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Strategies in supply chain management for the Trading Agent Competition

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Abstract

Negotiating with suppliers and with customers is a key part of supply chain management. However, with recent technological advances, the mechanisms available to carry out such activities have become increasingly sophisticated, and the environment in which these activities take place has become highly dynamic. As a consequence, the overall planning of these complex trades, and the coordination of the various production and scheduling activities, need to be carefully considered by the businesses involved in the supply chain management. In order to guide the overall planning, production, scheduling, and allocation of resources, especially designed strategies are increasingly used by the businesses. In this setting, it is crucial that the intended behaviour, and through that, the desired outcomes, of these strategies be precisely understood. Using an empirical analysis, this paper investigates two fundamental strategies in supply chain management: buy-to-build and build-to-order.

Keywords: Trading agent; Supply chain management; Buy-to-build; Build-to-order

1. Introduction

The Trading Agent Competition (TAC) [1] is an international forum designed to promote and encourage high quality research into the trading agent problem. The supply chain management game for the trading agent competition (TAC SCM) has been designed jointly by a team of researchers from the e-Supply Chain Management Lab at Carnegie Mellon University and the Swedish Institute of Computer Science (SICS) [2]. The first TAC SCM competition was held in 2003 [3]. The University of Macau team has designed an agent (called UMTac-04) and participated in the 2004 TAC SCM competition.[3] The UMTac-04 agent secured a 3rd position in the final competition.

A supply chain is defined as "a process that transforms materials into products and delivers them to customers through specific activities" [4]. The objective of the supply chain management is to improve the efficiency of the product delivery process by delivering the right product at the right time to the end customers by the suppliers while keeping the handling and storage cost low [5]. Major activities involved in a typical supply chain management scenario include planning and coordination of tasks such as securing raw materials, manufacturing, storing, negotiating, receiving customers orders, and delivering products. Traditional supply chains are fixed and dependent on long-term relationships among key trading partners. TAC SCM was

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[3] More details of this competition and its 29 entrants can be found at http://www.sics.se/tac.

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designed to provide a test-bed for the researchers in their investigation of the issues associated with managing a supply chain in a dynamic environment.

Two crucial tasks in supply chain management are the planning of raw material acquisition and competing for customer orders. Material requirement planning (MRP) can be categorized as *make-to-plan*, *make-to-stock*, and *make-to-order* [6]. In *make-to-plan*, the agent decides on the desired level of factory utilisation and acquires components to produce and maintain that level. The agent then bids for customer orders according to the available inventory. In *make-to-stock*, the agent maintains a safe inventory level. The agent then schedules the production and bids for customer orders based on the available inventory. In *make-to-order*, the agent acquires components from the suppliers and assembles them into finished products based on customer orders received. The agent bids for customer orders based on the spare factory cycle.

In the 2003 and 2004 TAC SCM competitions, the majority of the agents adopted the latter two MRPs, *make-to-plan* and *make-to-order* (also known as *buy-to-build* and *build-to-order* [7]) as their main strategies. Despite the popularity of these two strategies in the competition, little attention has been given to their empirical comparison. Recent work on the TAC SCM focuses on the strategies used by individual agents [7–12,6] or on specific aspects of an agent's operation such as scheduling [13], procurement of raw material [14], and the problem of supplier offer acceptance [15]. In this paper, we investigate the overall effect of these strategies to the market and the impact on the performance of other constituent agents. First, we describe the design of *buy-to-build* and *build-to-order* version of UMTac-04 agents. We then report on the results of empirical tests of these agents.

Although many efforts have been made to measure and track the performance of supply chain activities worldwide, "there have been no continually updated, easily accessible, and affordable means of benchmarking broadly across industries, regions, and operating practices" [16]. AMR research has developed a hierarchy of supply chain metrics for benchmarking studies [17]. From 45 operational metrics, key metrics from their study include: *perfect order detail* (detail of orders which are complete, accurate, on time, and in perfect condition), *total supply chain management operating costs* (which includes direct purchasing operating cost, manufacturing operating cost, warehouse cost, inventory holding cost), *plant utilisation*, *direct material cost*, *account payable*, *account receivable*, and *inventory total*.

For our analysis, we have chosen seven attributes (revenue, interest credited/charged, material and storage cost, number of orders received, factory utilisation, penalty accrued, and overall result (profit)) among 14 attributes which are provided by the game server. These seven attributes are not only consistent with the key metrics identified in [17], they also serve as crucial indicators in benchmarking the performance of different supply chain management strategies.

A brief introduction to the TAC SCM game is given in Section 2. The *buy-to-build* strategy is described in Section 3. The *build-to-order* strategy is described in Section 4. The virtual competition involving both types of strategies is detailed in Section 5. In Section 6 we briefly review related work before summarizing our ideas in Section 7.

2. Game overview

Six agents compete in each TAC SCM game [2]. Each game is played for 220 simulated days with each day being 15 s long. Each day, agents compete in two markets (supplier side and customer side) in order to maintain their inventory level to build and sell different types of PCs. In a TAC SCM game, 16 types of PCs can be built from four component types: CPUs, motherboards, memories, and hard drives. Each PC type is defined with its constituent components, the number of assembly cycles required and the market segment (low range, mid range, high range) they belong to. Each component type has two suppliers from the computer hardware manufacturing industry. The suppliers are Pintel for Pintel CPUs, IMD for IMD CPUs, Basus and Macrostar for motherboards, MEC and Queenmax for memories, and Watergate and Mintor for disks. There are eight suppliers in total. The total number of customers is undefined and they are treated as a single entity. An overview of the TAC SCM scenario is given in Fig. 1.

2.1. Suppliers

Each day an agent is allowed to send a maximum of 10 *Request For Quotes* (RFQs) to each supplier. Selection of an RFQ by a supplier depends on the priority of the agent which is calculated based on the ratio of the number of RFQs and the actual orders. If the supplier can satisfy the order specified in the RFQ in its entirety, an offer is sent as a response. If the supplier cannot supply the entire quantity requested in the RFQ by the requested due date, the supplier will respond by issuing up to two amended offers, each of which relaxes one of the two parameters – quantity and due date. All offers made by suppliers are valid for a day and hence require the agent, if interested, to send a confirmation by issuing a purchase order.

The production capacity C_p of a supplier on a day, d, is defined in the TAC SCM specification as follows:

$$C_p(d) = \max(0, C_p(d-1) + \text{random}(-0.05, 0.05) \times C_{\text{nominal}} + 0.01 \times (C_{\text{nominal}} - C_p(d-1))) \quad (1)$$

where C_{nominal} denotes the nominal capacity (500 components/day). $C_p(d-1)$ at the start of the game is $C_{\text{nominal}} \pm 35\%$. Suppliers assume that they will have C_{nominal} available every day. The available capacity on day $d+i$ can be defined as:

$$C_{\text{available}}(d, d+i) = \sum_{j=d}^{j=d+i-1} (C_{\text{nominal}} - C_{\text{ordered}}(j)) \quad (2)$$

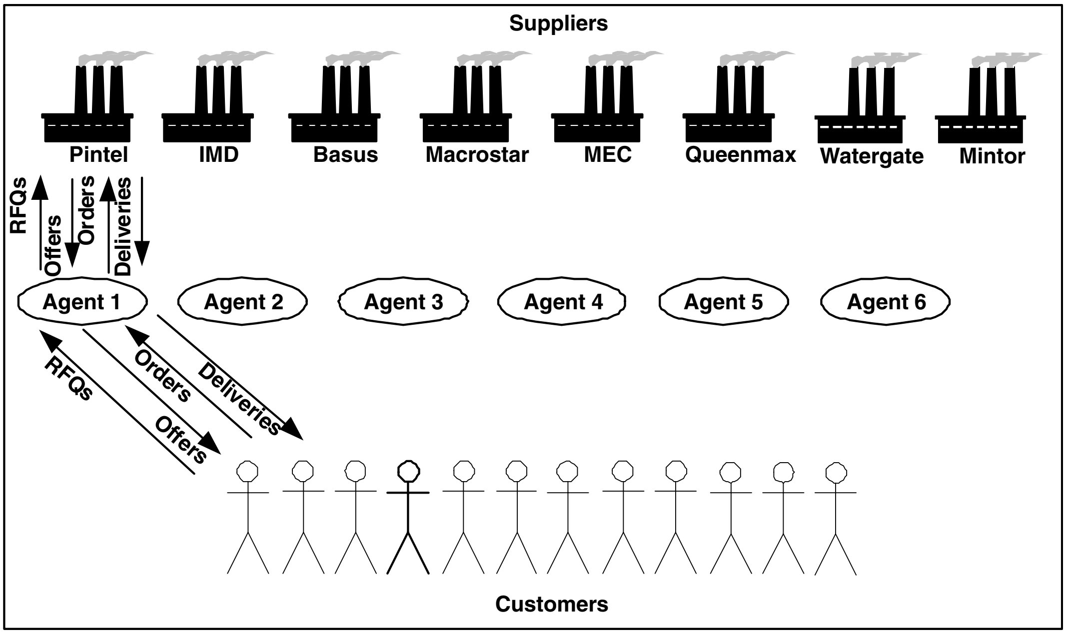

Fig. 1. TAC SCM scenario.

where $C_{\text{ordered}}(d)$ denotes the ordered capacity on day d.

On any day d the offer price of a component for day $d + i$ is given by

$$P(d, d+i) = P_{\text{base}}(\text{component}) \times \left(1 - \delta_{\text{p}}\left(\frac{C'_{\text{available}}(d, d+i) - \text{qty}}{C_{\text{current}}(d) \times i}\right)\right) \tag{3}$$

where δ_{p} is the price discount factor (50%), P_{base} is the baseline price of the components,[4] $C_{\text{current}}(d)$ is the suppliers capacity on day d, $C'_{\text{available}}(d, d+i) = \sum_{j=d}^{j=d+i-1}(C_{\text{current}}(d) - C_{\text{ordered}}(j))$, and qty is the quantity requested by the order.

2.2. Customers

Customers request PCs of different types to be delivered by a certain due date by issuing RFQs to the agents each day. Agents must bid to satisfy the entire order (both quantity and due date) specified in an RFQ. The customer selects the bid with the lowest price (which is less than or equal to the reserve price specified in the RFQ) as the winning bid and the winner will be notified at the start of the next day.

For each RFQ, a penalty is chosen uniformly in the interval of 5–15% of the reserve price. Penalties are charged daily when an agent defaults on a promised delivery date. If the agent fails to deliver over a period of five days, the order is cancelled and no further penalties are charged. After the last day of the game all pending orders are charged the remaining penalty (up to five days) as they can never be delivered.

2.3. Agents

Each day, agents issue RFQs to the suppliers. The next day, the suppliers reply to the agents with offers based on their availabilities. Agents then select from these offers (based on the quantities, delivery dates, and prices) and reply to the supplier on the same day.

Each day, customers issue requests for quotes of different types of assembled personal computers (PCs) to the agents and, within the same day, the agents reply with offers. Customers then select the best offer based on delivery dates and prices, and reply to the agents on the next day.

At the start of each day, each agent receives RFQs for PCs from the customers, and orders won by the agent in response to offers sent to the customers the day before. Also, each agent receives offers for the components in

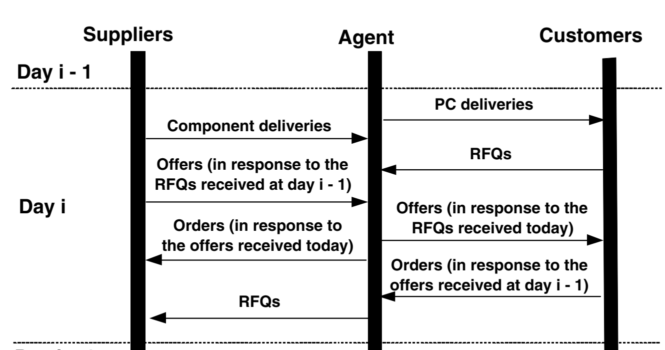

Fig. 2. A TAC SCM day.

[4] The pre-defined list of baseline price of the components can be found in [2].

response to the RFQs that the agent had sent to the suppliers the day before. Fig. 2 illustrates key daily events involved in running an agent.

Each agent is endowed with a PC factory which is capable of assembling any type of PC, and an inventory storing both components and finished PCs. Each day, the agent sends a production schedule to the factory for the production on the next day. The agent also sends a delivery schedule which will cause deliveries to the customer the next day. The supplies (components) can be used for production on the next day after the delivery and PCs are not allowed to be shipped on the day of their production.

Inventory (both finished goods and components) for each agent is charged a storage cost which is a percentage of the base price of components. The storage cost is chosen randomly in a pre-defined range at the start of the game. This cost is applied to the inventory held by the agent at the end of each day.

Agents have accounts in the bank and start the game with no money in the accounts. A fixed interest rate is charged if the balance is in debt or credited if the balance is positive. The storage cost for both finished goods and components is chosen randomly from a predefined range at the start of the game and revealed to all the agents. At the end of the game, the agent with the highest sum of money in the bank is declared as the winner.

In the 2004 TAC SCM competition, the UMTac-04 team took into consideration two common high-level strategies which are used by some of the agents in the 2003 competition: *buy-to-build* and *build-to-order* [7]. In the buy-to-build strategy, the agent acquires as many components as possible and assembles them into PCs regardless of the orders actually received from the customers. In the build-to-order strategy, the agent first bids for the customer orders. Based on the result of the bids, the agent will try to acquire necessary components and assemble PCs for the delivery.

According to the 2003 TAC SCM supplier pricing model, component prices are cheapest on day 0 of the game and as a result, several agents adopted an aggressive strategy in which large quantity of components are procured at day 0. (A detailed analysis of day-0 procurement and a preemptive counter strategy are discussed elsewhere [18]). To restrict day-0 procurement in the 2004 TAC SCM competition, the supplier pricing model (Eq. (3)) is modified so that components prices are determined not only by the demand but also the capacity that the supplier forecasts to have in the future.

In the 2004 TAC SCM qualifying game, the storage cost is defined within the range of 15–25% of the base price of components. The UMTac-04 agent was tested by issuing large orders at day 0 to the suppliers and the results show that the total storage cost at the end of a game is within the range of 2–3 million dollars, which is quite negligible compared to the savings achieved by obtaining cheaper component prices. Although there are occasions in which unused components (or even PCs) are left in the inventory at the end of the game, their cost is negligible compared to the total profit. The UMTac-04 team has also predicted that other agents will adopt a similar preemptive ordering approach at day 0 of the game. Based on these considerations, the UMTac-04 team adopted a buy-to-build strategy.

3. Buy-to-build strategy

The buy-to-build strategy has the following advantages:

- The agent can monopolise the supplier market by ordering a large number of components and thereby forcing other competitors to delay their production.
- The agent can monopolise the customer market by dumping on the market at any time [7] and therefore can induce a price war.

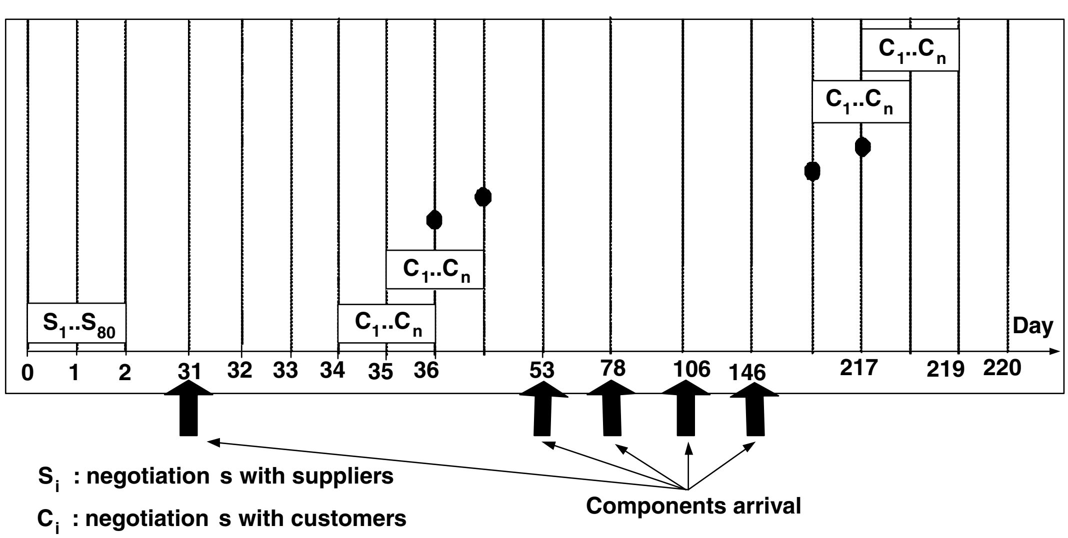

Fig. 3. The agent's time-line for negotiation in TAC SCM competition.

- The agent can achieve a higher profit margin when the other agents have low levels of stock [7].

The agent's time-line for negotiation is given in Fig. 3. On day 0, the agent issues 80 RFQs to the suppliers, five RFQs each for 16 types of components. The five RFQs for Pintel CPU 2.0 in game 1160 are as follows:

1. 2100 Pintels to be delivered on day 31,
2. 2300 Pintels to be delivered on day 53,
3. 2800 Pintels to be delivered on day 78,
4. 3600 Pintels to be delivered on day 106, and
5. 3750 Pintels to be delivered on day 146.

On day 1, the suppliers reply with offers for each RFQ. The agent only accepts those offers which can satisfy the exact quantities required.[5] The expected delivery dates for the components from the supplier are depicted as dark arrows in Fig. 3. Deliveries are intentionally performed five times in order to avoid a pileup of components in the inventory. Negotiations with the suppliers only take place at days 0 and 1. The first batch of components arrives on day 31 and the negotiation with customers begins on day 34 when some of the PCs have been built. The negotiation continues until day 218. From days 34 to 219, the agent maintains its factory utilization level at 100% whenever required components are available.

Based on the buy-to-build strategy, negotiation with suppliers can be depicted as $S_1..S_{80}$ in Fig. 3 each spanning over two days. Every S_k is scheduled on days i and the agent can decide whether to accept the offer from the supplier on day $i+1$. Using the same notation, negotiation with customers can be depicted as $C_1..C_n$ where n can be varied depending on the number of RFQs received from customers. Each C_k is responsible for securing an RFQ and each negotiation spans over two days. Every C_k is scheduled on days i and $i+1$. C_k will send binding proposals on day i and the reply will be received on day $i+1$.

In order to illustrate the negotiation with customers, we have extracted records for day 56 from game 1160. According to the records of game 1160, customers issued 159 RFQs (for 1660 PCs) to each agent on day 56. In response to the RFQs, the agent has replied with 159 offers within the same day. For the purpose of simplification, we have extracted three RFQs for the calculation of offers. These RFQs are given as follows:

[5] If the suppliers cannot provide the exact amount requested, the agent ignores the offers and resends the RFQs to the suppliers within the same day. The agent may repeat this process until day 10. If this situation continues until day 11, the agent will divide each component quantity into multiples of 80 U and send the RFQs (each with 80 U) every 10 days until all the required components are obtained. This strategy was added as an exception handling mechanism for an over heated supplier market.

1. *RFQ1*. 17 units of type-13 PC (IMD CPU 5.0 GHz, 1 GB Mem, 300 GB Hard Disk) for $33,184 to be delivered on day 63 (customer's reserve price: $2236 per unit).
2. *RFQ2*. 17 units of type-7 PC (Pintel CPU 5.0 GHz, 2 GB Mem, 300 GB Hard Disk) for $38,947 to be delivered on day 63 (customer's reserve price: $2452 per unit).
3. *RFQ2*. 3 units of type-6 PC (Pintel CPU 5.0 GHz, 1 GB Mem, 500 GB Hard Disk) for $6531 to be delivered on day 62 (customer's reserve price: $2565 per unit).

As soon as RFQs have been received, the agent has to decide on which RFQs to bid, and the value of the bids to be sent for these RFQs. The agent has adopted a simple approach for the selection of RFQs. The agent will send an offer for an RFQ only if it has sufficient numbers of requested PCs in the inventory. This strategy ensures that the agent will not bid beyond its capacity.

For the calculation of bids, the agent has used the probability prediction approach from the TacTex-03 agent's strategy [10]. Based on the statistics of the past 10 days provided by the game server, the TacTex-03 agent calculates the lowest price, the average low price, the midpoint between the average low and the average high price, the average high price, the highest price, and the probabilities of these offers being accepted. Based on this approach the agent calculates the five price values and respective probabilities for the type-13 PC using the server provided price report given in Table 1. The results of the calculation are given in Table 2.

According to the TAC SCM game description, 4–7 cycles of simulated factory production time are required to assemble a PC. On average, 5.5 cycles are required for each type of PC. Each day, an agent is endowed with 2000 cycles for production of PCs. Therefore, the factory can produce approximately 370 PCs each day.

Next, the probability of an offer for a specific type of PC being accepted is calculated by dividing the total requested units from all the RFQs by 370. For instance, according to the records of game 1660, 190 type-13 PCs are requested in

Table 1
Price report of type-13 PC during day 46–55 in Game 1160

Day	HighPrice	LowPrice	Day	HighPrice	LowPrice
46	1976	1973	51	1969	1939
47	1970	1967	52	1970	1965
48	1974	1969	53	1968	1907
49	1975	1933	54	1962	1935
50	1969	1967	55	1960	1917

Table 2
Calculation of price prediction points for type-13 PC at day 56

	Lowest	Avg. low	Mid	Avg. high	Highest
Price	1907	1947.2	1958.25	1969.3	1976
Prob.	0.95	0.7	0.45	0.15	0.05

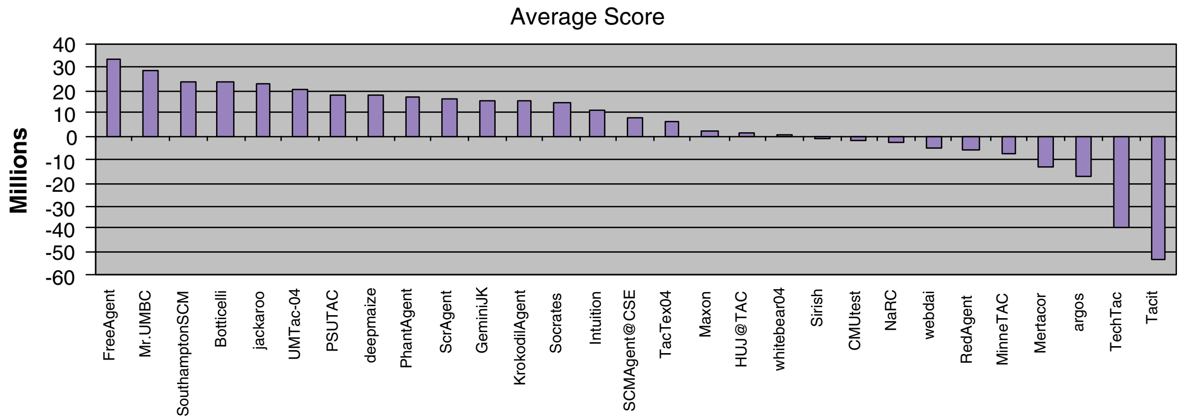

Fig. 4. The seeding round in 2004 TAC SCM competition.

day 56 by customers, and therefore, the probability of an offer being accepted for that type of PC is 0.51. In a similar way, the probabilities of type-7 (83 U) and type-6 PCs (79 U) can be calculated. These probabilities are then linearly interpolated with the probabilities from Table 2 to determine the offer prices. According to the calculation the offer prices of RFQ1, RFQ2, and RFQ3 are $1952 (probability 0.51), $2346 (probability 0.22), and $2283 (probability 0.21).

3.1. Performance

The UMTac-04 agent with buy-to-build strategy has scored 3rd position (with average score 28.41 millions) in qualifying rounds. During the TAC SCM 2004 seeding rounds, the game administrators increased the storage cost (70–125% of the base price of the components) in order to deter agents from ordering large number of components at day 0. As a result, the performance of the UMTac-04 agent was significantly degraded and the agent slipped to 6th position among 29 teams. The ranking of UMTac-04 agent in seeding round is given in Fig. 4.

After the seeding rounds, some of the agents have been revised to avoid ordering large amount of components at day 0. These agents have either reduced their orders or revised to use build-to-order strategies. The score of UMTac-04 agent in the final rounds in given in Fig. 5. We can observe that the average score of UMTac-04 agent in final rounds (7 millions) is significantly lower than the average score in seeding rounds (20 millions).

Although a buy-to-build strategy offers some promising results, it also revealed several disadvantages when the game progressed to the final rounds.

- In low-demand markets, the agent was unable to sell all the products and, as a result, a large number of PCs were left in the inventory at the end of the game.
- The agent's schedule was severely affected when other agents began to adapt the buy-to-build strategy by issuing large numbers of component orders at day 0. The suppliers were overwhelmed by the number of orders and failed to produce/deliver the components on time. Hence, the agent was forced to delay its production.

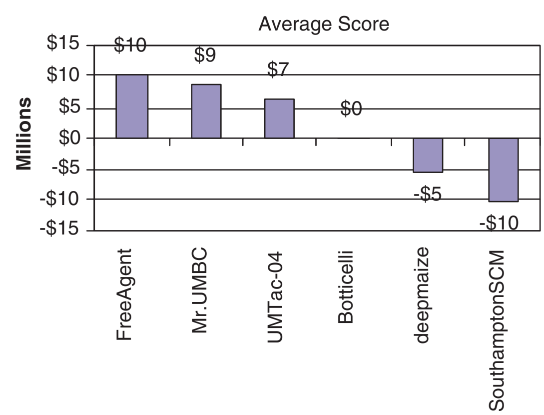

Fig. 5. The final score in 2004 TAC SCM competition.

From these observations, it is obvious that the agent should incorporate other strategies in order to increase its flexibility and reactiveness to the market demands. One of the possibilities is to revise the agent so that it does not have to rely on ordering large components at day 0. One conservative approach is to only order components in sufficient quantity to maintain a target inventory level. The agent then produces only when it has received the orders from the customers.

4. Build-to-order strategy

In the build-to-order strategy, the agent first bids for the customer orders and then assembles the PCs based on the actual orders received from the customers. During the 2004 TAC competition, we also developed a version of build-to-order agent and tested its performance.[6] In the

[6] We did not deploy the build-to-order version of UMTac-04 agent in 2004 TAC competition since it was found to be less resistent to market monopolisation by buy-to-build agents.

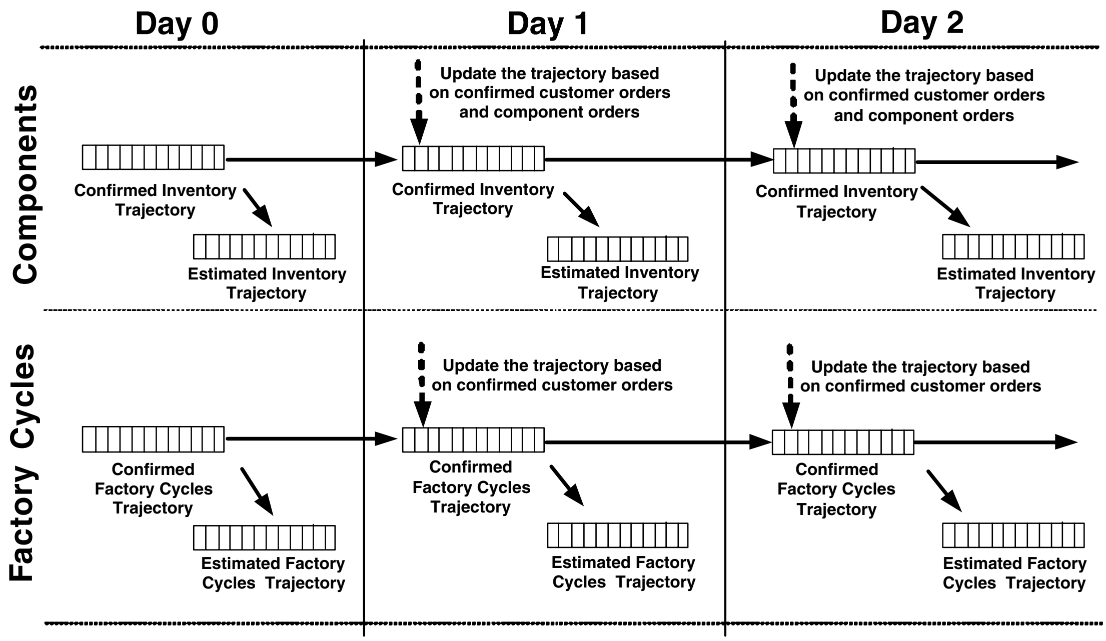

Fig. 6. Projection of inventory and factory cycles.

build-to-order strategy, the agent only orders components and builds PCs after it has secured some deals from the customers. The build-to-order strategy has the following advantages:

- The agent can easily estimate the delivery date (usually within 10 days) from the suppliers since the orders with small number of components require less manufacturing time by the suppliers.
- The agent can maintain low inventory throughout the game and therefore can keep the storage cost low.
- By maintaining the inventory level at minimum, the bank interest incurred is also low.
- By ordering the components on demand, the agent can reduce the risk of having a large number of unused components at the end of the game.

4.1. Sourcing from the suppliers

On day 0 of the game, the build-to-order agent sends RFQs to the suppliers for 1000 pieces for each kind of components. On day 1, the suppliers reply with offers for each RFQ. The build-to-order agent only accepts those offers which can satisfy the exact quantities requested.[7]

Throughout the game, the agent maintains the inventory level of the components constant (i.e. 1000 for each type of component). Everyday, the agent calculates the number of components left in the inventory and RFQs are issued to the suppliers if the total number of a component is less than 1000. Upon receiving the offers, orders are issued to the suppliers regardless of the price of the components. Sourcing from the suppliers stops at day 210 so that the components remaining in the inventory can be gradually reduced until the end of the competition.

4.2. Bidding for the customers' orders

The agent begins processing the customers' RFQs as soon as it receives the first delivery of components from the suppliers. From our testing, we find that the first batch of components are usually delivered approximately on day 10. Each customer RFQ includes the number of PCs required, the reserve price, and the expected delivery date. In order to process customer RFQs, the agent maintains two sets of trajectory [9] covering 220 days for inventory and factory cycles. *Confirmed trajectory* is used to record the actual available level of the resource and *estimated trajectory* is used to project the available resources so that offers can be sent to the customers (see Fig. 6). At the beginning of each day, the agent updates the confirmed trajectories as follows:

- *Updating confirmed inventory trajectory*. Once confirmed orders are sent to the suppliers, the agent adds the number of components it is going to receive to the trajectory. For instance, if the agent is going to receive 500 components on day 25, and the existing component level on that day is 75, the new component level on day 25 will be updated to 575. Based on the orders received from the customers, the agent subtracts the components it is going to use from the trajectory. For instance, if an

[7] If the suppliers cannot provide the exact quantities requested, the agent ignores the offers and resends the RFQs to the suppliers within the same day. The agent may repeat this process until it receives the offers with the exact amount required. However, this situation is unlikely since the agent's request for the components is relatively small.

customer order requires 100 components on day 35 for production and the existing component level on that day is 500, the new component level on day 35 will be updated to 400.

- *Updating confirmed factory cycles trajectory*. Based on the orders received from the customers, the agent reserves the necessary factory cycles by subtracting them from the trajectory. For instance, if a customer order requires 400 factory cycles on day 25 and the available number of cycles on that day is 600, the new level of factory cycles on day 25 will be updated to 200.

Once the confirmed trajectories are updated, the agent then creates new estimated trajectories by copying from the confirmed trajectories. This situation is depicted in Fig. 6. Based on the estimated trajectories, the agent processes the customer RFQs as follows:

1. First the agent calculates the offer prices for customer RFQs based on the same method adopted by the buy-to-build agent.
2. The agent then sorts the customer RFQs based on the estimated profit.
3. Starting from the RFQ with the highest profit, the agent performs the following steps:
   (a) The agent checks the estimated inventory trajectory to see whether it has sufficient components on the day which is two days prior to the expected delivery date.
   (b) If it has sufficient components, the agent then checks the estimated factory cycles trajectory to see whether it has sufficient cycle times to assemble the PCs on the day which is two days prior to the expected delivery date.
   (c) If it has sufficient components and cycle time, the agent replies to the customer with an offer.

At the end of a TAC SCM day, the estimated trajectories are discarded.

4.3. Scheduling for production

Whenever the agent receives an order from the customer, it issues a request to the factory two days prior to the expected delivery date stated in the RFQ. Once the factory receives the request, it starts assembling the PCs on the next day (i.e. one day prior to the expected delivery date). Since the agent has already allocated sufficient cycle times for that order, the factory can finish the assembly process within the same day. On the expected delivery date, the assembled PCs are delivered to the customer.

By adopting this strategy, the agent can avoid having large number of components/PCs in the inventory and therefore can reduce the storage cost significantly. However, adopting this strategy alone can cause following undesirable outcomes:

- Component prices are relatively high when they are ordered in small numbers with shorter delivery time.
- Delivery dates for the small orders will be delayed by the suppliers when large orders are being processed. As a result, the agent may fail to acquire the components on time.
- The agent has low factory utilisation since PCs are only assembled on demand.

5. Simulation

In order to compare the strength and the weakness of the two types of strategy, we have set up a virtual competition involving only buy-to-build and build-to-order agents. All together, 350 games are played in the virtual competition broken down into seven categories corresponding to possible combinations of the two types of agents as shown in Table 3. This simulation is performed using the TAC SCM server available at http://www.sics.se/tac. Each simulated game is one hour long and thus the total simulation time is 350 h.

5.1. Overall result

The overall results of the virtual competition are analysed based on eight critical attributes (Figs. 7 and 8). We summarise the results of the analysis as follows:

(a) *Revenue*. The highest average revenue (approx. 60 millions) of the agents is recorded when all six agents in the game are buy-to-build agents. It shows that although six buy-to-build agents fiercely compete for the components, they still manage to generate more revenue by increased production capacity.
(b) *Interest*. The lowest average interest is charged by the bank when all six agents are build-to-order agents. Whenever there is at least a buy-to-build agent in the game, the interest charged by the bank increases dramatically. It also reveals that buy-to-build agents need to borrow the money from the bank for ordering large number of components at the beginning of the game and as a result, high interest is charged by the bank.

Table 3
Simulation with two types of strategies

Category	Buy-to-build agents	Build-to-order agents	Games played
1	0	6	50
2	1	5	50
3	2	4	50
4	3	3	50
5	4	2	50
6	5	1	50
7	6	0	50

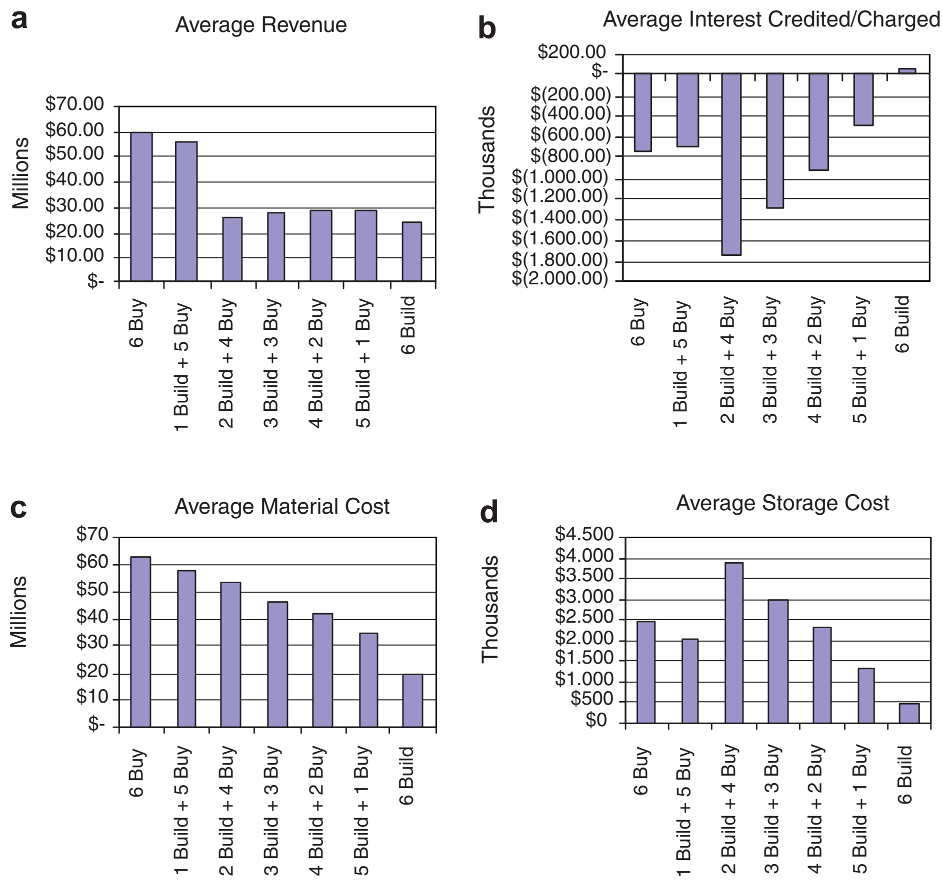

Fig. 7. Simulation result – part 1.

(c) *Material cost*. The highest average material cost is recorded when all agents in the game are buy-to-build agents. The average material cost decreases when the number of build-to-order agents increases. This result is obvious since buy-to-build agents acquire large number of components throughout the game.

(d) *Storage cost*. The highest average storage cost is recorded when there are two build-to-order agents and four buy-to-build agents in the game. Although the result is not anticipated, it could have been contributed by three factors: (a) high inventory level of four buy-to-build agents; (b) constant inventory level maintained by two build-to-order agents; and (c) decrease in low customer demand resulting unusually large number of unused components at the end of the game.

(e) *Customer orders*. The average customer orders processed by the agents is relatively high when there are more than five buy-to-build agents. The average customer orders drops significantly when there are more than two build-to-order agents in the game.

(f) *Factory utilisation*. As expected, the average factory utilisation increases with the number of buy-to-build agents in the game since the agent maintains its factory utilization level at 100% whenever required components are available. Build-to-order agents have low factory utilisation since PCs are assembled only when it has received customer orders.

(g) *Penalty*. The average penalty is the lowest when all six agents are build-to-order agents. This result match our expectation since build-to-order agents are designed to accept customer orders if and only if there are sufficient components and cycle time. The average penalty is the highest when there is one build-to-order agent in the game. The penalty is caused by the missed deliveries, and by analysing Fig. 9, we find that the build-to-order agent has failed to secure necessary components and therefore has caused missed deliveries.

(h) *Overall result (i.e. profit)*. The highest average overall result is obtained when all six agents are build-to-order agents and the lowest overall result is obtained when there are two build-to-order agents and four buy-to-build agents.

5.2. Performance comparison

In order to better understand the behaviour of the agents, we further analyse our virtual competition results

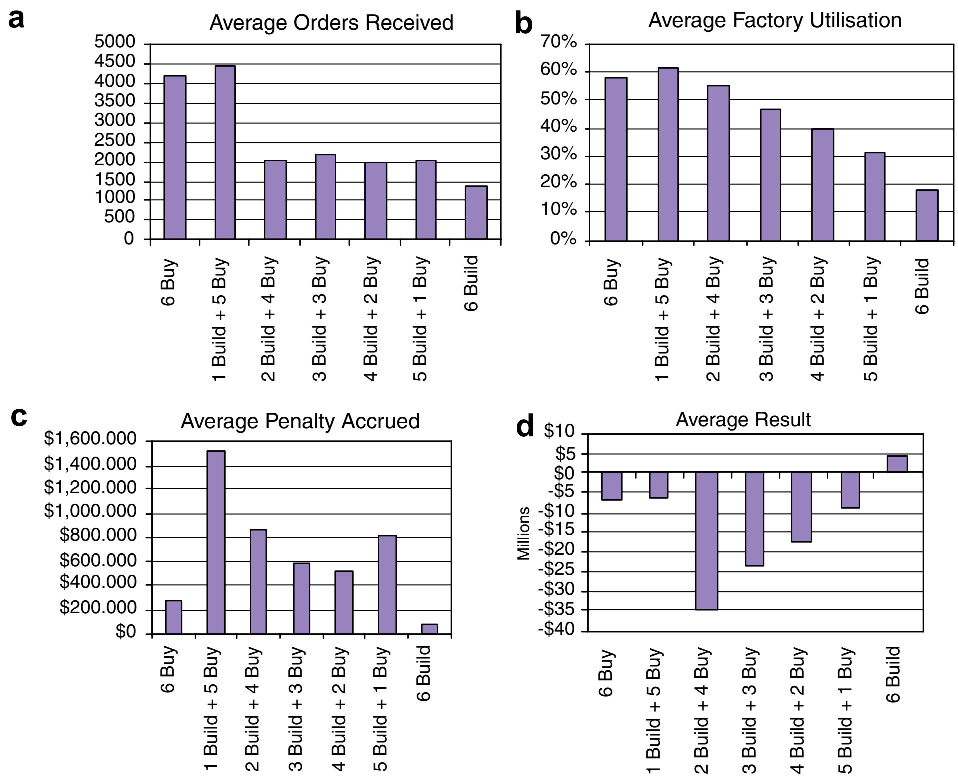

Fig. 8. Simulation result – part 2.

by comparing the performance of each type of agent in Fig. 9. We summarise the results as follows:

(a) *Revenue*. The highest revenue (approx. 60 millions) generators in the games are buy-to-build agents. The maximum revenue is achieved when there are more than five buy-to-build agents in the game. The average revenue of build-to-order agents varies in the range of 20–30 millions and the figures are relatively stable regardless of the number of different agents in the game. It also suggests that the build-to-order agents can generate moderate revenue regardless of the market situation.

(b) *Interest*. The highest interest charged by the bank was recorded when the game has one build-to-order agent. It reveals that the single build-to-order agent is incapable of competing with five other buy-to-build agents in securing customer orders. There are two possible answers to this cause:

- Due to the aggressive buying strategies of buy-to-build agents, in certain games, the suppliers may have delayed the component deliveries to the build-to-order agent. As a result, the requested components of the build-to-order agent can only be delivered during the closing period of the game. Since the agent is unable to use all the components, a large number of unused components are left in the inventory. Due to these surplus inventories, the agent 'goes into red'.
- Buy-to-build agents can acquire components at cheaper prices since they have adopted day-0 big order strategy. In contrast, build-to-order agents only acquire components when they are needed and the component prices beyond the first day are relatively high compared to day 0. Due to the high component prices, the build-to-order agents have lost the leverage in bidding for customer orders. As a result, the agent has failed to secure sufficient level of customer orders to generate much needed profit. Subsequently, the agent is unable to repay the loan from the bank.

The result also shows that the buy-to-build agents are more efficient than we have previously anticipated. The average interest charged by the bank is relatively stable regardless of the number of buy-to-build agents in the game. It also demonstrates that buy-to-build agents are capable of generating revenue faster than build-to-order agents.

(c) *Material cost*. The buy-to-build agents spend twice as much on the material cost compared to build-to-order agents. We also observe that the average material cost for buy-to-build agent is independent on the number of agents with the same type in the game. It also shows that the component prices are relatively stable for bulk orders regardless of the fluctuation in demand. The average material cost of build-to-order agent decreases when the number of build-to-order agent increases.

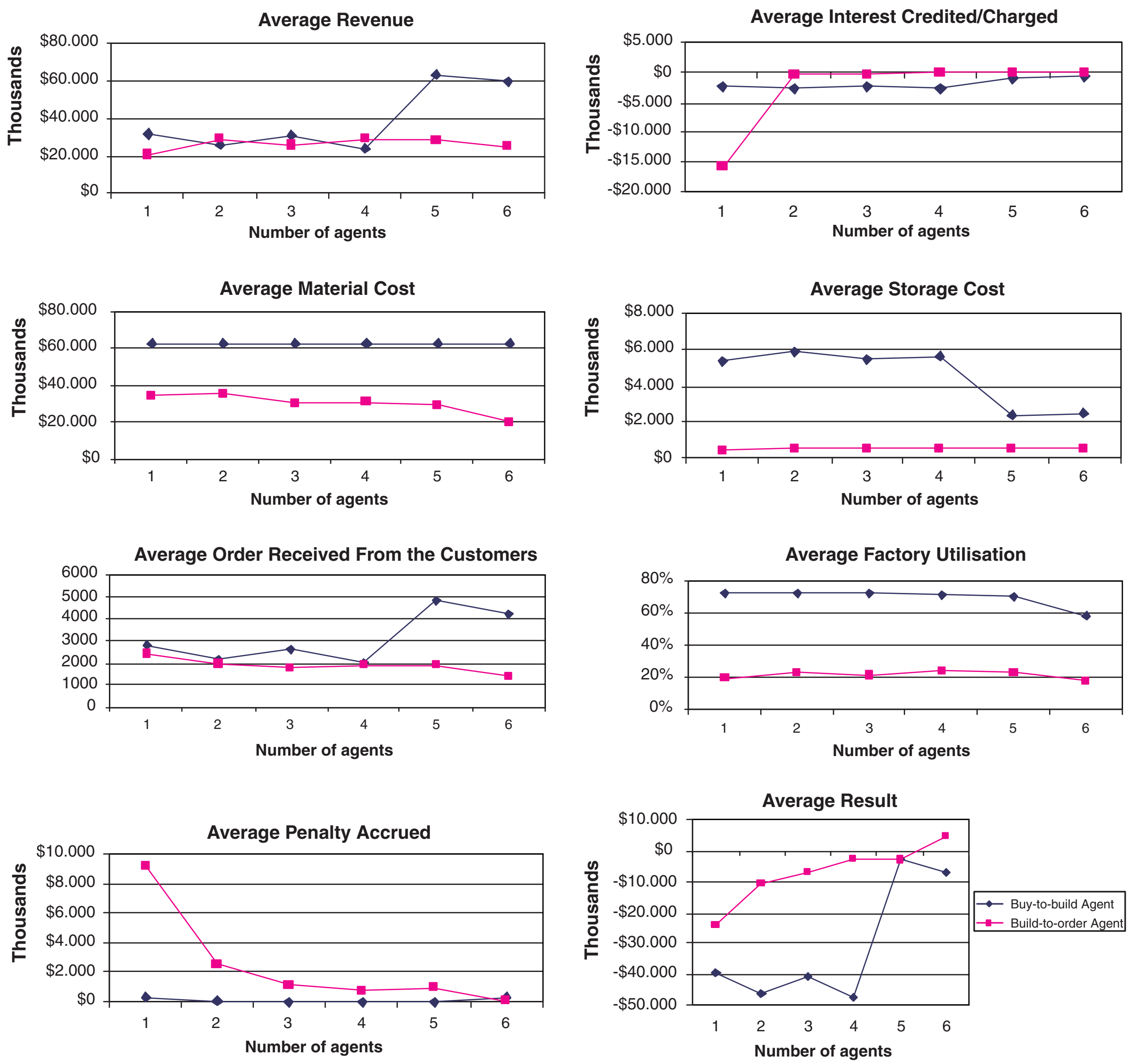

Fig. 9. Comparison of buy-to-build and build-to-order agents.

(d) *Storage cost*. The buy-to-build agents spend twice as much on storage cost compared to the build-to-order agents except for the case in which the game is played with five buy-to-build agents. This result is consistent with our expectation since buy-to-build agents order large number of components at day 0 and since they always maintain a high inventory level.

(e) *Customer order*. The average customer order received by the build-to-order agent decreases when the number of agents with the same type increases. However, the average customer orders received by the buy-to-build agents is relatively high compared to the orders received by the build-to-order agents when there are more than five buy-to-build agents. When the market is monopolised by the buy-to-build agents, the price war will be induced by them[8] since buy-to-build agents have large number of components and assembled PCs in the inventory. Because of the price cutting by buy-to-build agents, the minority build-to-order agents which do not have such capacities are unable to secure customer orders.

(f) *Factory utilisation*. As expected, the average factory utilisation of buy-to-build agents is approximately 70% except when there are six such agents in the game. The high factory utilisation is the result of the strategy adopted by the agent in which it constantly tries to maintains the factory utilization level at 100% whenever required components are available. In contrast, the average factory utilisation of build-to-order agents is approximately 20% since it only assemble when components are available and when orders have been received from the customers.

(g) *Penalty*. The average penalty of build-to-order agent decreases when the number of agents with the same type increases in the game. The penalty is caused by

[8] Buy-to-build agents's customer pricing algorithm is described in Section 3.

the missed deliveries. When there are five buy-to-build agents and when the demand for components is high, the single build-to-order agent has failed to secure necessary components and therefore has caused high number of missed deliveries. In contrast, the delivery schedule of buy-to-build agents are less influenced by the market situation.

(h) *Overall result*. To our surprise, in four out of six cases, the average overall results of buy-to-build agents are much lower than those of build-to-order agents. The buy-to-build agents achieve highest results when there are more than five similar agents in the game. From these results, we can observe that the buy-to-build strategy is more profitable when majority of the agents adopt similar strategy and place bulk orders for components. The result is also consistent with our UMTac-04 agent's score in 2004 competition in which majority of the agents adopted variants of buy-to-build strategy. In the seeding round, the average score of UMTac-04 agent was 20 millions (see Fig. 4). In the final round, some of the agents were revised to adopt build-to-order strategy and as a result, the UMTac-04 average score dropped to 7 millions (see Fig. 5).
The average overall result of build-to-order agents increases when the number of agents with the same type increases in the game. However, the increase in the score is relatively small compared to those of buy-to-order agents.

6. Related work

The TAC's web site (http://tac.eecs.umich.edu) contains information about the scenarios of the competition and links to reports describing strategies employed by participants. As mentioned earlier, an analysis of the strategies used in the 2003 TAC SCM competition [7] shows that they can be roughly classified into two idealised categories: buy-to-build and build-to-order. In this section, we review the participant agents from 2003 and 2004 TAC SCM competition. In the 2003 TAC SCM competition, majority of the agents adopted day-0 strategy in which required components are ordered at the beginning of game.

RedAgent [7] deploys an internal market for the allocation of various resources. The internal market consists of order agents, component agents, production agents, assembler agents, and the bidder agents. The internal market also provides price estimates for components and bidding prices for the customer orders. RedAgent uses buy-to-build strategy in the qualifying round of the 2003 TAC SCM competition. It was later revised to include day-0 ordering in which the component agents send RFQs to the suppliers on day-0 requesting the total amount needed for the average game.

Deep Maize [8] is composed of three separate functional modules (procurement module, sales module, and factory module). It constantly evaluates the supply and demand to find the equilibrium point for defining reference inventory trajectory [9]. Deep Maize deploys a preemptive day-0 strategy [18] by requesting an extremely large quantity of a particular component thereby blocking the supplier from making reasonable offers to other agents. It requests 85,000 units of components to be delivered on day 30. Since the supplier cannot fulfill the request, the suppliers will reply with two types of offers: a partial-delivery offer (to be delivered on day 30) and earliest deliverable complete offer (for 85,000 U). Deep Maize then accepts the partial offer which is to be delivered on day 30 containing less components than requested. Overall, Deep Maize's strategy can be classified as build-to-order with an aggressive day-0 ordering approach to defend itself from component monopolisation by buy-to-build agents. The build-to-order version of UMTac adopts the idea of reference inventory trajectory implemented by Deep Maize.

TacTex-03 [10] also follows the general strategy of sending large requests (RFQs with 8800, 4400, 4400, 1100, and 550 for each components) to the supplier on day-0. On the following days, it predicts the number of components needed based on the customer RFQs and from the projection of future production requirements. TacTex-03 uses an heuristic to find the set of offers to the customers that maximises the TacTex-03 expected profit. TacTex-03 also uses a greedy production scheduler which projects several days into the future and produces each order as late as possible. Like Deep Maize, TacTex implements an essentially build-to-order strategy with an aggressive day-0 stock-building approach.

PackaTAC [11] uses a conservative low risk strategy to combat mutually destructive big-order strategies that were used during the 2003 qualifying rounds. PackaTAC orders 1800 for each component on the first day divided over six deliveries. The agent then maintains a target inventory level (1500 for each components) and reorders from the suppliers whenever the inventory is below the target. PackaTAC uses a greedy scheduler which favours on-time orders over late ones. The scheduler also give higher priority to earliest due-date orders. PackaTAC only bids for the customer orders if and only if it has sufficient inventory level and free factory cycles. PackaTAC can be categorised as a hybrid agent which buys-to-build until reaching its target inventory level, and then behaves more on a build-to-order mode.

HarTAC [12] employs a state-based approach in which the agent is designed to stay in the steady state which can make most of the profit. HarTAC is similar to PackaTAC in the sense that it purchases components throughout the game and maintains a sufficient inventory level. HarTAC does not deploy day-0 strategy. Instead, it only buys when it can predict the average market level and when it can achieve good components prices. In low demand games, HarTAC was reported to outperform RedAgent which uses aggressive buying strategy. In high demand game, HarTAC was reported to outperform

PackaTAC which deploy conservative bidding strategy [12].

PSUTAC [6] uses a *Make-to-Plan* (i.e. buy-to-build) approach. The agent first decides a required level of production and then purchases all components at the beginning of the game. The agent uses full factory capacity for the production. The agent then selects the bids that have a reserve price higher than the bidding price. The agent bids customer orders based on the available inventory and uses a Gaussian function to set the bidding prices randomly. As soon as the orders are received from the customers, the agent delivers immediately.

7. Conclusion

In this paper, we have reported the results of an empirical comparison of two basic types of strategies in supply chain management, namely buy-to-build and build-to-order, in the light of their application to the TAC SCM competition. The conclusions of our study are in line with the results obtained by our UMTac-04 agent in the preliminary and final rounds of the TAC SCM 2004 competition. The overall results of the simulation analysis and the performance comparison of these strategies are also consistent with our preliminary assumptions during the UMTac-04 agent design. In particular, they confirmed our intuition that a buy-to-build strategy could deliver better results and be more resilient to market monopolisation attacks, given that several other agents were using the same strategy.

Although the UMTac-04 agent with buy-to-build strategy only secured third position in the 2004 TAC SCM final round, its performance was better than we had anticipated. In particular, the agent was very resistant to market monopolisation attacks by other agents implementing variants of build-to-order agents, and achieved all our design objectives.

One of the main highlights of our study is that it shows that the build-to-order strategy delivers better results when the other agents which share the same component providers, apply this same strategy. However, as soon as one of the agents adopts the buy-to-build strategy, it becomes more profitable for the others to adapt it as well.

Our analysis also reveals the strengths and weaknesses of both strategies in various aspects. Agents with buy-to-build strategy are resistant to market monopolisation. They are also more successful in securing customer orders and, as a result can generate much needed revenue quickly. They also maintain high factory utilisation throughout the competition. Because they maintain high levels of stock, they are able to meet the delivery deadlines and thus incur less penalty. However, these agents achieve low profit due to high material and storage cost. In contrast, agents with build-to-order strategy spend less on material and storage. Our analysis also reveals that build-to-order agents are relatively stable when the majority of the agents deploy similar strategy. They are also able to generate higher profit than buy-to-build agents.

One of the challenges in TAC SCM is to design the agent which can adapt its fast changing business landscape. In addition, the agent should be designed in such a way that it can exploit the advantages of both strategies. We are currently investigating the possibility of implementing a hybrid approach which includes both buy-to-build and build-to-order strategies. In this hybrid approach, the agent will be designed to adapt to the market situation by forecasting the supplier capacity and customer demand based on previous episodes, the observed set of RFQs, and data obtained by probing the suppliers.

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