Implications of Agent-based Supply Chain Games

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Abstract – **The increased prevalence of network-enabled supply chains and out-sourcing of business processes suggests a stronger role for simulation tools, such as multi-agent systems, in supply chain management. We report on a new supply chain management game in the 2003 Trading Agent Competition and the design and experiences of our agent, PSUTAC. We discuss how using a shared mental model approach can help SCM designers attack the role of information flow in an uncertain market environment. We conclude with a discussion about future implications to SCM of such trading agent simulations.**

I. INTRODUCTION

The recent trends towards out-sourcing of many business processes, and modularization of supply-chains, result in a growing need for review and revision of traditional supply chain management (SCM) tools. Such tools generally model decisions as being made by one centralized decision maker, rather than as a decentralized negotiation and decision-making process. At the same time, analytical models are limited in their ability to model complex, multi-firm, multi-dimensional relationships. New simulation tools, including multi-agent systems, are starting to be investigated. Multi-agent system design meshes well with modeling supply chain networks, as it inherently assumes that agents have their own goals, which may be anywhere from pure self-interest to cooperative, thus allowing more freedom of analysis compared to traditional simulation or analytical tools. The 2003 Trading Agent Competition added a Supply Chain Management game (TAC/SCM) [1] to stimulate interest and research in this area. We discuss the design of our agent, PSUTAC, our experiences in this game, and what lessons we have taken away with us for the future role of intelligent agents in supply chain management.

II. RELATED WORK

Our approach draws from two main research areas: management and decision science and multi-agent systems, including agent-based coordination. Management science and decision sciences have started to propose simple analytic models aimed at improving the information flow necessary in dynamic coordinated supply chains to both avoid the *bullwhip effect* (where demand variance increases up the supply chain) and other destructive feedback effects[2], as well as to decrease inventory costs [3-5]. Using multi-agent systems as an SCM system development tool has been explored in recent publications [6-10]. The recent TAC/SCM game grew out of substantial previous work in agent-based negotiation and coordination, see reference [11] for more background.

III. PSUTAC AGENT

Our primary goal in entering the TAC/SCM was to create a reusable and extendable agent architecture that could be used in future research efforts. Our system design is shown in Fig. 1 below.

The agent's decision cycle has three phases: data processing, strategic planning, and operational decisions. In the data processing phase, the agent creates business objects (*request-for-quotes* (RFQs), offers, or reports) by processing in-coming messages from business partners such as customers and suppliers. Business objects also identify information about related market conditions and put them into the agent's knowledge base. For example, upon receiving RFQs from the customer, the agent assesses whether the demand for each product is high or low. The DB Connector module saves these objects out to a database for further analysis.

In the strategic planning phase, the agent uses its knowledge base to identify both relevant market conditions and business logic. A business logic rule for making supply pricing decisions has the following form: *If customers' demand is high, then bid with high market price.* In the second step of strategic planning, the agent applies the appropriate rules to current conditions, which results in fuzzy values for the various RFQs, bid prices, etc., that are needed to make operational decisions such as *'which RFQ'* and *'what price'*.

Through an agent's configuration module, the agent is configurable to different planning, operating, and competing modes. For the 2003 TAC/SCM game, the PSUTAC agent followed a fairly conservative strategy, and made it to the semi-finals, but not the finals of the competition. In light of our overarching, more emphasized goal of reusability, we believe the PSUTAC agent faired well.

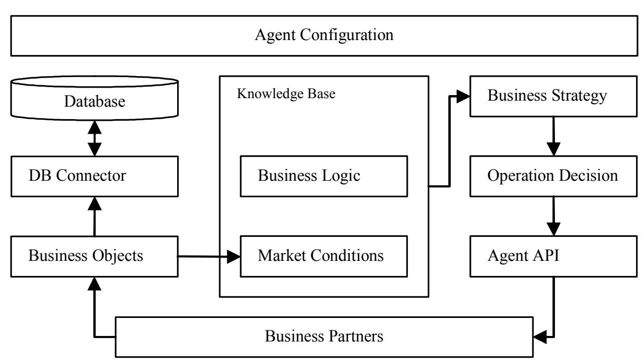

Fig. 1. PSUTAC system design.

IV. TAC/SCM GAME

In each TAC/SCM game[1], six participants provide their PC assembly agent, which will interact with customer and supplier agents created by the game developers. A total of 16 different types of PCs can be assembled, depending on different configurations for CPU, motherboard, memory, and hard disk. Each game takes place over a simulated year. The assemblers must respond to daily RFQs from customers with bids, and negotiate with suppliers for PC components by sending out RFQs. Suppliers respond with offers, which the assembly agents either accept or reject. An accepted RFQ becomes an order.

PSUTAC's 2003 game strategy was a simple "Make to Stock" approach aimed at maximizing its responsiveness to customers' demand. This approach involves (1) deciding on a required level of production, (2) purchasing all components at the beginning of the game, (3) producing with full capacity, and (4) selling on-hand stock at optimum prices. Each day, PSUTAC agent used the following rules to make its decisions:

1. *Pricing for supplier PC component RFQs:* our agent used a Gaussian distribution, with its mean based on the current component's market price, to set bidding prices semi-randomly. The variance of the distribution is determined by two weighted decision factors: the current stock level and the overall demand. Our agent evenly distributed its RFQs across all vendors.
2. *Selection of customer RFQs to bid on:* our agent selects bids that have a reserved price higher than the bidding price and the agent offers no more than what is on hand. In addition, the agent delivers an order immediately after it receives one from the customer. Therefore, by bidding and delivery conservatively, the agent achieves a high fill rate and a low penalty rate.
3. *Production scheduling:* the agent schedules its productions by prioritizing according to the inverse of the various products' stock level.
4. *Offer acceptance and delivery scheduling:* PSUTAC accepts all offers and schedules delivery in order of product completion.

Our aggressive buying strategy and relative conservative selling strategy worked well given that an initial demand surge made it all but impossible to buy supplies later in the game. However, the strategy was found to be inadequate to address the problems caused by highly dynamic consumer demand changes.

V. REFLECTIONS ON THE TAC/SCM GAME

We see the purpose of supply chain games such as TAC/SCM being two-fold. The first is to raise interest and discussion in the area by providing a relatively simple game that still captures some compelling aspects of the overall problem. To make the game too complicated would shut out many participants, who are often graduate and undergraduate students. The second is to raise research issues that can best be explored outside of the game constraints. Therefore we divide our comments into those focused on the game structure and those focused on future research directions that are suggested by our experiences in the TAC/SCM game.

The main challenge in the TAC/SCM game design is to find the right incentives that can make the whole supply chain optimum, given the self-interested behavior of the PC assembler agents. For this first game, the main problems involved the initial conditions (e.g., assembler agents start with no on-hand stock, prices never go lower than the first day, etc.). These problems caused some anomalous behavior, including strong incentives for participants to buy all their stock at the beginning of the game rather than spaced throughout. The TAC development team has already solicited, and received, comments and suggestions on how to best avoid these unintentional problems in the next game, which are also addressed in [12]. Other potential ways to align the game more closely with real-world issues include having customer agents keep track of which assembler agents delivered PCs on time, rather than evaluating them solely on the basis of price. Finally, one critical SCM factor, transportation, is currently not considered, but presumably can be incorporated as the game design stabilizes.

Games like TAC/SCM allow us to do "wind tunnel" experiments, singling out the contribution of individual components, and suggest directions for new theories/practices. We believe that TAC/SCM provides a natural framework for investigating the following research questions:

- What are the effects of reputation and multi-criteria negotiation on supply chain performance?
- What are the effects of different market properties and information flow? In particular, what are the effects of game assumptions, such as what information is observed and known, determination of capacity (no exogenous capacity constraint), lack of budget constraints, lack of discounting, etc. Also, the game allows only spot-market interactions. However, firms often engage in a combination of long-term contracts and spot-market purchases [13], which could affect results significantly.
- How effective is agent learning in this environment? Can agents learn good price setting strategies or good stock management strategies, as did the agents playing the beer game [14], in previous TAC games [15], and in [16]?

However, agent games do not capture many aspects of the real world, including real-world data and interacting with human decision-makers, expert and novice alike. We see the need for simulations involving real-world data and company decision-maker. We also see a role for team-based agents to provide training for human decision-makers given rapidly changing business conditions.

Finally, the legal implications of incorporating semi-autonomous agents into a supply chain have not been sufficiently examined [17]. Adapting traditional law to new technologies is challenging, often with serious impact on related fields. Such difficulties are well documented in

[1] See full game specification at http://www.sics.se/tac

intellectual property and commercial transactions. This pattern is repeated with the achievement of legal status for electronic agents under statutes such as UETA, Federal E-SIGN and UCITA. A hodge-podge, patchwork of recent and controversial case law from contract, tort and property law threatens the coherence and predictability of the nascent law of electronic agency. Information technologists are making considerable investment to advance the intelligence and utility of electronic agents. The development of electronic agency law is approaching a tipping point recognizing the increasing autonomy of electronic agents - many of which exhibit artificial intelligence, operate autonomously and conduct independent negotiation - such as in the digital rights management and privacy preference contexts. Agency law can enhance both traditional and electronic transactions through the major phases of transaction processing - from the initial information exchange, through contract negotiation and formation, to performance, modification and payment. For example, electronic agents can play a major role in the investigation of counter-parties, maintenance of detailed records, reduction of communication costs and risks, and performance monitoring. In exploring the implications of eAgency law to SCM, we hope to be able to derive design guidelines for building *legally-aware* agents.

VI. TEAMWORK in SCM

With supply chains becoming more dynamic, information flow in the supply chain needs to be improved for better responsiveness, not only to dynamics of customers' demand, but also to various unexpected market events—opportunities or negative impacts. When designing a supply chain, however, people often face a dilemma on what information to communicate. On one hand, missing information can cause deleterious effects. In TAC'03, for example, our failure to respond to the preemption strategy [18] employed by Deep Maize in the semi final rounds proved fatal. The unexpected event (the breakdown of supplies) was not easily identified by the designers. On the other hand, the information rich nature of the SCM domain can cause serious problems of information overflow: useful information will be buried in a huge volume of data. From published reports on TAC'03 teams, few of them can fully use all of the information because the amount of data that an agent needs to process (under time-pressure) is huge [1].

In this section, we introduce a team-based agent approach to tackle this problem. Our objectives in applying this approach are three-fold. First, we hope the approach can provide a decision support tool to help supply chain designers identify specific information and knowledge sharing needs. Second, we expect the approach can help supply chains be more responsive to unexpected market events. Lastly, the approach can shed some light on how to adopt industry standards to enable stronger coordination in supply chains.

A. Proactive communication in CAST

Researches on human teams have repeatedly point out that members of high performance human teams can often anticipate the needs of other teammates, and proactively help them regarding their needs [19]. One of the team cognition theories that attempt to explain these teamwork behaviors introduces the notion of "shared mental model" [20], which refers to an overlapping understanding among members of the team regarding their objectives, their structure, their process, and so on. Along this direction, Yen et al. implemented a team-oriented agent architecture called CAST(Collaborative Agents for Simulating Teamwork) [21], which realized a computational shared mental model and allows agents in a team to anticipate the potential information needs of teammates and help them proactively.

The main distinguishing feature of CAST is proactive team behavior enabled by the fact that agents within CAST architecture share the same declarative specification of team structure and process. Therefore, every agent can reason about what other teammates are working on, what the preconditions of the 'teammates' actions are, whether the teammates can observe the information required evaluating a precondition, and hence what information might be potentially useful to the teammates. As such, agents can figure out what information to proactively deliver to teammates, and use a decision theoretic cost/benefit analysis of the proactive information delivery before actually communicating. The proactive inform behavior has been demonstrated to be useful for enhancing teamwork in the various domains including battle space situation awareness and information fusion[22], army logistic coordination [23], and anti-terrorist information analysis [24].

B. Use CAST for supply chain decision support

A typical supply chain can be viewed as two levels of teamwork: intra-organizational teams (sub-teams) and inter-organizational teams (top-teams). A sub-team is composed of various functional areas within an organization such as purchase, sales, and inventory management (see the vendor in Fig. 2). Team members communicate each other directly. A top team is composed of all the business partners (i.e., sub-teams) in the supply chain such as vendors, manufacturers, and retailers. Typically, each sub-team communicates with its business partners through the appropriate business-relationship contact point. In Fig.2, for example, communication between the vendor (*A*) and the manufacturer (*B*) is realized as communication between the business contact points—*Sales_A* and *Purchase_B* or the logistic contact points—*Inventory_A* and *Inventory_B*.

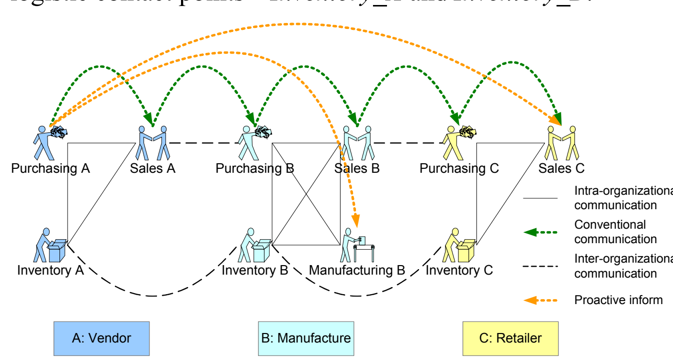

Fig. 2. Proactive communication in a supply chain.

In the supply chain domain, business partners communicate at three different levels: data, information, and knowledge. First, in an organization, data represents business transactions, decisions, and market intelligence. Data can be captured and accessed through powerful Enterprise Resource Planning (ERP) systems, which allows data sharing among different departments in an organization. Basic collaborations within a supply chain are also based on selective data exchange [25]. Second, information is used to make operational decisions. For example, supply changes will affect decisions in production planning. Standard methods such as statistics are used for information analysis. For example, information can be obtained as online reports. Limited information is shared in current supply chains [26]. Knowledge is more valuable than data or information, because knowledge is the key to make sense of data and information such that it reflects a company's core competence. There are only limited ways of obtaining knowledge such as from employee's experiences, or from advanced knowledge discovery technologies.

In the CAST framework, agents communicate at information and knowledge levels. From cognitive science point of view, rational decision making requires information and knowledge. Therefore, our framework can help support more straightforward and human-friendly decision support. CAST agents will be deployed on top of information level systems such as ERP systems or business intelligence systems. How to retrieve information from data, or how to share data among business partners will not be discussed in this paper.

We use Fig. 2, a typical supply chain, to illustrate how CAST agents can reason about information needs of business partners and communicate information and knowledge proactively. Suppose

1) a supply chain includes three business partners *A* (the vendor), *B* (the manufacture), and *C* (the retailer), where *B*'s organizational structure includes purchase, inventory, production, and sales department;
2) *A* knows from *B*'s general processes that it needs a certain raw material *X* for its production;
3) *A* knows that the final product *Y* is made from *X*;
4) *A* observed an event—the supply of a raw material *X* was interrupted by an aggressive competitor.

In this simple case, naturally, *A* should inform *B* about this event that *X* is unavailable now. We describe how CAST agents realize this feature by shared business processes and organizational structures.

In CAST, processes and team structures are represented as MALLET (Multi-Agent Logic Language for Encoding Teamwork) [27] that is a logic-based language for specifying the structures and processes of agent teams. The process describes the procedure of how a team will accomplish their task. To be expressive, MALLET provides a rich set of constructs to define such procedures. A process consists of invocations of operators or plans, or arbitrary combinations using various constructs such as sequential, parallel, conditional, or iterative, blocks, etc. For instance, Table 1 describes the two levels of teams in the supply chain and business processes of *B*'s production and *C*'s sales.

Table 1. An example of MALLET.

```
// Structure (1)
(team Supply_Chain  (A_logistic) (B_logistic)
                    (C_logistic))
(team B_logistic    (Manufacturing_B) (Sales_B)
                    (Purchase_B) (Inventory_B))
(plays-role Manufacturing_B (production))
// Process (2)
(plan B_production ()
(pre-cond (available X))
  (process
    (do Manufacturing_B produce)))
// Process (2)
(plan C_sales ()
(pre-cond (available Y))
  (process
    (do Sales_C sales)))
// Knowledge (3)
((Is_composed_of Y X))
```

The precondition of the production process includes the availability of material *X*, i.e., *(available X)*. By matching the *Manufacturing_B*'s needs with a Dynamic Inter-Agent Rule Generator (DIARG) algorithm [21], A will proactively deliver the information about unavailability of *X* to *B*'s production department. With similar process sharing, *A* can also inform *B*'s sales, purchase, and inventory department.

Now, the question is whether *A* should inform *C* about the event. Generally *A* does not want to overwhelm its business partners with irrelevant information. However, given the knowledge that *C* may soon be considering a sales promotion of *Y*, and that the shortage of *X* will cause a shortage of *Y*, it is clear that timely dissemination of this information is crucial. Although the information can be send to *C* by conventional communication means, directly informing *C* can greatly reduce the delay and improve the responsiveness of the whole supply chain. Thus by sharing some elements of their business processes, and incorporating the knowledge that *Y* is made from *X*, *Purchase_A* can reason that the information is also relevant to *Sales_C*. However, suppose *Sales_C* does not know that *Y* is made from *X*. Then *Sales_C* will not understand why Purchase_A sent this information. In that case, *Purchase_A* can send both the information and the relevant knowledge, which allows the receiver to make sense of the information.

C. Discussion

In CAST, shared mental model is the driving force of efficient teamwork. From the above example, we find that business process and organizational structure are two elements of the shared mental model in SCM context. We imagine that to implement shared mental models in competitive business environment is challenging. For example, business may not want to disclose their advanced processes to their competitors. However, more and more businesses are adopting standard processes such as RosettaNet [28]. Consequently, the standardization of business processes is becoming common practice and it forms an innate shared mental model for supply chains.

Furthermore, trust issue is another problem that is associated with this approach: how to handle the information or knowledge that is sent by the business partners? The recipient needs to make decisions about the reliability of the information and knowledge provided by their business partners. Their reliability may be affected by uncertain knowledge on their part (e.g., “I think X will be in short supply next month”) or active disinformation. This is an area we are interested in investigating further.

VII. Conclusions

We see several main contributions of such agent games to both SCM research and teaching. Currently, systems such as TAC/SCM are not common in SCM research but given the complex, decentralized nature of the problem, these systems offer many potential contributions to knowledge as well as teaching. In teaching, business students tend to have difficulties with complex analytical models but can understand simulations such as TAC/SCM. In research, these systems would add a fifth methodology to the current SCM arsenal of analytical modeling, experiments, empirical analysis based on market/firm collected data, and traditional simulation or numerical analysis. One of the key research strengths of multi-agent systems, as compared to the above methodologies, is their ability to explore markets and contractual mechanisms in a dynamic environment.

Last, we describe how using a team-based agent system such as CAST, that models business processes and information flow so that they can be automatically reasoned about and provide additional benefits to supply chains faced with uncertain environments.

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