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ORIGINAL ARTICLE

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Study on multi-agent-based agile supply chain management

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Abstract In a worldwide network of suppliers, factories, warehouses, distribution centres and retailers, the supply chain plays a very important role in the acquisition, transformation, and delivery of raw materials and products. One of the most important characteristics of agile supply chain is the ability to reconfigure dynamically and quickly according to demand changes in the market. In this paper, concepts and characteristics of an agile supply chain are discussed and the agile supply chain is regarded as one of the pivotal technologies of agile manufacture based on dynamic alliance. Also, the importance of coordination in supply chain is emphasised and a general architecture of agile supply chain management is presented based on a multi-agent theory, in which the supply chain is managed by a set of intelligent agents for one or more activities. The supply chain management system functions are to coordinate its agents. Agent functionalities and responsibilities are defined respectively, and a contract net protocol joint with case-based reasoning for coordination and an algorithm for task allocation is presented.

Keywords Agile supply chain · Multi-agent system · Coordination · CBR · Contract net protocol

1 Introduction

Advanced technology and management are constantly being adopted to improve an enterprise's strength and competitive ability in order to achieve predominance among hot global competition. In a report on 21st century manufacturing strategy development, the author suggests that various production resources, including people, funds, technology and facilities should be integrated and managed as a whole; thus optimising the utilisation of resources and taking full advantage of advanced manufacturing technology, information technology, network technology and computer [1]. Agile manufacture based on dynamic alliance is coming into being so that enterprises can remain competitive in a constantly changing business environment and is becoming a main competitive paradigm in the international market. Agility, which has basically two meanings: flexibility and reconfigurability, has become a very important characteristic of a modern manufacturing enterprise. Flexibility is an enterprise's ability to make adjustments according to customers' needs. Reconfigurability is the ability to meet changing demands [2, 3].

The ability to quickly respond to market's changes, called agility, has been recognised as a key element in the success and survival of enterprises in today's market. In order to keep up with rapid change, enterprises need to change traditional management in this hot competition. Through dynamic alliance, enterprises exert predominance themselves, cooperate faithfully with each other, and compete jointly so as to meet the needs of the fluctuating market, and finally achieve the goal of win-win [2, 3]. So how to improve agility in the supply chain, namely flexibility and reconfigurability, is one of the important factors to win against the competition.

Supply chain management (SCM) is an approach to satisfy the demands of customers for products and services via integrated management in the whole business process from raw material procurement to the product or service delivery to customers. In [4], M. S. Fox et al. describe the goals and architecture of integrated supply chain management system (ISCM). In this system, each agent performs one or more supply chain management functions, and coordinates its decisions with other relevant agents. ISCM provides an approach to the real time

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performance of supply chain function. The integration of multi-agent technology and constraint network for solving the supply chain management problem is proposed [6]. In [7], Yan et al. develop a multi-agent-based negotiation support system for distributed electric power transmission cost allocation based on the network flow model and knowledge query & manipulation language (KQML). A KQML based multi-agent coordination language was proposed in [8, 9] for distributed and dynamic supply chain management. However, the coordination mechanisms have not been formally addressed in a multi-agent-based supply chain. In most industries, marketing is becoming more globalised, and the whole business process is being implemented into a complex network of supply chains. Each enterprise or business unit in the SCM represents an independent entity with conflicting and competing product requirements and may possess localised information relevant to their interests. Being aware of this independence, enterprises are regarded as autonomous agents that can decide how to deploy resources under their control to serve their interests.

This paper first introduces concepts and characteristics of agile supply chains and emphasises the importance of coordination in supply chain. Then, it presents an architecture of agile supply chain based on a multi-agent theory and states the agents' functions and responsibilities. Finally, it presents a CBR contract net protocol for coordination and the correlative algorithm for task allocation in multi-agent-based agile supply chains.

2 Agile supply chain

A supply chain is a network from the topologic structure which is composed of autonomous or semi-autonomous enterprises. The enterprises all work together for procurement, production, delivery, and so on [10]. There is a main enterprise in the supply chain that is responsible for configuring the supply chain according to the demand information and for achieving supply chain value using fund flow, material flow and information flow as mediums. There are three discontinuous buffers to make the material flow fluently and satisfy the change in the demand. On the one hand, as every enterprise manages inventory independently, plenty of funds are wasted. As the demand information moves up-stream, the forecast is inaccurate and the respond to the change in demand is slow [11]. Accordingly, the key method for competitiveness is improving and optimising supply chain management to achieve integrated, automated, and agile supply chain management and to cut costs in the supply chain.

To optimise supply chain management and coordinate the processes for material flow, fund flow and information flow, it is necessary to make material flow fluent, quickly fund turnover and keep information integrated. Prompt reconfiguration and coordination is an important characteristic of agile supply chain according to dynamic alliance compositing and decompositing (enterprise reconfiguration). Agile supply chain management can improve enterprise reconfiguring agility. The agile supply chain breaks through the traditional line-style organizational structure. With network technology an enterprise group is formed by a cooperative relationship which includes an enterprise business centre, a production design centre, a supplier, a distribution centre, a bank, a decision-making centre, etc. It reduces the lead time to the market to satisfy customer demand.

Agile supply chain without temporal and spatial limits promptly expands the enterprise scale, marketing share and resource by allied enterprise. So, a key factor of the agile supply chain is to integrate heterogeneous information systems adopted in various enterprises. The integration information system can provide marketing information and supplier details. Feasible inventory, quantity and cycle of replenished stock, delivery, etc. is designed using the shared information.

It is evident that agile supply chain is a typical distributed system. A multi-agent system (MAS) which is characterised by flexibility and adaptability is suitable for an open and dynamic environment. Thus MAS is a good method for agile supply chain management.

3 The concept of agents and MAS

Some people define an agent as any piece of software or object which can perform a specific given task. Presently the prevailing opinion is that an agent must exhibit three important general characteristics: autonomy, adaptation, and cooperation [8, 12, 13]. Autonomy means that agents have their own agenda of goals and exhibit goal-directed behaviour. Agents are not simply reactive, but can be pro-active and take initiatives as they deem appropriate. Adaptation implies that agents are capable of adapting to the environment, which includes other agents and human users, and can learn from the experience in order to improve themselves in a changing environment. Cooperation and coordination between agents are probably the most important feature of MAS. Unlike those stand-alone agents, agents in a MAS collaborate with each other to achieve common goals. In other words, these agents share information, knowledge, and tasks among themselves. The intelligence of MAS is not only reflected by the expertise of individual agents but also exhibited by the emerged collective behaviour beyond individual agents. Of course various agents have different functions, but some functions are needed for each agent. A generic structure of agents that includes two parts is presented: agent kernel and function module. Figure 1 exhibits the generic structure of agents which is a plug-in model.

In Fig. 1, the generic agent includes the following components:

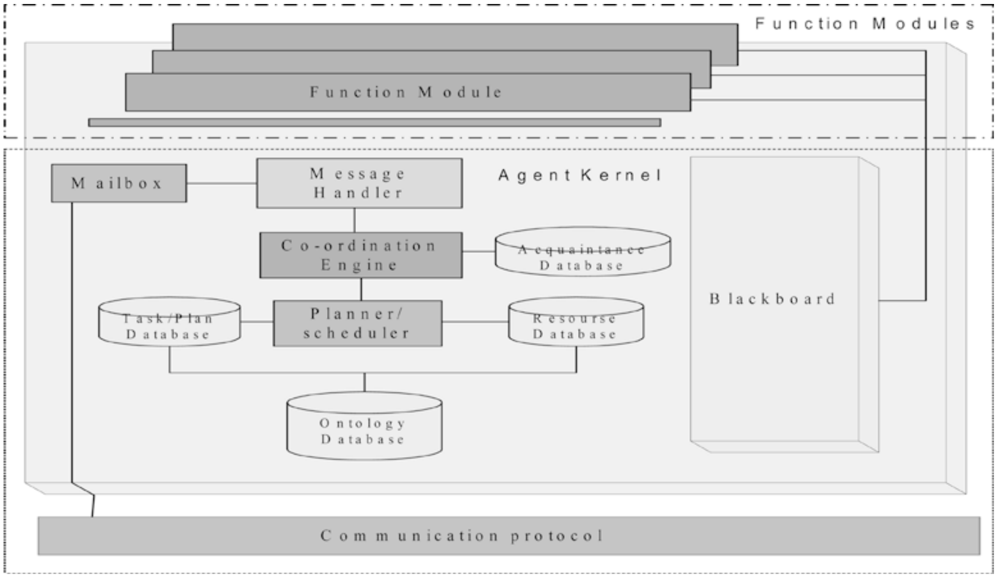

Fig. 1 Generic structures of agents

The mailbox handles communication between one agent and the other agents.

The message handler processes incoming message from the mailbox, orders them according to priority level, and dispatches them to the relevant components of the agent.

The coordination engine makes decisions concerning the agent's goals, e.g. how they should be pursued, when to abandon them, etc., and sends the accepted tasks to the planner/scheduler. It is also responsible for coordinating the agents' interactions with other agents using coordination protocols and strategies.

The planner and scheduler plans the agent's tasks on the basis of decisions made by the coordination engine and on resources and task specifications available to the agent. If not, a message is sent to the coordination engine for finding extra resources.

The blackboard provides a shared work area for exchanging information, data, and knowledge among function modules. Every function module is an independent entity. These function modules execute concurrently by the control of planner/scheduler and collaborate through the blackboard.

The acquaintance database describes one agent's relationships with other agents in the society, and its beliefs about the capabilities of those agents. The coordination engine uses information contained in this database when making collaborative arrangements with other agents.

The resource database reserves a list of resources (referred to in this paper as facts) that are owned by and available to the agent. The resource database also supports a direct interface to external systems, which allows the interface to dynamically link and utilise a proprietary database.

The ontology database stores the logical definition of each fact type—its legal attributes, the range of legal values for each attribute, any constraints between attribute values, and any relationship between the attributes of that fact and other facts.

The task/plan database provides logical descriptions of planning operators (or tasks) known to the agent.

4 Multi-agent-based agile supply chain management

Multi-agent-based agile supply chain management performs many functions in a tightly coordinated manner. Agents organise supply chain networks dynamically by coordination according to a changing environment, e.g. exchange rates go up and down unpredictably, customers change or cancel orders, materials do not arrive on time, production facilities fail, etc. [2, 14]. Each agent performs one or more supply chain functions independently, and each coordinates his action with other agents. Figure 2 provides the architecture of multi-agent-based agile supply chains. There are two types of agents: functional agents and mediator agents. Functional agents plan and/or control activities in the supply chain. Mediator agents play a system coordinator role s by promoting cooperation among agents and providing message services. Mediator agents dispatch the tasks to the functional agents or other mediator agents, and then those functional or mediator agents complete the tasks by coordination. All functional agents coordinate with each other to achieve the goals assigned by mediator agents. The mediator-mediator and mediator-agent communication is asynchronous, and the communication mode can be point-to-point (between two agents), broadcast (one to all agents), or multicast (to a selected group of agents). Messages are formatted in an extended KQML format. The architecture is characterised by organizational hierarchy and team spirit, simplifying the organisational architecture and reducing the time needed to fulfil the task. The rest of this section briefly describes each of the mediator agents under development.

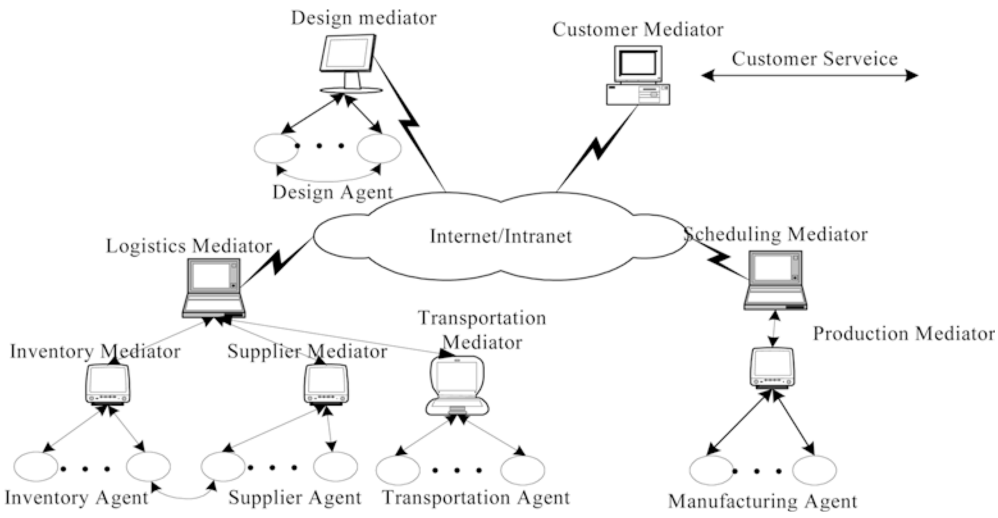

Fig. 2 An architecture of multi-agent based agile supply chain management

- Customer mediator agent: This agent is responsible for acquiring orders from customers, negotiating with customers about prices, due dates, technical advisory, etc., and handling customer requests for modifying or cancelling respective orders, then sending the order information to a scheduling mediator agent. If a customer request needs to be re-designed, the information is sent to a design mediator agent, then to a scheduling mediator agent.
- Scheduling mediator agent: This agent is responsible for scheduling and re-scheduling activities in the factory, exploring hypothetical "what-if" scenarios for potential new orders, and generating schedules that are sent to the production mediator agent and logistics mediator agent. The scheduling agent also acts as a coordinator when infeasible situations arise. It has the capability to explore tradeoffs among the various constraints and goals that exit in the plant.
- Logistics mediator agent: This agent is responsible for coordinating multi-plans, multiple-supplier, and the multiple-distribution centre domain of the enterprise to achieve the best possible results in terms of supply chain goals, which include on-time delivery, cost minimisation, etc. It manages the movement of products or materials across the supply chain from the supplier of raw materials to the finished product customer.
- Production mediator agent: This agent performs the order release and real-time floor control functions as directed by the scheduling mediator agent. It monitors production operation and facilities. If the production operation is abnormal or a machine breaks down, this agent re-arranges the task or re-schedules with the scheduling mediator agent.
- Transportation mediator agent: This agent is responsible for the assignment and scheduling of transportation resources in order to satisfy inter-plant movement specified by the logistics mediator agent. It is able to take into account a variety of transportation assets and transportation routes in the construction of its schedules. The goal is to send the right materials on time to the right location as assigned by the logistics mediator agent.
- Inventory mediator agent: There are three inventories at the manufacturing site: raw product inventory, work-in-process inventory, and finished product inventory. This agent is responsible for managing these inventories to satisfy production requirements.
- Supplier mediator agent: This agent is responsible for managing supplier information and choosing suppliers based on requests in the production process.
- Design mediator agent: This agent is responsible for developing new goods and for sending the relevant information to the scheduling mediator agent for scheduling, as well as to the customer mediator agent for providing technological advice.

5 Coordination in a multi-agent-based agile supply chain

Coordination has been defined as the process of managing dependencies between activities [15]. One important characteristic of an agile supply chain is the ability to reconfigure quickly according to change in the environment. In order to operate efficiently, functional entities in the supply chain must work in a tightly coordinated manner. The supply chain works as a network of cooperating agents, in which each performs one or more supply chain functions, and each coordinates its action with that of other agents [5]. Correspondingly, a SCMS transforms to a MAS. In this MAS, agents may join the system and leave it according to coordinating processes. With coordination among agents, this MAS achieves the goal of "the right products in the right quantities (at the right location) at the right moment at minimal cost".

5.1 Contract net protocol combined with case-based reasoning

The contract net is a negotiation protocol (CNP) proposed by Smith [15]. In the CNP, every agent is regarded as a node, such as a manager or a contractor. The manager agent (MA) is responsible for decomposing, announcing, and allocating the task and contractor agent (CA) is responsible for performing the task. This protocol has been widely used for multi-agent negotiation, but it is inefficient. For this reason, contract net protocol is combined with case-based reasoning (CBR).

In case-based reasoning (CBR), the target case is defined as problem or instance which is currently being faced, and the base case is problem or instance in the database. CBR searches the base case in the database under the direction of the target case, and then the base case instructs the target case to solve the problem. This method is efficient. But at the very beginning, it is very difficult to set up a database which includes all problems solving cases. The cases may be depicted as follows:

$$C = <task, MA, task - constraint, agent - set>$$

Here, MA is task manager. Task-constraint represents various constraint conditions for performing the task, depicted as a vector $\{c_1, c_2, c_3, \ldots, c_m\}$. Agent-set is a set of performing the task as defined below:

$$Agent\_set = \{<sub\_task_i, agent\_id, cost, time, resource>\}$$

$$task = \bigcup_{i=1}^{n} sub\_task_i$$

In the supply chain, the same process in which a certain product moves from the manufacturer to the customer is performed iteratively. So, case-based reasoning is very efficient. Consequently, combining contract net protocol with CBR could avoid high communicating on load, thus promoting efficiency. The process can be depicted as follows (Fig. 3).

5.2 The algorithm for task allocation base on CBR contract net protocol

There are two types of agents in the supply chain, cooperative and self-interested agents. Cooperative agents attempt to maximise social welfare, which is the sum of the agents utilities. They are willing to take individual losses in service of the good of the society of agents. For example, function agents come from the same enterprise. In truth, the task allocation among cooperative agents is combinational optimisation problem.

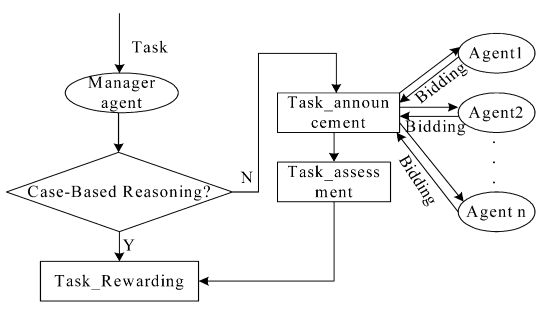

Fig. 3 CBR contract net process

Self-interested agents seek to maximise their own profit without caring about the others. In such a case, an agent is willing to do other agents' tasks only for compensation [16]. Function agents, for example, come from different enterprises.

In the following section the algorithm for task allocation among self-interested agents based on CBR contract net protocol will be addressed. Before describing the algorithm, there are some definitions that must be clarified:

Task—A task which is performed by one agent or several agents together: $T = <$task, reward, constraints$>$, where task is the set of tasks (task $= \{t_1, t_2, \ldots, t_m\}$), reward is the payoff to the agents that perform the task (reward $= \{r_1, r_2, \ldots, r_m\}$), and constraints refer to the bounded condition for performing the task (constraints $= \{c_1, c_2, \ldots, c_n\}$).

Agent coalition (AC)—A group of agents that perform task T, described as a set AC $= \{agent_i, i = 1,2,\ldots,n\}$.

Efficiency of agent—Efficiency of an agent i is described as follows:

$$E_i = (reward - cost)/cost \quad (1)$$

where reward is the payoff to the agent performing task T, and cost refers to that spend on performing the task. If agent i is not awarded the task, then $E_i = 0$.

Efficiency of agent coalition—

$$E_{coalition} = \left(reward - \sum_{i}^{m} cost_i - \theta\right) \Big/ \left(\sum_{i}^{m} cost_i + \theta\right) \quad (2)$$

where reward is the payoff of the agent coalition performing task T; $cost_i$ refers to that spend on performing task t_i; and θ is the expense on forming coalition, which is shared by the members of the coalition. If the coalition is not awarded task T, then $E_{coalition} <= 0$.

6 Algorithm:

1. After MA accepts the task $T = <$task, reward, constraint$>$ (task is decomposable), then it searches the database.
2. If it finds a corresponding case, it assigns the task or subtask to the related agents according to the case, and the process is over
3. If no case is found, then the task T is announced to all relevant agents (agent i, $i = 1,2,\ldots n$).
4. The relevant agents make bids for the task according to their own states and capabilities. The bid

from agent i can be described as follows: $Bid_i = \langle agentid_i, T_i, price_i, condition_i \rangle$, where i expresses the bidding agent ($i=1,2,\ldots,h$); $agentid_i$ is the exclusive agent identifier; T_i is the task set of agent i's fulfilment; $price_i$ is the recompense of agent i fulfilling the task T_i; and $condition_i$ is the constraint conditions for agent i to fulfil the task T_i.

5. If $\bigcup_{1\le i\le h} \subset T_i$ then the task T can not be performed. Otherwise MA makes a complete combination of the agents, namely to form a number of agent coalitions (or agent sets, amounting to $N=2^h-1$).
6. First MA deletes those agent coalitions where no agents are able to satisfy the constraint condition. Next the rest of the coalitions are grouped by the number of agents in coalitions and put into set P ($P=\{P_1,P_2,\ldots,P_h\}$) in order of the minimum recompense increase of the coalitions, where P_i is the set of agent coalitions, including i agents.
7. MA puts the first coalition from each group P_i ($i=1,2,\ldots,h$) into set L, and if L is null then it returns to (10), otherwise it calculates the minimum recompense of each coalition as follows:

$$Min\sum_{i}^{m} price_i * T_i$$

$$s.t.\quad \sum_{i=1}^{h} T_i \supseteq T$$

$$\sum_{i}^{m} condition_i \subseteq constrait$$

Then it searches for the minimal agent coalition AC_{min} from the set L.

8. MA sends the AC_{min} to the relevant agents, namely MA requests that these agent fulfil the task together. The relevant agents calculate the $E_{coalition}$ and E_i according to Eqs. 1 and 2. If $E_{coalition} \ge \max_i^m E_i$, then all agents in the AC_{min} accept the proposal to form a coalition to perform the task T together. MA assigns the task to the AC_{min}, and the process is over. Otherwise it deletes the AC_{min} from P_i and returns to (7).
9. If the relevant agents accept the task or subtask, then MA assigns the task to them. The process is over. If some agents cannot accept the subtask and the stated time is not attained, then it returns to (3), otherwise it returns to (10).
10. The process is terminated (namely the task cannot be performed).

After all processes have been completed, case-based maintenance is required to improve the CBR. Thus efficiency is continuously promoted.

6.1 An example

– A simple instantiation of a supply chain simulation is presented here and the negotiating process among agents is shown. In this supply chain instantiation, the transportation mediator agent (TMA) has a transport task T, in which it has to deliver the finished product to the customer within 15 units of time and must pay 1500 monetary units for it, that is $T=\langle t, 1500, 15\rangle$. Four transport companies can perform task T. Each company is an autonomous agent, that is four agents, agent A, agent B, agent C and agent D. So the TMA announces the task T to the four agents. Then the four agents make a bid for the task T as shown in Table 1.

– So the four agents can form 2^4-1 coalitions (see Fig. 4), which are put into set P. Cooperation between agents in the coalition requires expense and the expense for forming the coalition increases with the growth of in coalition size. This means that expanding the coalition may be non-beneficial. The expense of each agent in forming a coalition θ is 100. First, the coalitions in which no agents can satisfy the constraint conditions are deleted from the set P. The rest of the coalitions are grouped by the number of agents in the coalition and ordered according to the recompense of each group that was increased due to the coalition, namely $P_1=\{B\}$, $P_2=\{\{A,B\},\{A,C\},\{B,C\},\{A,D\},\{B,D\}\}$, $P_3=\{\{A,B,C\},\{A,B,D\},\{B,C,D\}\}$, $P_4=\{\{A,B,C,D\}\}$. Then the cost and efficiency of coalition $\{B\}$,$\{A,C\}$ and $\{A, B, C\}$ are calculated as follows:

$$Price_{\{A,B\}} = Min(800x_1 + 1200x_2)$$
$$s.t.\, 20x_1 + 12x_2 \le 15$$
$$x_1 + x_2 \ge 1$$
$$x_1 \ge 0.x_2 \ge 0$$

$$Price_{\{A,B,C\}} = Min(800y_1 + 1200y_2 + 2000y_3)$$
$$s.t.\, 20y_1 + 12y_2 + 5y_3 \le 15$$
$$y_1 + y_2 + y_3 \ge 1$$
$$y_1 \ge 0.y_2 \ge 0, y_3 \ge 0$$

Table 1 The bids of four agents

Agent Id	Price	Conditions
Agent A	800	20
Agent B	1200	12
Agent C	2000	5
Agent D	2500	3

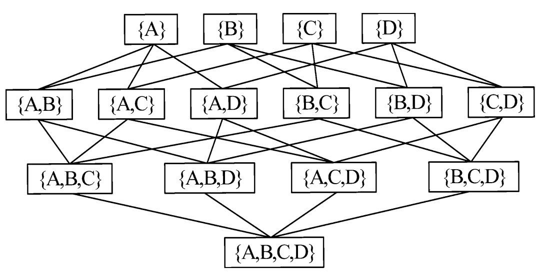

Fig. 4 Agent coalition graph

the following result can be obtained: $Price_{\{B\}} = 1200$; $x_1 = 0.3750$, $x_2 = 0.6250$, $Price_{\{A,B\}} = 1050$; and $y_1 = 0.3750$, $y_2 = 0.6250$, $y_3 = 0$. The above result shows that agent B does not attend the coalition {A,B,C}, that is both agent B and coalition {A,B} can fulfill the task and satisfy the constraint conditions. According to Eqs. 1 and 2, E_A, E_B, $E_{\{A,B\}}$: $E_A = 0$ (because TMA does not assign the task to A.), $E_B = (1500-1200)/1200 = 0.25$, $E_{\{A,B\}} = (1500-1050-2*100)/(1050+2*100) = 0.2$ can be obtained. Because of $E_{\{A,B\}} < \max\{E_A, E_B\}$, agent B does not agree to form a coalition. Therefore, the TMA selects agent B to fulfil the task.

7 Conclusions

In this paper, the concept and characteristics of agile supply chain management are introduced. Dynamic and quick reconfiguration is one of important characteristics of an agile supply chain and agile supply chain management is one of the key technologies of agile manufacturing based on dynamic alliances. As agile supply chain is a typical distributed system, and MAS is efficient for this task.

In the architecture of agile supply chain management, the supply chain is managed by a set of intelligent agents that are responsible for one or more activities. In order to realise the agility of supply chains, coordination amongst agents is very important. Therefore, it can be suggested that contract net protocol should be combined with case-based reasoning to coordinate among agents.

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