexist in this region. Most of the petroleum companies in this region are controlled by CNPC, while a few of them are import companies and from CNOOC. The MAS for simulation is constructed, as shown in Fig. 15. The demands and supply capacities of agents are shown in Table 1, and the locations of individual agents are listed in Table 2. To simplify the analysis without loss of correctness, the following assumptions are made for the simulation of multi-agent negotiation for dynamic supply chain formation in CP-SCM.

Assumption 1: Only three supply tiers are considered in the simulation, i.e., Consumer, Refining, and Exploitation and Exploration (or Imported Petroleum).

Assumption 2: The final product is the Petroleum Product, and the original material is the Crude Oil. All petroleum products or crude oils are available in any refinery or oil field, respectively.

Assumption 3: There is no price fluctuation of products and services in the petroleum supply chain.

Assumption 4: The term of supply is one year. All the production capabilities, and transportation capabilities are based on a year. The settings for the simulation of the petroleum supply chain are the actual statistics in 2004.

Table 2
Locations of customer, refinery and oil field agents

City of agent	X (km)	Y (km)
Daqing, Daqing Oil Field Agent and Daqing Petrochemical Agent	13908.3	5842.6
Jinzhou, Jinzhou Petrochemical Agent	13550	4700
Fushun, Fushun Petrochemical Agent	13800	5100
Dalian, Dalian Petrochemical Agent	13525	4675
Liaoyang, Liaoyang Petrochemical Agent	13711.3	5023.5
Jinxi, Jinxi Petrochemical Agent	13450	4950
Panjin, Liaohe Oil Field Agent	13586.7	5010.8
Songyuan (Fuyu), Jilin Oil Field Agent	13900	5625
Tianjin, Bo Sea Oil Field Agent	13045	4713.1
Angarsk, Russia Import Agent	11575	6875
Shenyang, Liaoning Province Agent	13725	5100
Changchun, Jilin Province Agent	13950	5425
Harbin, Heilongjiang Province Agent	14100	5700

(Source: http://www.multimap.com/).

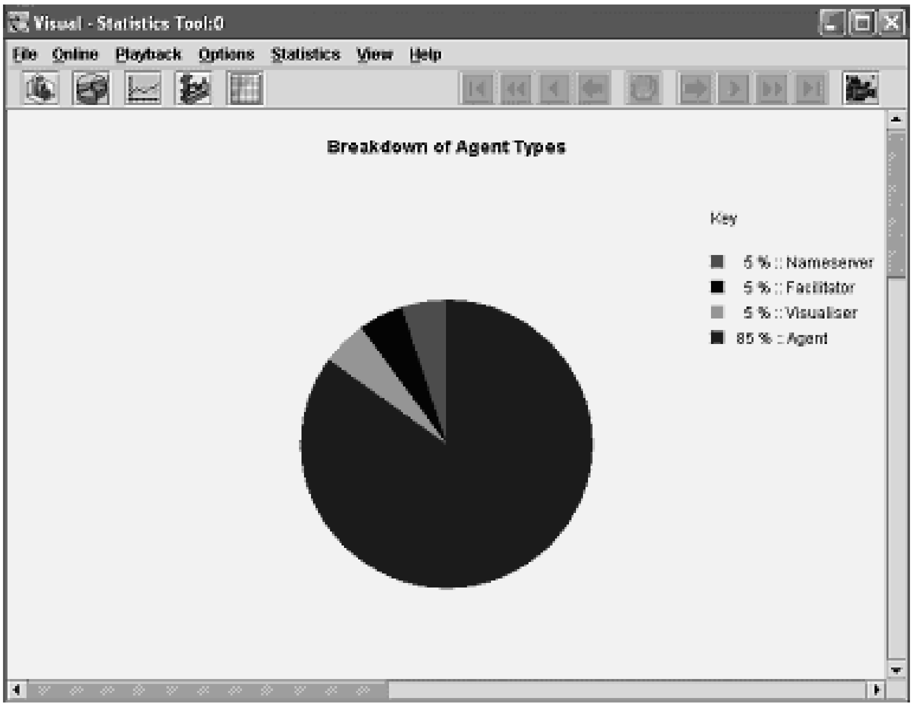

Fig. 16. Screenshot of agent types in Zeus.

Assumption 5: The refining rate for transferring crude oils into petroleum products is 72%, the utilization rate of the processing capabilities in refineries is 100%, and the loss rate in transportation and distribution is 5%.

Assumption 6: The supply nodes are the individual petroleum companies, and the distances between supply nodes are calculated using the geographical survey coordinates of the cities where petroleum companies are located. The geographical distances are calculated by function $f(x,y) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$, where (x_1, y_1) and $(x_2, y_2)$are the geographical survey coordinates of cities where the supply chain partners are located.

Assumption 7: There is sufficient infrastructure for transportation and distribution of petroleum or crude oil.

The simulation for semi-monopolized market is implemented in Zeus 1.1, an agent platform developed by British Telecommunication plc. [34]. The agent types in the system are shown in Fig. 16.

In a semi-monopolized market, all partners are re-

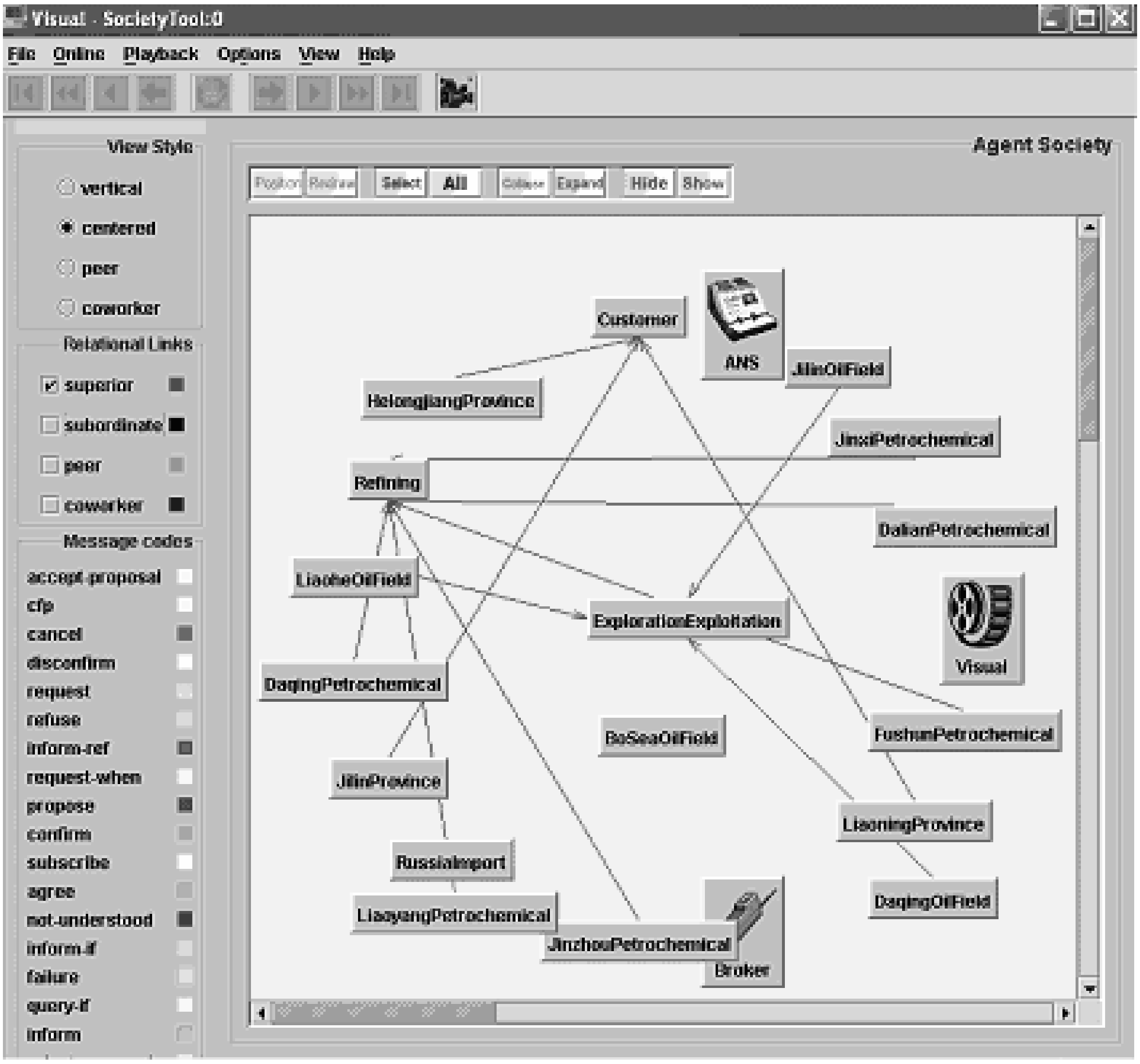

Fig. 17. Screenshot of the agent society in a semi-monopolized market.

stricted to supply chains within the corporation. Thus the BoSeaOilField agent is excluded from the negotiation in Exploration and Exploration supply tier, as shown in Fig. 17. The statistics of the interaction between agents is shown in Fig. 18.

Under the assumptions for simulation, the transportation distance is the only negotiation factor for procurement cost in a semi-monopolized market. According to the negotiation algorithm, the shorter a transportation distance, the less the procurement cost, so a supplier with shorter transportation distance should first be selected. The negotiation outcomes between customer, refinery and oil field agents in a semi-monopolized market are shown in Tables 3 and 4. The deals leave remaining 550.31×10^4 tonnes of petroleum product, of which 485.64×10^4 tonnes are from Dalian Petrochemical Agent, and 64.67×10^4 tonnes from Jinzhou Petrochemical Agent; and $3,137.36 \times 10^4$ tonnes of crude oil, of which $2,114.21 \times 10^4$ tonnes are from Daqing Oil Field Agent, and $1,023.15 \times 10^4$ tonnes from Import Agent from Russia.

In emergency, all partners in the supply chain can negotiate with each other as monopolization is disregarded. Thus the BoSeaOilField agent can participate in the negotiation in Exploration and Exploration supply tier, as shown in Fig. 19. The statistics of the interactions between agents in emergency is shown in Fig. 20.

Table 3
Negotiation outcome between customer and refinery agents

Consumer	Supplier	Petroleum Product Supply (10^4 tonnes)	Transportation Distance (km)
Liaoning Province Agent	Fushun Petrochemical Agent	632.81	75
Liaoning Province Agent	Liaoyang Petrochemical Agent	513	77.72
Helongjiang Province Agent	Daqing Petrochemical Agent	412.26	238.92
Liaoning Province Agent	Jinxi Petrochemical Agent	24.19	313.25
Jilin Province Agent	Jinxi Petrochemical Agent	386.21	689.66
Jilin Province Agent	Jinzhou Petrochemical Agent	63.79	828.02
Helongjiang Province Agent	Jinzhou Petrochemical Agent	247.74	1,141.27

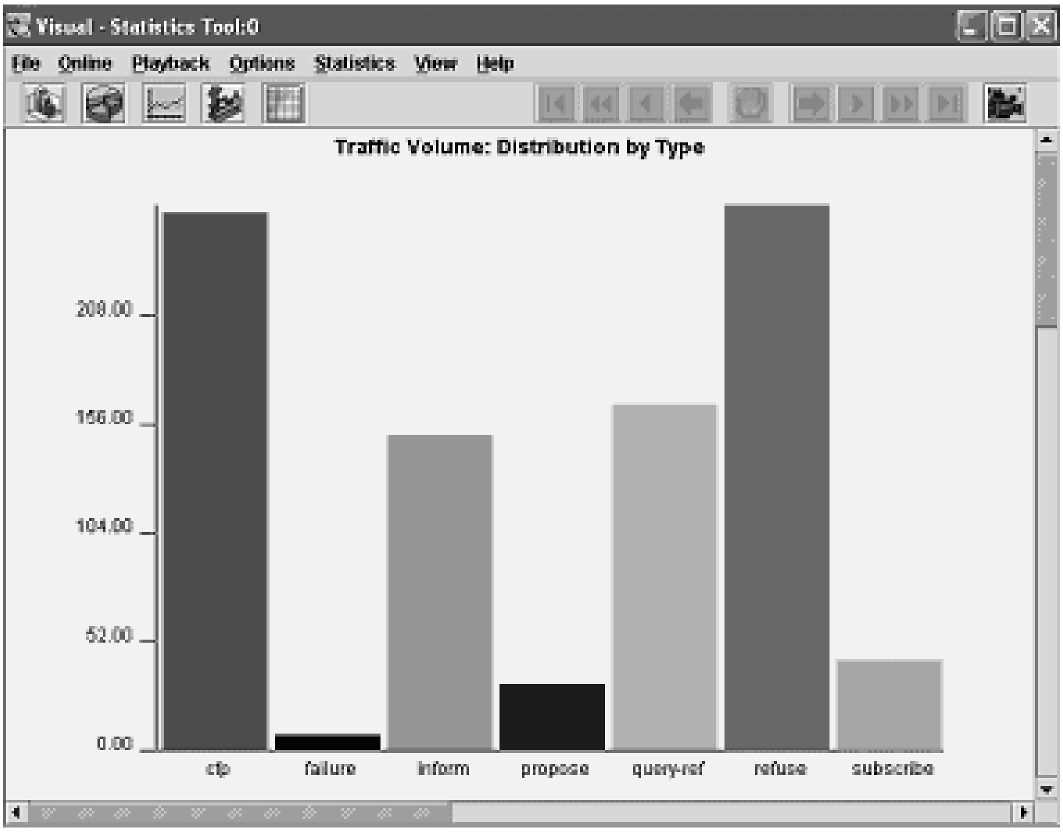

Fig. 18. Screenshot of the interaction statistics between agents in a semi-monopolized market.

In the simulation in emergency, under the assumptions for simulation, the shorter a transportation distance, the less the procurement time. Therefore, the supplier with shorter transportation distance is firstly selected. The negotiation outcomes between customer, refinery and oil field agents in emergency are similar to those in a semi-monopolized market. The main difference in the negotiations is that the suppliers outside the monopolized corporation are selected, because the monopolization is disregarded in emergency, as shown in Table 5. The deals leave remaining $3,828.87 \times 10^4$ tonnes of crude oil, of which $2,805.72 \times 10^4$ tonnes are from Daqing Oil Field Agent, and $1,023.15 \times 10^4$ tonnes from Import Agent from Russia.

6. Related works

The conventional negotiation protocols suitable for supply chain formation include contract net protocol, third-party negotiation protocol, double bid based protocol, simulated trading algorithm, and multi-attribute negotiation, etc.

Table 4
Negotiation outcome between refinery and oil field agents in a semi-monopolized market

Consumer	Supplier	Petroleum Product Supply (10^4 tonnes)	Transportation Distance (km)
Daqing Petrochemical Agent	Daqing Oil Field Agent	602.72	1
Liaoyang Petrochemical Agent	Liaohe Oil Field Agent	750	125.25
Jinxi Petrochemical Agent	Liaohe Oil Field Agent	600	149.61
Fushun Petrochemical Agent	Liaohe Oil Field Agent	13.87	231.2
Fushun Petrochemical Agent	Jilin Oil Field Agent	480.23	534.44
Fushun Petrochemical Agent	Daqing Oil Field Agent	431.07	750.46
Jinzhou Petrochemical Agent	Daqing Oil Field Agent	550	1,197.46
Dalian Petrochemical Agent	Daqing Oil Field Agent	710	1,228.91

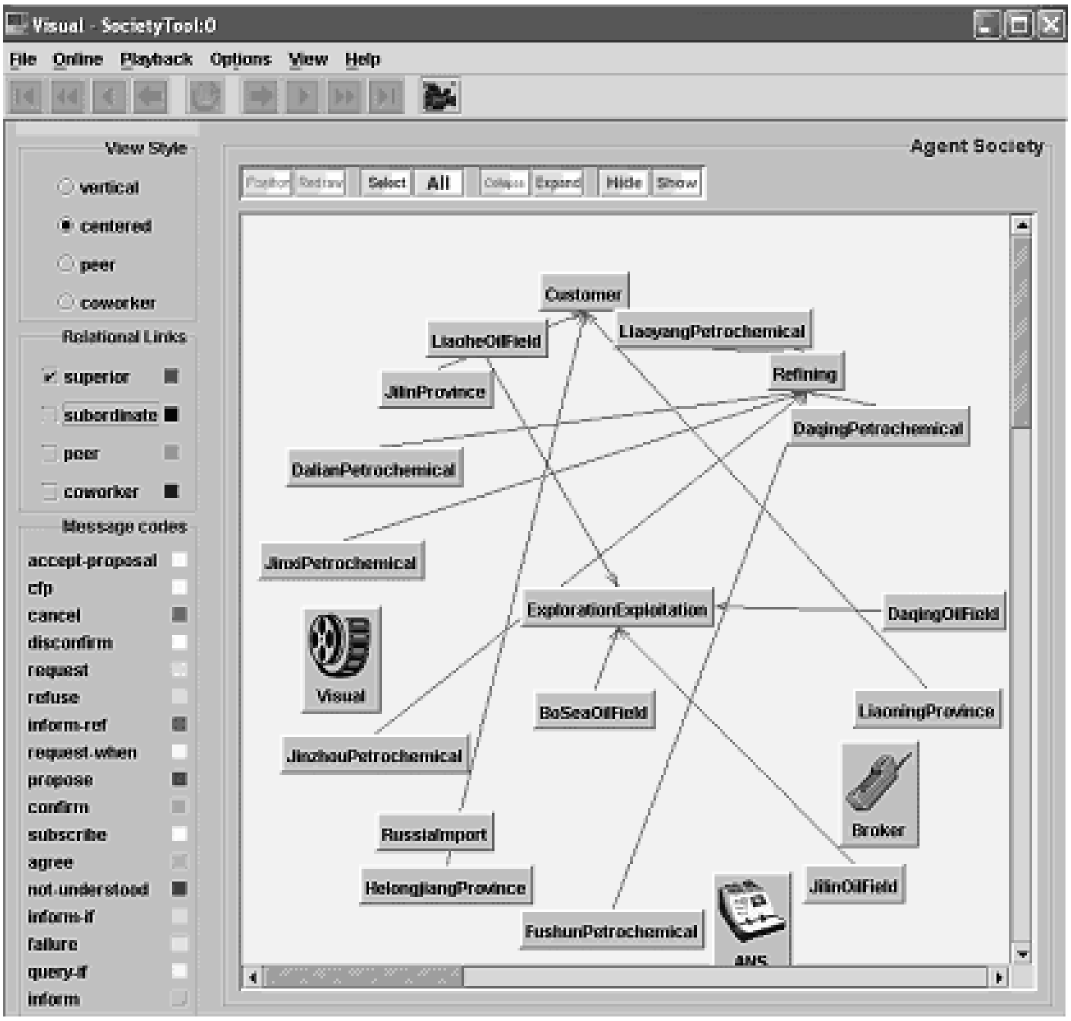

Fig. 19. Screenshot of the agent society in emergency.

6.1. Contract net protocol

A contract net protocol achieves cooperation through task sharing or task assignment in networks of communicating problem solvers [21,22]. In a contract net protocol a manager announces a task to a set of contractors. Based on their local cost estimates, the contractors formulate bids, and send them to the manager. The manager selects the best bid, rejects the others and grants the task to the best bidder. This contractor is

Table 5
Negotiation outcome between refinery and oil field agents in emergency

Consumer	Supplier	Petroleum Product Supply (10^4 tonnes)	Transportation Distance (km)
Daqing Petrochemical Agent	Daqing Oil Field Agent	602.72	1
Liaoyang Petrochemical Agent	Liaohe Oil Field Agent	750	125.25
Jinxi Petrochemical Agent	Liaohe Oil Field Agent	600	149.61
Fushun Petrochemical Agent	Liaohe Oil Field Agent	13.87	231.2
Dalian Petrochemical Agent	Bo Sea Oil Field Agent	691.51	481.51
Fushun Petrochemical Agent	Jilin Oil Field Agent	480.23	534.44
Fushun Petrochemical Agent	Daqing Oil Field Agent	431.07	750.46
Jinzhou Petrochemical Agent	Daqing Oil Field Agent	550	1,197.46
Dalian Petrochemical Agent	Daqing Oil Field Agent	18.49	1,228.91 km

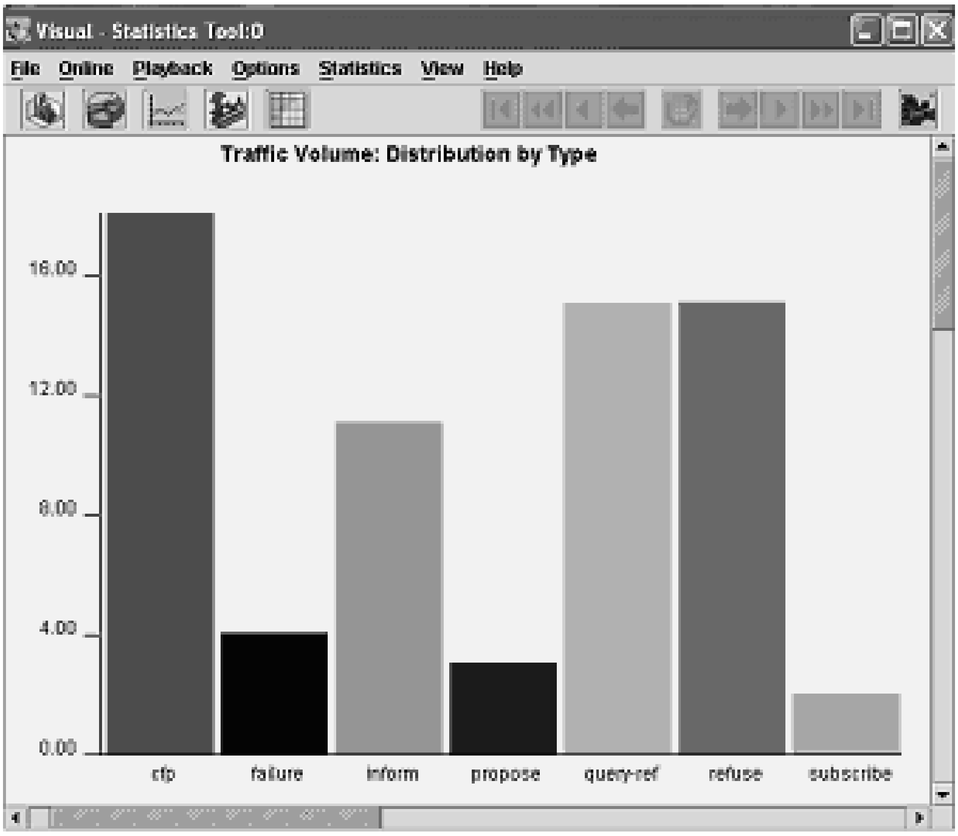

Fig. 20. Screenshot of the interaction statistics between agents in emergency.

committed to reporting the success or failure of the execution to the manager [6]. For a simple 2-tier supply chain, a contract net protocol can readily fit to a contract manager and its contractors. For multi-tier supply chains, a contractor may further announce requests for bids and award contracts to its own suppliers [14,15].

A contract net protocol is a simple method to find an allocation of a set of tasks to an agent society. However, since agents act independently during their decision processes, the plans only become locally optimized [6]. One drawback of (extended) contract net protocol is that the results are dependent upon the incoming order of tasks. By changing the incoming order of tasks, the plans of agents can be completely different as well as the result of the overall solution [25]. Contracts in contract net protocol are "binding" for the partners involved, and there is no flip-flop of decisions once contracts are made. It is difficult to adjust the contracts to accommodate dynamic changes such as the arrivals of urgent new orders [15].

6.2. Third-party negotiation protocols

A third-party negotiation protocol, which is also called an auction protocol, can be described as the mechanism between a general contractor and many specialty contractors through an auctioneer. In a third-party negotiation protocol, the general contractor agent (seller) starts the negotiation by sending a message to the auctioneer. This message contains the tasks that it wants to sell, the highest desired price, and the preferred auction type. After receiving the message, the auctioneer will broadcast it to the specialty contractor agents (bidders) and organize an auction according to the requirements the seller submits. After several rounds of conversation, the negotiation process will end with a deal reached between the seller and the best bidder [12]. A third-party negotiation protocol is well suited for trading tasks where the number of specialty contractors is too large to employ practically a simple bilateral negotiation protocol.

Common auctions protocols include Dutch, English, Vickrey, and First-Price-Sealed-Bid auctions [26,29]. Although it is possible that, under some conditions, all the four auction protocols are revenue equivalent for a private-value object, only English and Vickrey auctions rely on agents playing their dominant strategies. An English auction is more robust with respect to changing circumstances than a Vickrey auction. An English auction is still revenue superior in a very large class of situations, because the information revealed during the auction ensures that bidders will move closer to their reservation prices [16].

6.3. Double bid based protocol

Normal auction protocols may have a problem when there are multiple calls for bids/tasks which use the same resources belonging to a single bidder during the same period of time. The most undesirable scenario may be that a bidder fails to get any task assignment although it has the sufficient capacity ready. A possible solution to this kind of problem is a double bid [23].

A double bid consists of two different bids, that is, one is a real bid computed according to the temporal resource schedule updated by the previous bid, and the other is a virtual bid which is better than the former and is generated based on the same resource schedule. Both bids are evaluated by the auctioneer along with the bids from other bidders. Suppose there are two auctioneers C_1 and C_2, and bidders S_1 and S_2, respectively. If the virtual bid is determined as the winner, there are two options for C_2 to choose. One way is conservative, i.e., to accept the real bid which is only inferior to the virtual bid; the other is more profitable but also more risky, i.e., to accept the best virtual bid and at the same time preserve the second best real bid as a spare candidate. If C_2 selects the latter, it must postpone the final winner determination for a period of time to wait for the definitive real bid from S_1 replacing the previous virtual one and simultaneously send a ‘request for waiting’ message to the second best bidder. Once the update-bid of S_1 arrives at C_2 which offers no less competitive conditions than what the earlier virtual bid does within the time limitation, auctioneer C_2 will inform S_1 of an accept-bid. Otherwise, if the expected update-bid doesn’t return in time, the second best auctioneer will be sent the final accept-bid message.

6.4. Simulated trading algorithm

To handle the enormous complexity of optimizing interdependent plans in a supply chain, an optimization procedure is needed to improve the result after a first valid solution is found. Simulated trading is such a coordination mechanism. Trading is done in several rounds, each of which consists of a number of decision cycles. In each cycle, participants submit offers to sell or buy a task. At the end of each round a central manager agent tries to match the sell and buy offers of the contractors such that the cost of the whole solution decreases. Simulated trading procedure assumes a stable cooperative environment. An initial solution has to be found by using a contract net protocol before optimization algorithm can be used. Simulated trading is also an anytime algorithm, which is based on two nested loops, i.e., trading rounds nested by decision cycles [6].

Each trading round represents a complete exchange of tasks. After each trading round the agents’ plans are well defined and valid again. The number of trading rounds may be pre-specified before the optimization starts, if time is limited and an optimized solution is needed at a certain point of time. Otherwise, the number of trading rounds is unbounded, which means the optimization never stops until someone stops it manually.

Each trading round is then sub-divided into several decision cycles (which is usually $\leqslant 10$) and for each one the agents generate a bid to sell or buy a task. When the current plan at the end of a trading round is better than the saved plan, the saved plan is replaced by the current plan. When the algorithm is terminated or interrupted, it returns the saved plan which is the best plan ever considered. Hence, the anytime property of monotonically growing quality of the solution is guaranteed.

6.5. *Multi-attribute negotiation*

A number of factors, such as cost, time, quality, safety, and environment, must be considered in the decision-making process of SCM. The multi-attribute negotiation technique is developed based on the multi-attribute utility theory, which is an analytical tool for making decisions involving multiple interdependent objectives based on uncertainty and utility analysis, and an evaluation scheme for estimating various products and performance [9–11,32].

A multi-attribute negotiation process contains five steps [8], i.e., (1) evaluation of the attributes of the initial solutions made by the participants; (2) these evaluations are aggregated into overall utilities of these initial solutions; (3) provision of the target utility; (4) based on the target utility and the distribution of attributes, the values of the target attributes are determined, which lead to a new round of decision making; and (5) for each of the target attributes, an attribute value is chosen that has an evaluation value as close as possible to the target evaluation value for the attribute.

7. Evaluations

In terms of the average procurement cost in a petroleum supply chain, the simulation results are not globally optimal. The reason is that individual agents only consider their decision to select the supplier that makes the lowest procurement price or the nearest procurement date, and do not regard the effects for the common benefits of the society.

However, for CP-SCM, conventional negotiation protocols are incapable due to the domain specific requirements of CP-SCM.

Auction protocols [26,29] are mainly suitable for the negotiation for a relatively stable product or service, or their costs are easy to calculate. Because of the huge demands worldwide for petroleum and high risks of petroleum exploration and exploitation, as well as many unexpected factors, it is difficult for a bidder to submit an appropriate bid for auctions. Moreover, a contract net protocol directly takes place between supplier and consumer of a petroleum supply chain, thus the negotiation should be prompt and effective since there is no third-partner in the negotiation.

Although multi-attribute negotiation technology [30] considers the multiple factors which may influence the decisions in a supply chain, it mainly depends upon the utilities of attributes. Because utilities often deviate from the values or costs of products or services, even the same products for the same consumers can have different utilities after consuming. Petroleum consumers are very different from one another and thus the utilities of petroleum are diversified. Thus in practice an appropriate utility for petroleum during a certain period is difficult to determine.

A simulated trading protocol [6] adopts a contract net protocol and provides optimization mechanism by several rounds consisting of a number of decision cycles. However, it assumes that there is a stable cooperative environment in a supply chain. If the demands for petroleum get alleviated this may be an ideal negotiation mechanism for petroleum SCM.

A double bid based protocol [23] considers that a bidder can simultaneously respond to multiple calls for bids in auctions by providing a real bid and a virtual bid. However, there may be no essential difference between the real and the virtual bids, because they are calculated based on the same resources and schedules. Very likely the real and the virtual bids will result in the same petroleum supply chain formation.

Compared to conventional negotiation protocols, the proposed negotiation mechanism has the following advantages.

First, the domain specific requirements of CP-SCM are taken into account. Conventional negotiation protocols usually assume that there is a pure market, and the bidder and the auctioneer are in an open market.

Second, the negotiation is carried out by many repeated rounds, and any round will produce an ideal negotiation result, i.e., to make the lowest procurement price or nearest procurement date for consumers. Conventional negotiation protocols are usually completed by one round. For example, all auction protocols are to choose one bidder based on their bids.

Third, multiple factors are considered, including not only the quantitative factors such as price, date, and quantity, etc., but also the strategic ones such as collaborative partnership between consumers and suppliers, and the semi-monopolized market nature. Conventional negotiation protocols usually only consider part of the factors and most of the conventional protocols consider price as an important factor.

Fourth, the main difference of the proposed negotiation mechanism from conventional negotiation protocols is that the final agreement on the bids is decided by both consumers and suppliers, and demands drive and control the negotiation rounds.

8. Conclusions

This paper has demonstrated that MAS is an effective methodology for SCM problems, called MA-SCM. The main benefit of MA-SCM is dynamic supply chain formation via multi-agent negotiation. While conventional negotiation protocols are based on the assumption of a pure market, this paper has proposed a new negotiation mechanism to solve dynamic supply chain formation in a semi-monopolized market. The future works of this research can be undertaken in the following directions.

(1) To quantitatively evaluate the proposed negotiation mechanism, particularly the effectiveness of the negotiation, the adaptation to emergency events, and the supply chain optimization;
(2) To expand the multi-agent simulation scheme to other semi-monopolized markets, and to compare the simulation results with real-world supply chain data; and,
(3) To develop a commercialized agent software platform for dynamic supply chain formation suitable for the petroleum industry.

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Authors' Bios

Jiang Tian was a PhD research student in Glasgow Caledonian University from September 2002 to December 2005. He obtained his Higher Diploma in Petroleum Engineering from Chongqing Higher College of Petroleum Technology in 1989, Bachelor Degree in Industrial Economy from Southwest University of Finance and Economics in 1995, and Bachelor (Honors) Degree in Accounting from Southwest University in 1999, and Postgraduate Diploma in Technology Economy and Management from Southeast University in 2002. Prior to his PhD research, he had worked twelve years in Chinese petroleum industry. His research areas include Supply Chain Management, Multi-Agent Systems, Virtual Organizations, and E-Business. So far he has published about ten research papers in journals and conference proceedings.

Richard Foley obtained his BSc (Honors) from University of Strathclyde, Glasgow in 1980, and PhD from Glasgow Caledonian University in 1994. Since 1984 he has been a lecturer at Glasgow Caledonian University. His original PhD study was in the use of Non-Monotonic logic in the provision of Knowledge Base Systems. However, since then his interests have been in the application of AI systems to different areas of Software Engineering, such as Software Quality Planning and supporting Virtual Software Corporations.

Xin Yao obtained his BSc from the University of Science and Technology of China (USTC) in Hefei in 1982, MSc from the North China Institute of Computing Technology in Beijing in 1985, and PhD from USTC in Hefei in 1990. Xin Yao was an associate lecturer and lecturer between 1985 and 1990 at USTC while working on his PhD. His PhD work on simulated annealing and evolutionary algorithms was awarded the President's Award for Outstanding Thesis by the Chinese Academy of Sciences. He took up a postdoctoral fellowship in the Computer Sciences Laboratory, headed by Professor Richard Brent, at the Australian National University (ANU) in Canberra in 1990, and continued his work on simulated annealing and evolutionary algorithms. He joined the Knowledge-Based Systems Group, led by Dr Ron Sharpe, at CSIRO Division of Building, Construction and Engineering in Melbourne in 1991, working primarily on an industrial project on automatic inspection of sewage pipes. He returned to Canberra in 1992 to take up a lectureship in the School of Computer Science, University College, the University of New South Wales (UNSW), the Australian Defence Force Academy (ADFA), where he was later promoted to a senior lecturer and associate professor. Attracted by the English weather, he moved to the University of Birmingham, England, as a professor of computer science in 1999. Currently he is the Director of CERCIA (the Centre of Excellence for Research in Computational Intelligence and Applications), a Distinguished Visiting Professor of the University of Science and Technology of China in Hefei, and a visiting professor of three other universities. He is an IEEE Fellow. He has more than 200 publications and won the 2001 IEEE Donald G. Fink Prize Paper Award for his work on evolutionary artificial neural networks. In his spare time, he does the voluntary work as the editor-in-chief of IEEE Transactions on Evolutionary Computation, an associate editor or editorial board member of several other journals, and the editor of the World Scientific book series on “Advances in Natural Computation”. He has given more than 30 invited keynote and plenary speeches at conferences and workshops world-wide. His research has been supported by many funding bodies (more than 4M pounds in the last four years). His major research interests include evolutionary artificial neural networks, automatic modularization of machine learning systems, evolutionary optimization, constraint handling techniques, computational time complexity of evolutionary algorithms, co-evolution, iterated prisoner’s dilemma, data mining, and real-world applications.

Huaglory Tianfield

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