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A MULTI-AGENT-ENABLED EVOLUTIONARY APPROACH TO SUPPLY CHAIN STRATEGY FORMULATION

Ray Y. Wu
University of Westminster
r.wu1@westminster.ac.uk

David Z. Zhang
University of Exeter
d.z.zhang.exeter.ac.uk

ABSTRACT

This paper presents a research framework for investigating the impact of different supply chain strategies on operational performances of companies, and exploring how such strategies could be formulated in a given competitive environment. Supply chains consist of multiple independent companies with a dynamic relationship of interaction and competition. They appear to be dynamic adaptive systems presenting complex emergent behaviour with uncertainty which causes difficulties for the management to cope with. The research framework employs multi-agent technology and associated systems modelling methods to represent and simulate such interactive and competitive behaviour in a supply chain network. Furthermore, on the basis of the multi-agent simulation platform, an evolutionary approach is developed for identifying best strategies for supply chains operating in different competitive settings. The research will gain further understanding as to how strategies evolve in fast-changing, interactive and competitive situations, which will suggest significant research implications and form practical guidance for industries.

KEYWORDS

Supply Chain Strategy, Software Agent, Simulation, Operational Performance

1. BACKGROUND

In the last two decades, with the implementation of lean practices, the introduction of mass customisation, and the move towards globalisation, companies face more severe competition in the markets than ever before. Constant pursuance, by all companies, of the maximum fulfilment of customer requirements for product variety, cost efficiency, and responsiveness has resulted in a dramatic change in the way supply chains are organised and operate. For instance, many companies now source globally rather than locally. With the move of manufacturing sites to locations where cost could be reduced, there has been a redistribution of profits from manufacturers towards the downstream of the supply chains. In order to obtain better competitive positions, companies have made significant efforts to improve the relationships with their customers and suppliers and to develop strategic cooperation. As a result, today's competition is emerging to a greater extent between supply chains rather than between companies (Fawcett and Magnam, 2002).

As individual participants in a supply chain tend to maximise their own profit and there are few incentives to improve the performance of the overall supply chain, the global optimisation of supply chain operations is difficult to achieve. Cooperation among companies in the same supply chain is necessary. However, goodwill from one company is not sufficient to support cooperation since other companies may simply take advantages of it. Therefore, there is a need for a mechanism to coordinate the operations of participants, such that individuals' efforts to maximise their own performance also make contribution towards the global maximum of the supply chain performance.

Cooperation can take place in the form of close production priority and delivery relationships and through information sharing (Li and Liu, 2006). Close relationships speed up flows of information, goods and money and yield reliable supply chains.

Information sharing, on the other hand, enables precise forecasting and improved planning and scheduling, and reduces bullwhip effect (Lee *et al*, 2000; Cachon and Fisher, 2000; Forza and Salvador, 2001). The coordination of cooperation between members can be achieved by the use of coordination strategies which include policies and contracts that define the forms of relationships, information sharing, risk sharing, and profit sharing between companies (Tsay, 1999; Li and Kouvelis, 1999; Klastorin *et al*, 2002; Qin *et al*, 2007; Xiao *et al*, 2007; and Miragliotta *et al*, 2009). Some policies may also have to be dynamic to cope with complex interactions between members and the dynamic nature of competition (Tsay *et al*, 1998; Kamrad and Siddique, 2004; and Jammernegg and Kischka, 2005). The questions are: what constitute an effective coordination strategy for a supply chain and how to identify a good strategy?

In the literature, work has been carried out to investigate ways to model the effects of some of the policies, such as pricing, on supply chain performances. The investigations so far have been based on analytical techniques. However, as supply chains are cooperative and competitive systems where interactions among members are complex (Surana *et al*, 2005) and could lead to chaotic behaviour (Wu and Zhang, 2007), mathematical models were found to be unable to represent fully the level of complexity involved and predict the dynamic behaviour of such systems (Axelrod, 1997). In this regard, game theory appears to provide an alternative methodology. However it requires explicit strategies-payoff data dependent on interactions between customers and suppliers which are not always available. Multi-agent technology, with the ability to model complex systems using distributed agents which interact to produce emergent behaviour, appear to offer an advantage. However, work carried out so far (Krothapall and Deshmukh, 1999; Calinescu *et al*, 2003; van der Zee and van der Vorst, 2005; and Piramuthu, 2005) in this area mainly focused on operational, rather than strategic policies. For instance, Zhang *et al* (2007) and Akanle and Zhang (2008) have investigated the use of multi-agent technology to model and optimise operational decisions involved in a dynamically integrated manufacturing system or supply chain network. Others from the University of Michigan have used multi-agents to model supply chain operational environment and have developed an internet-based game (the Trading Agent Competition Supply Chain Management game, or TAC SCM) (Eriksson *et al*, 2006), for manufacturers to explore the effectiveness of different operational decisions. The game considers a three-tier supply chain, where suppliers and customers are modelled as resources in the environment and participants take part as manufacturers competing against each other. It provides a useful platform for manufacturers to explore alternative operational decisions, but does not support the implementation of coordination strategies across supply chain members.

Therefore, in the area of supply chain coordination, there is currently no technology available to support the identification of effective strategies. In fact, a comprehensive understanding of the whole concept of coordination strategies for supply chains is missing as investigations so far have only managed to consider few policies that might form part of the strategies. The fundamental questions are: What are the sets of policies and business practices that define a coordination strategy for a supply chain? Are there strategies which will result in better overall supply chain performance than others? If there are, how are they to be identified? Can they be identified through an "optimisation" process rather than through an ad-hoc trial and error process? Furthermore, how does the best coordination strategy, according to a given set of performance measures, vary with customer demand patterns and the characteristics of market, products and competitions?

This research will make an initial attempt to answer these questions. In particular, the project will investigate whether or not a hybrid approach combining multivariate analysis, multi-agent modelling, and evolutionary optimisation presents a way of developing answers to these questions. Multivariate analysis will be used to investigate elements that constitute coordination strategies. Multi-agent modelling will be investigated as possible ways of simulating the effects of individual strategies under specific competition environment, while evolutionary optimisation will be investigated as a possible mechanism for finding better and better strategies. The detailed research methodology is described below.

2. METHODOLOGY

Software agents are considered as autonomous and good candidates for application requiring constant adaptation. This feature makes multi-agent system (MAS) a desired tool for supply chains/network simulation.

During the past decades, with the development of computer technology, application of software agents for simulation provided manufacturing industry with a convenient way of modeling processes that were distributed over space and time (Kwon and Lee, 2001). In this condition, the MAS technology was subsequently focused by the research community. The concept of MAS is on the basis of distributed artificial intelligence (DAI) and meanwhile it also refers to system design and analysis using object-oriented methodology with human interfaces (Jennings *et al*., 1998). It is acknowledged that MAS is characterized by autonomous interaction, adaptability to environmental changes and rational manner (Lee and Kim, 2008; Li and Xiao, 2006). The MAS consists of a group of software agents, each of which takes specific roles within an environment and interacts with others for achieving their responsibilities and objectives (Fox *et al*., 2000; Kwon and Lee, 2001),

In the context of supply chain networks which are composed of interacting entities and exhibit a wide range of dynamic behaviors in terms of environment changes, the MAS has spurred enormous application with respect to SCM and been considered as the most promising technology regarding this discipline. Fox *et al*. (2000) proposed procedures for constructing models and tools which facilitate MAS to sort out coordination and communication in real-world application for SCM. Huang and Nof (2000) described an approach through agent formation and protocol formation to reduce uncertainty and to keep productivity in manufacturing systems. By resorting MAS, some issues such as the decision making problems (Hu *el at*., 2001), the adaptive inventory controlling in ERP (Kwon and Lee, 2001), knowledge management (Wu, 2001) were also supported and developed. Furthermore, Allwood and Lee (2005) presented new agent architectures to model competitive supply chain networks dynamics, which had novel features including vendor selection, preferred distribution, production and inventory management, and price determination based on competitive behavior.

The project uses multi-agent technology to simulate the competition in a supply chain. Each player in the supply chain is simulated by an software intelligent agent which intends to maximise its own performance. The details of the methodology are described as follows.

3. SIMULATION MODEL AND ITS ARCHITECTURE

The architecture of the model, as shown in Figure-1, includes a three-tier supply network comprising customers, retailers, manufacturers and suppliers for a particular category of products. Competitions take place among the supply chains of each product brand. The participants in the same tier compete though they do not communicate with each other. A retailer may sell multiple brand products of different manufacturers. A supplier may also provide raw materials or components to different manufacturers.

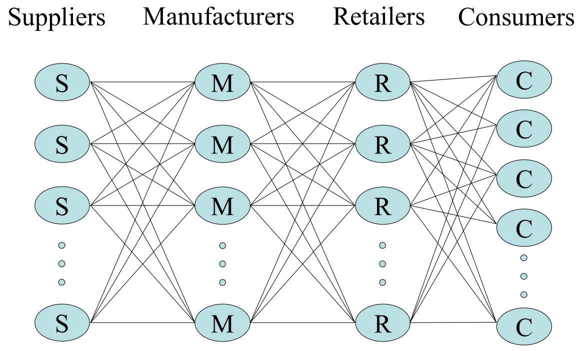


Figure 1 – An illustration of a supply network

3.1. CONSUMER AGENTS

Consumers are the final customers of products. They generate demand and are simulated by customer agents. The consumers' purchase behaviour and decision-making process are simulated by the "decoy effect" (Meyer and Johnson, 1995), in which the consumer perceived trade-off is projected into the product attributes.

Consumers are classified into groups according to age, income, occupation, education, and psychological status. Each customer agent representing a consumer is assigned to a consumer group according to a statistical distribution and the agent assumes the attributes of the group. Such attributes determine the purchase behaviour of individual agents. For instance, a consumer in a high income group tends to pursue high end products. Some consumers request products to be available as soon as they purchase, while others do not bother waiting for a few days. Some consumers are easily affected by friends or relatives, while some others trust only the reviews made by experts. Some are loyal to big brands while some put emphasis on functions. Consumers are connected by networks through which they affect each other's purchase decisions resulting in collective emergent behaviour. There are different types of connections which are all being simulated in this work.

3.2. GENERIC SUPPLIER AGENTS

The suppliers, manufacturers and retailers are modelled with a generic supplier agent architecture, which includes a sales sub-agent, a production sub-agent, a procurement sub-agent, a coordination sub-agent, and an integrated decision-making sub-agent, as shown in Figure-2.

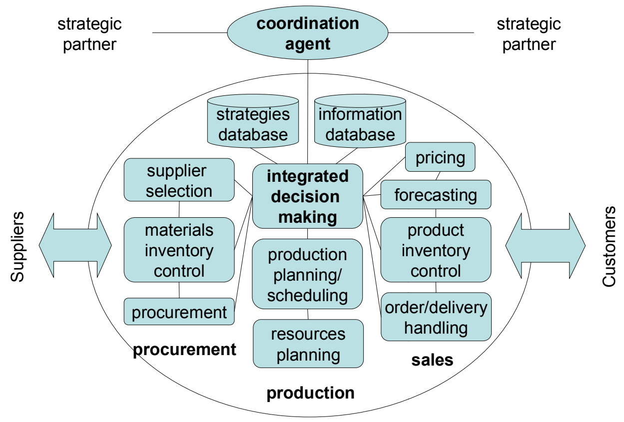


Figure 2 – The architecture of a generic supplier agent

The sales sub-agent negotiates with customers, determines the sales price, forecasts and manages demands, controls inventory, and handles orders and deliveries. The production sub-agent produces production schedule, determines production priority and makes resources plans, such as investment for production capacity. The procurement sub-agent carries out purchasing, manages raw materials and components inventory, and negotiates with suppliers. The coordination sub-agent determines the coordination strategy to optimise the supply chain operations. In a coordinated supply chain, as shown in Figure-3, the manufacturer has a closer relationship (coordinated links) with some of the retailers and suppliers. The coordination strategy, which includes profit, information, work and risk sharing policies, applies to these coordinated links. The integrated decision-making sub-agent makes higher (strategic) level decisions than other sub-agents by setting strategic rules or constraints for other sub-agents. The generic agent architecture is configured to generate retailer agents, manufacturer agents and supplier agents.

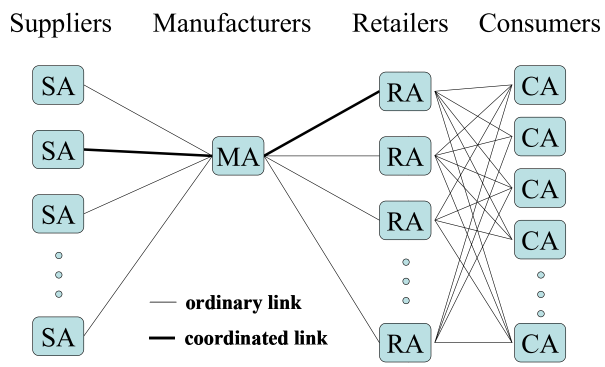
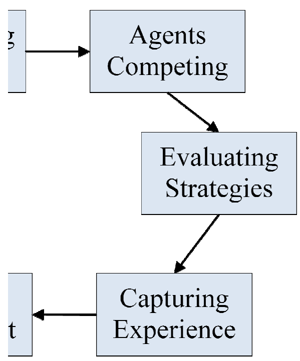


Figure 3 – The supply chain of a product

4. SIMULATION AND EVOLUTION PROCEDURE

A run of simulation is arranged so that there are several manufacturing agents (brand owners), suppliers, retailers operating together to fulfil customers' demand in a competing environment. At a particular time, each manufacturing agent is governed by a "strategy" comprising a set of strategic rules corresponding to manufacturing, marketing, purchasing and supply chain coordination respectively. These rules will determine the agent's decisions about production and inventory, its relationships with distributors, retailers and consumers, its policies as to how to align with suppliers, and its policies about information and profit sharing along the supply chain. The scenarios of confliction of interests among partners along the supply chain can also be simulated in comparison with a coordinated supply chain.

The process of strategy simulation and evolution will take the form of an iterative process. At the beginning, each manufacturing agent will be allocated with a "basic strategy". These agents will then enter an iterative loop of competition and strategy evolution. As shown in Figure-4, within each iterative cycle, agents implement their respective strategies through reconfiguration and compete for a period of time using the strategies.



he cycle of evolution

The results of competition are then analysed. Agents with top performance will carry their strategies to the next iterative cycle. Those in the middle will carry out an incremental improvement to their strategies, while those at the bottom will make a drastic change to their strategies. The strategies will be implemented as a combination of rules and data and their adaptation carried out through techniques similar to evolutional computation. The agents then carry the updated strategies forward to the next cycle of competition and evolution. This process is repeated until a satisfactory winner resulted. The strategies of the winner in the final cycle will be considered a paradigm for companies operating in the specific competition environment.

5. IMPLEMENTATION

The simulation architecture of supply network is built by an agent server and individual agents in Java. Consumers and their behaviour are implemented within the agent server. All other participates in the supply network are implemented by the generic supplier as mentioned in section 3. The role of each individual agent can be configured when the agent is registered. The strategy adopted in an agent can be reconfigured during simulation.

The agent server is responsible for registration of individual agents by recording their identifications. It controls the time frame, i.e., the order and supply cycle, during simulation. The agent server also provides a supporting platform for information exchanges among different agents and records the simulation data into the central database. For example, the agent server includes a few supporting software tools such as a simulation manager, a time-manager and an internal bank for the virtual materials, information and cash flows within the supply network.

An individual agent in the simulation model is built with different methods and objectives within each function of an organization as described in section 3 to reflect different strategies in supply chain management, for example, minimised inventory for lean practice, order trigged replenishment for just-in-time (JIT), and keep a certain level inventory with priority scheduling for quick responsiveness or agility. These different strategies are dynamically reconfigurable during the simulation to implement evolutionary approaches.

6. SUMMARY

This paper have proposed a research framework to investigate the effect impact of the different supply chain strategies on operational performances of companies and how such strategies could be developed in a given competitive environment.

The research framework employs multi-agent technology and associated systems modelling methods to represent and simulate such interactive and competitive behaviour in a supply chain network. On the basis of the multi-agent simulation platform, an evolutionary approach is developed for identifying best strategies for supply chains operating in different demand and competitive settings. Through simulation, the research will gain further understanding as to how strategies evolve in fast-changing, interactive and competitive situations, which may suggest significant research implications and form practical guidance for industries.

The future work includes case studies to collect real world data to test the simulation model and run the evolutionary programme for application guidance and meaningful implications to each specific case.

REFERENCES

Allwood JM and Lee JH, "The design of an agent for modeling supply chain network dynamics". *Int. J. Prod. Res.*, Vol. 43, 2005, pp 4875-4898

Akanle OM and Zhang DZ, "Agent-based model for optimising supply chain configurations", *Int. J. of Prod. Econ.*, Vol. 115, No. 2, 2008, pp 444-460

Axelrod R, "The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration", Princeton University Press, Princeton, New Jersey, 1997

Cachon GP and Fisher M, "Supply chain inventory management and the value of shared information", *Management Science*, Vol. 46, No. 8, 2000, pp 1032–1048

Calinescu A, Efstathiou J and MacCarthy B, "Agent-Based Modelling in Manufacturing and Supply Chains: Potential Benefits and Open Questions", The International Workshop on Complex Agent-based Dynamic Networks, 5 - 7 October 2003, Saïd Business School, University of Oxford

Eriksson J, Finne N and Janson S, "Evolution of a supply chain management game for the Trading Agent Competition", *AI Communications*, Vol. 19, 2006, pp 1–12

Fawcett SE and Magnam GM, "The rhetoric and reality of supply chain integration", *Int. J. Physical Distribution & Logistics*, Vol. 32, No. 5, 2002, pp 339-361

Forza C and Salvador F, "Information flows for high-performance manufacturing", *Int. J. Prod. Econ.*, 70, 2001, pp 21-36

Fox MS, Barbuceanu M and Teigen R, "Agent-oriented supply-chain management". *Int. J. Flex. Manuf. Sys.*, Vol. 12, 2000, pp 165-188

Hu Q, Kumar A and Zhang S, "A bidding decision model in multiagent supply chain planning". *Int. J. Production Research,* Vol. 39 2001, pp 3295-3310

Huang C-Y and Nof SY, "Formation of autonomous agent networks for manufacturing systems". *Int. J. Prod. Res.,* Vol. 38, 2000, pp 607-624

Jammernegg W and Kischka P, "Dynamic, customer-oriented improvement of supply networks", *European Journal of Operational Research*, Vol. 167, 2005, pp 413–426

Jennings NR, Sycara K and Woodridge M, “A roadmap of agent research and development”. *Autonomous Agents and Multi-agent Systems*, Vol. 1, 1998, pp 7-38

Kamrad B and Siddique A, “Supply contracts, profit sharing, switching, and reaction options”, *Management Science*, Vol. 50, No. 1, 2004, pp 64–82

Klastorin TD, Moinzadeh K and Son J, “Coordinating orders in supply chains through price discounts”, *IIE Transactions*, Vol. 34, 2002, pp 679–689

Kwon OB and Lee JJ, “A multi-agent intelligent system for efficient ERP maintenance”. *Expert system with application,* Vol. 21, 2001, pp 191-202

Krothapall NKC and Deshmukh AV, “Design of negotiation protocols for multi-agent manufacturing systems”, *Int. J. Prod. Res.*, Vol. 37, No. 7, 1999, pp 1601-1624

Lee JH and Kim CO, “Multi-agent systems applications in manufacturing systems and supply chain management: a review paper”. *Int. J. Prod. Res.*, Vol. 46, 2008, pp 233-265

Lee HL, So KC and Tang CS, “The value of information sharing in a two-level supply chain”, *Management Science*, Vol. 46, No. 5, 2000, pp 626-643

Li CL and Kouvelis P, “Flexible and risk-sharing supply contracts under price uncertainty”, *Management Science*, Vol. 45, 1999, pp 1378–1398

Li J and Liu L, “Supply chain coordination with quantity discount policy”, *Int. J. Prod. Econ.*, Vol. 101, No. 1, 2006, pp 89-98

Li H and Xiao R, “A multi-agent virtual enterprise model and its simulation with Swarm”. *Int. J. Prod. Res.,* Vol. 44, 2006, pp 1719-1737

Makris, S and Chryssolouris, G, "Customer's behavior modeling for manufacturing planning", *Int. J. Com. Int. Manuf.*, Vol. 23, No. 7, 2010, pp 619-629

Makris, S, Xanthakis, V, Mourtzis, D, and Chryssolouris, G, "On the information modeling for the electronic operation of supply chains: A maritime case study", *Robot. Com.-Int. Manuf.*, Vol. 24, No. 1, 2008, pp 140-149

Meyer R and Johnson EJ, “Empirical generalizations in the modeling of consumer choice”, *Marketing Science*, Vol. 14, 1995, pp 180-189

Miragliotta G, Brun A and Soydan IA, “Coordinating multi-business sales through management simulators”, *Int. J. Prod. Econ.*, Vol. 121, No. 2, 2009, pp 533-549

Piramuthu S, “Knowledge-based framework for automated dynamic supply chain configuration”, *European J. Oper. Res.*, Vol. 165, 2005, pp 219–230

Qin Y, Tang H and Guo C, “Channel coordination and volume discounts with price-sensitive demand”, *Int. J. Prod. Econ.*, Vol. 105, 2007, pp 43-53

Surana A, Kumara S, Greaves M and Raghavan, UN, “Supply-chain networks: a complex adaptive systems perspective”, *Int. J. Prod. Res.*, Vol. 43, No. 20, 2005, pp 4235-4265

Tsay AA, “The quantity flexibility contract and supplier–customer incentives”, *Management Science* Vol. 45, No. 10, 1999, pp 1339–1358

Tsay AA, Nahmias, S and Agrawal, N, “Modeling supply chain contracts: a review”, In: Tayur, S., Ganeshan, R., Magazine, M. (Eds.), Quantitative models for supply chain management, Kluwer Academic, New York. 1998

Van der Zee DJ and van der Vorst JGAJ, “A modelling framework for supply chain simulation: opportunities for improved decision making”, *Decision Science*, Vol. 36, No. 1, 2005, pp 65-95

Wu DJ, “Software agents for knowledge management: coordination in multi-agent supply chains and auctions”. *Expert Systems with Applications*, Vol. 20, 2001, pp 51-64

Wu Y and Zhang DZ, “Demand fluctuation and chaotic behaviour by interaction between customers and suppliers” *Int. J. Prod. Econ.*, Vol. 107, No. 1, 2007, pp 250-259

Xiao T, Qi X and Yu G, “Coordination of supply chain after demand disruptions when retailers compete, *Int. J. Prod. Econ.*, Vol. 109, No. 1-2, 2007, pp 162-179

Zhang Z, Anosike A and Lim MK, “Dynamically Integrated Manufacturing Systems (DIMS) – a multi-agent approach”, *IEEE T. Sys., Man and Cyb.*, *Part A: Systems and Humans*, Vol. 37, No. 5, 2007, pp 824-850