Temporal Strategies in a Multi-Agent Contracting Protocol

John Collins, Scott Jamison, Maria Gini, and Bamshad Mobasher

Department of Computer Science, University of Minnesota
Minneapolis, MN 55455
{jcollins, jamison, gini, mobasher}@cs.umn.edu

Abstract

Much recent work in automated contracting in multi-agent environments has focused on the design and analysis of protocols that encourage customers and suppliers to negotiate fairly, and that attempt to reduce unproductive strategic counterspeculation. Most of these studies focus on how the static structure of the protocol may result in strategic behavior on the part of the participants. In this paper, we show that the timing of various protocol elements can also encourage or curtail counterspeculation. We first present a general and flexible negotiation protocol for a market domain in which a group of heterogeneous, self-interested agents formulate, or are given, goals to accomplish for which they may lack resources or capabilities. Therefore, they must enter into contracts with each other in order to accomplish these goals. We then show how selection of the timing elements within our protocol can affect the behaviors of the agents involved in the negotiation. We also show how placing limits on the values of some of these timing elements can reduce or eliminate some types of time-based counterspeculation.

Keywords

multi-agent contracting, negotiation protocols, planning, counterspeculation, electronic commerce, virtual markets, multi-enterprise manufacturing, market mechanism design

Introduction

When self-interested human or automated agents negotiate with each other, they do so within a framework of rules and understandings that influence their behaviors. Smith's Contract Net (Smith 1980) and Sandholm and Lesser's extensions (Sandholm and Lesser 1995) are examples of protocols designed to govern the behaviors of agents engaged in negotiations over agreements to exchange tasks, goods, and services. There is currently considerable interest in using such protocols to support electronic commerce in virtual markets.

The design of market mechanisms and negotiation protocols can have a profound influence on the behavior of the participants, encouraging and enabling certain kinds of behavior and outcomes, and discouraging or disabling others. The Vickrey auction mechanism (Vickrey 1961, Varian 1995), for example, is designed (under certain conditions) to promote "truth telling" among agents since the dominant strategy is for each agent to report its true utility.

Previous work in analysis of negotiation protocols has focused on static economic and utility factors. In this paper we show that the *timing* of protocol elements in a virtual market environment also can affect the strategic behavior of participating agents. We focus our attention on contracting domains, such as multi-enterprise manufacturing, where a *customer* agent formulates plans and uses the negotiation process to gain commitment from *supplier* agents for their execution. Since the elements of the contracting protocol affect the formulation of a plan by the customer agent, we call this process *Planning by Contracting*.

In particular, we introduce and present a flexible and practical contracting protocol for the type of customer-supplier interactions mentioned above. Our protocol includes components for submitting and accepting bids in a virtual market, as well as subprotocols governing customer or supplier decommitments at various stages. We then analyze how the timing of various protocol components could lead to time-based strategic behavior on the part of customers and suppliers.

In the remainder of this paper, the following section provides some background material on protocols for automated contracting. We then describe our proposed protocol for planning by contracting. Next, we analyze the interaction between timing parameters in the protocol and the behavior of the agents involved, paying special attention to factors that could encourage counterspeculation. Finally, we conclude and note further research opportunities along these lines.

Negotiation among Self-Interested Agents

The protocol described here is intended to be used by independent agents in an electronic commerce environment. This environment is *open* in the sense that agents may be designed and added to the environment by multiple parties, who intend their agents to act on their behalf in the market. Such agents are assumed to be *self-interested*. That is, they will act and make commitments to others only when it is individually rational for them to do so, regardless of the benefits of those actions and commitments to the other agents or to the community as a whole. Agents are also assumed to be limited in their rationality, meaning that they cannot in general determine precisely what is in their best interest, without spending arbitrarily long periods of time computing.

The behavior of self-interested agents has been studied in the literature on game theory and economics (Fudenberg and Tirole 1992, Kreps 1990). The assumption of limited rationality is not well-treated in that literature, but more recently the work of Sandholm (Sandholm 1996) and others has shown how the results of game theory apply to such agents. In particular, he shows that the Vickrey auction mechanism may not retain its desirable properties under conditions of limited rationality.

Two important properties of limited-rational agents is that they cannot solve arbitrary combinatorial optimization problems, and the process of working on such problems, even for finding approximations, takes time. For an agent that must deal with such problems in a real-time environment, an *anytime* optimization algorithm (Dean and Boddy 1988, Hamidzadeh and Shekhar 1995) has the desirable property that the more time it is given to operate on a problem, the better (closer to optimal) its solution will be. In a virtual market environment such as ours, agents must also make decisions about which problems they will spend time on.

The Role of the Market

Many virtual market mechanisms assume that agents will negotiate directly with each other. Sandholm, for example, has devised enforcement-free exchange mechanisms explicitly to permit agents to deal directly with each other, without any intermediary (Sandholm 1996). In contrast, the protocol under consideration in this paper is specifically designed to operate with an intermediary, called a market, that performs a number of functions (Collins et al. 1997, Tsvetovatyy et al. 1997). For the purposes of this paper, some significant roles include:

- Advertising: Abstract planning operators representing available capabilities are listed in the market in a domain-specific format.
- Synchronization: The market provides a time reference relative to which all timing information in a negotiation is measured. This is necessary to avoid disagreement among agents as to the times of significant events, such as the time of a decommitment message, especially in cases where the time affects agent utilities.
- Enforcement: In order to avoid the complication of an enforcement-free exchange mechanism, and to ensure that penalties are paid, the market is given enforcement powers.
- Authentication: The market verifies the identities of the agents involved in a negotiation.
- Neutral Auctioneer: The market is available to operate as a neutral, trusted auctioneer for bidding protocols like the Vickrey second-price mechanism where the trustworthiness of the auctioneer is required for success.

Opportunities for Counterspeculation and Deceit

Counterspeculation in negotiation occurs when agents adjust their behavior based on their perceptions of their opponents' values, capabilities, and knowledge. For example, in a sealed-bid auction, participants are motivated to bid just high enough to win, but not higher than their own valuations. If they have prior knowledge of their opponents' valuations, they can avoid paying more than an increment higher than the highest opponent's valuation, rather than their own valuation. Consider two agents bidding on a particular good. Agent 1 values a good at 1, and agent 2 values the same good at 2, but believes that agent 1's valuation is $1/2$. In this case, agent 2 would bit $1/2 + \varepsilon$, thereby losing the bid and causing the auction process to fail to allocate the good to the agent with the highest valuation (Varian 1995). Careful protocol design can reduce counterspeculation by reducing the value of such information. For example, using the Vickrey protocol in a private-value auction, the dominant strategy is to bid one's own true valuation (Vickrey 1961).

Deceit occurs when agents find it advantageous to misrepresent their true intentions or capabilities. For example, if two agents are negotiating over how to divide a set of tasks, an agent may be able to gain advantage by declaring a phantom task that distorts the set of shared tasks and allows the agent to come out of the negotiation with a lighter work load than the other agent. Rosenschein and Zlotkin have treated this problem extensively in a variety of domains, and show how the design of the negotiation protocol can eliminate the motivation for deceit in many circumstances (Rosenschein and Zlotkin 1994).

In a domain where both customers and suppliers are forced to spend significant amounts of time reasoning during the transaction, there is also an opportunity for time-based counterspeculation. This occurs when agents adjust their behavior to take advantage of their perceptions of the limits on the reasoning capabilities of their opponents. For example, if a bidder has the opportunity to limit the time interval during which its bid is valid, it can force the customer to make a decision before it has had time to do an adequate estimation of the marginal utility of the bid. This problem and similar situations are discussed in more detail below.

Negotiating over Plans

Rosenschein and Zlotkin have done an extensive treatment (Rosenschein and Zlotkin 1994) of the problem of negotiating over plans, in which both agents involved in the negotiation have identical capabilities and possibly different goals. The problem they address is how to find mutually beneficial deals under which both parties to the negotiation can expect to achieve their own goals more efficiently than they could if acting alone. They also treat aspects of conflict resolution among self-interested agents with possibly conflicting goals.

In this paper we are concerned with negotiations among heterogeneous agents, in which one agent, the *Customer*, negotiates with other agents, the *Suppliers*, for services that will help the Customer achieve its goal.

A Protocol for Planning by Contracting

Our protocol is designed to balance the demands of flexibility and practicality in a market-based negotiation environment. For simplicity, we assume the negotiation is always initiated by the customer, and we do not permit counterproposals. Therefore, the interaction is a three-step process: a customer issues a *call-for-bids*, a supplier replies with a *bid*, and the customer completes with a *bid-acceptance*. After these three steps have taken place, both parties (the customer and the supplier) are committed to the agreement, subject to the decommitment penalties specified in the transaction. Because these penalties are designed to be functions of time, and because the time limits governing the interaction are explicitly specified in the messages, a fairly rich set of alternative negotiation styles are available.

Following is an overview of a customer's reasoning process; subsequent sections provide details on the elements of the protocol.

1. Develop a partial plan, assign a value to the goal, and estimate tentative values for plan components based on the goal value and the "criticality" of each component.
2. Announce tasks to be bid upon.
3. Receive bids from suppliers.
4. For each bid, map the bid to the plan, and evaluate bid price vs. value — the value could include time limits, decommitment penalty, task coverage, location of work, identity of bidder, etc.
5. Extend or modify the plan, and potentially announce further bids.
6. Award contracts to selected suppliers.

Call for bids

The negotiation process begins when the customer creates a high-level plan to achieve its current goal. If that plan requires (or could benefit from) the use of resources of other agents, the customer will collect the *subtasks* it wishes to contract out into one or more *tasks*, each of which in turn is used to formulate a Call-for-bids message. The subtasks must be selected from a catalog of available domain-specific capabilities advertised by the *market*. The call-for-bids message will include, for each subtask listed, the time window during which the work must be done.

The call-for-bids message will also include, among other information:

1. a bid deadline, or the time by which the suppliers must respond with bids,
2. the time at which the customer will begin considering the bids,
3. the earliest time at which bid acceptances will be sent, and
4. penalty functions for each subtask, which will be assessed against the supplier if the supplier commits to work, but fails (or decides not) to do it.

The call-for-bids message will typically be posted (made public) in the market, which for present purposes is a variant of the MAGMA market mechanism (Tsvetovatyy et al. 1997). A companion paper describes in more detail the role played by the market in the negotiation (Collins et al. 1997).

The penalty functions are typically piecewise-linear functions of time (see Figure 1 below) that are intended to encourage suppliers to perform the work they commit to. If they are unable to perform, the increasing value of the penalty function encourages them to explicitly decommit as early as possible. Because the supplier can bid on a subset of the subtasks listed in the call-for-bids, and because the customer can accept partial bids, a separate decommitment function is provided for each subtask.

The decommitment penalty functions are included to allow supplier and customer to communicate about the tradeoff between the customer's desire to have a strong assurance that accepting a supplier's bid will result in the task being completed on time, and the supplier's desire to protect itself from commitments which may later turn out to be disadvantageous. A more complete description of the form of the decommitment function and its uses is given below in the section on Timing Analysis.

Bidding

Each supplier will inspect the Call-for-bids, and will decide whether or not it should respond with a bid, according to its resources, time constraints, knowledge of the work to be done, and other commitments. The supplier must send bid messages, if it chooses to do so, before the bid deadline. This bid message can include a combination of subtasks, which will be a subset of the subtasks listed in the call-for-bids.

In the bid, the supplier must indicate the cost to the customer, the time window, and the estimated duration of the work for the whole subtask combination listed in the bid, and this same data for each of the separate subtasks. The bid acceptance deadline must also be included, as well as a penalty function for each subtask, which the customer will have to pay if it commits to giving this supplier the work but then does not do so. This penalty function will have the same structure as the supplier penalty function.

A supplier can submit multiple bids for each call-for-bids, involving different costs and time windows. However, in the context of a single call-for-bids, the customer will award each supplier at most one subtask combination, which may be all or part of a single bid. With this structure, a supplier can send multiple bids, giving the customer a varied set of bids to choose from, yet not overcommit itself.

As stated above, this bid is a commitment by the supplier to do work listed in the bid, should the customer accept it. Knowing this, the bidding supplier should consider the decommitment penalty, as described in the call-for-bids, for each subtask on which it bids, before sending the bid message.

If the supplier sends no bid message before the customer's bid deadline, the customer will assume that the supplier has decided not to send a bid for this particular call for bids. Thus, rejection is passive, in that no response means "no".

Bid Acceptance

At some point, the customer must decide which of the bids to accept. The decision process requires satisfying constraints and maximizing utility. The plan imposes a set of temporal and resource constraints that must be satisfied by the set of bids accepted. Utility is a function of several factors specified in a bid, including bid price, expected decommitment costs, and schedule risk.

After completing this process, the customer has three courses of action for each bid, the first two of which create a commitment by the customer to the supplier:

1. accept the whole bid,
2. accept a subset of the subtasks in the bid, or
3. reject the bid (by taking no action).

Our goal with this mechanism is to make negotiation unnecessary. The subtask data are included in each bid to provide the customer with more flexibility in cases where no set of bids put together would cover every subtask to the satisfaction of the customer. With this option, our protocol avoids the need for negotiation, in that the customer agent knows how the supplier will break down the costs of the accepted subtasks, should it become necessary for the customer to accept a subset of the original bid combination (choice 2). This, coupled with our use of time-based decommitment functions, has allowed us to maintain this protocol as a three step process.

If there is one or more subtasks in the customer's plan which are part of no acceptable bid combination, the customer must decide how it is going to get those subtasks accomplished. Its options include doing the subtask(s) with its own resources, putting it up for bid in a different call-for-bids, or breaking down the whole task in a different way, if possible.

Decommitment

After receiving a bid accept message from the customer, each supplier must determine if there are any subtasks in this message that it wishes not to perform. If it wishes to decommit from all or part of the work as described in the bid-accept message, it sends a supplier-decommit message to the customer, specifying which of the subtasks it will not be performing, and pay the agreed-upon supplier decommitment penalty to the customer. When the customer receives supplier decommitment messages, it will take one of the following actions:

- send a bid-accept message for the decommitted subtasks to another supplier whose acceptance deadline has not yet passed,
- formulate and issue a new call-for bids for the decommitted subtasks,
- revise the current plan in some way, and issue new calls-for-bids, or
- abandon the goal and decommit from other commitments related to the goal.

If the customer determines that it wishes to decommit from subtasks already committed to a supplier, it must send a customer-decommit message to the supplier, specifying which subtasks are being retracted, and pay the agreed-upon customer decommitment penalty to the supplier.

Protocol Timing Analysis

The protocol described above contains several degrees of freedom that can influence the behavior of customers and suppliers. We start by defining a set of variables, below. All times are with respect to t_0, the time at which the call-for-bids is issued by the customer. In the initial call for bids, we have

- t_{LB} Latest Bid time — the latest time at which the Customer will accept a bid from a Supplier.
- t_{EA} Earliest Accept time — the earliest time at which the Customer will accept a bid.
- t_{EB} Earliest Bid time — the earliest time at which any bid will be considered by the Customer. In order to

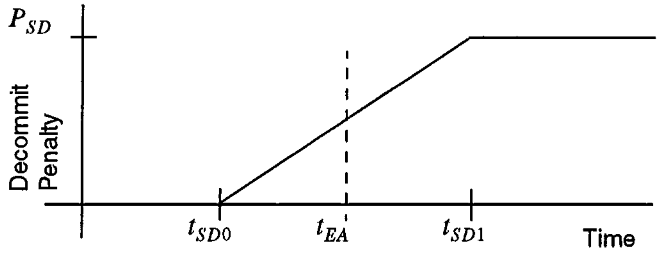

Figure 1: Example Supplier Decommitment Function

run a sealed-bid or Vickrey auction, this time must be no earlier than t_{LB}.

$D_S(t)$ Supplier Decommitment function — A piecewise-linear function (see Figure 1 below) used to determine the penalty incurred by a supplier for decommitting from a bid. This function is defined by the following 3 parameters:

- t_{SD0} Until this time, the supplier's decommit penalty is 0.
- t_{SD1} After this time, the penalty incurred by the supplier for decommitting is equal to P_{SD}. Between t_{SD0} and t_{SD1}, the decommitment penalty varies linearly between 0 and P_{SD}.
- P_{SD} The final value of the supplier decommitment penalty.

In the bid returned by a supplier, the following parameters may be set:

t_{LA} Latest Accept time — the Supplier's bid is valid until this time.

$D_C(t)$ Customer Decommitment function — the function used to determine the penalty incurred by the customer for decommiting after award on a bid. Like the Supplier Decommit function, this is a piecewise linear function defined by 3 parameters:

- t_{CD0} Until this time, the decommit penalty is 0.
- t_{CD1} After this time, the decommit penalty is equal to P_{CD}. Between t_{CD0} and t_{CD1}, the decommit penalty varies linearly between 0 and P_{CD}.
- P_{CD} The final value of the customer decommit penalty.

Within this framework, there are two basic styles of plan-bid interaction. Because the initial time limits are defined by the customer, the style and most of the details are chosen by the customer, possibly limited by the market (since the call for bids passes through the market, the market can impose limits by restricting the settings of parameters in outgoing bids). In the following sections we consider each of these styles in detail.

Immediate Response Interaction

The first style of plan-bid interaction is called *immediate response*. It is characterized by $t_{EB} < t_{LB}$ and $t_{EA} < t_{LB}$. In the simplest case, $t_{EB} = t_{EA} = t_0$. Under these conditions, the customer is able to begin reasoning over incoming bids as soon as they arrive, and can make awards at any time. Figure 2 illustrates this situation.

This style can be appropriate when the customer's plan is simple, and there is little risk of failing to receive a set of bids that make the plan feasible. It also may be necessary when the customer's deadline for accomplishing the goal is very early relative to t_0 and the expected duration of the plan. This approach will allow lower bids by suppliers, who gain by minimizing the time during which resources have to be reserved to meet bid commitments. This could be significant in an environment where task durations are short compared to the duration of a bid cycle, because in such an environment the supplier must choose between overcommitting or underutilizing its resources. When resources are overcommitted, the supplier risks payment of decommitment penalties; when they are underutilized, overall costs are increased.

The immediate response model doesn't allow use of sealed-bid or Vickrey auction protocols, because both require that all bids be processed together, which requires

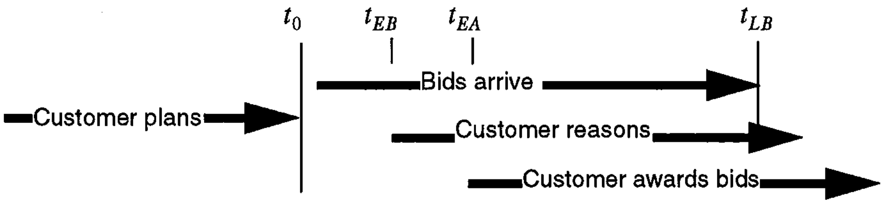

Figure 2: Immediate Response interaction

$t_{LB} \le t_{EB}$. Also, a supplier can set t_{LA} earlier than t_{LB}, forcing the customer to make decisions regarding acceptance of a bid without knowing whether other, possibly more advantageous, bids might be forthcoming. This in turn allows a supplier to manipulate the customer by submitting a bid very quickly, and allowing minimal decision time on the part of the customer. If the supplier speculates that one or more subtasks in the bid are critical to the customer's plan, then the supplier may bid early, overprice the bid, and use a very short acceptance deadline to force the customer to either accept immediately or risk plan failure.

In the supplier decommitment function, $t_{SD0} \le t_{EA}$ means the supplier is obligated to either perform the work or pay a penalty as soon as bids are awarded. If $t_{SD1} \le t_{EA}$, then the supplier is discouraged more strongly from making speculative bids. This assures the customer that bids received can be incorporated into its plan at low risk. If $t_{SD0} > t_{LB}$ and $t_{SD0} > t_{EA}$ then speculative bidding is allowed, since the supplier incurs no cost by decommitting up until time t_{SD0}. In this case, the customer exchanges a risk of plan failure for lower expected bid costs and possibly greater availability of bids. In general, earlier settings of t_{SD0} and t_{SD1}, and higher values of P_{SD}, increase the supplier's expected costs and will result in higher bid prices to the customer.

In the customer decommitment function, $t_{CD0} \le t_{EA}$ means the customer incurs an obligation to either follow through with the contract or pay a penalty as soon as a bid is awarded. This may make sense if the supplier must keep resources reserved to perform the work, and would miss out on other opportunities if the customer were to back out. On the other hand, specifying $t_{CD0} > t_{LA}$ allows the customer to make speculative awards and back out if it later turns out to be advantageous to do so. The supplier may want to do this to make its bid more attractive. If the nature of the work is such that the supplier need not keep resources reserved and thereby pass up other opportunities, it may make sense to set t_{CD0} to the time work is actually expected to commence on the bid. In general, earlier settings of t_{CD0} and t_{CD1}, and higher values of P_{CD}, increase the expected cost of a bid to a customer.

Delayed Response Interaction

The second style of interaction is called *delayed response*, and is useful when the customer expects to need a significant period of time, possibly involving multiple bidding cycles, before making award decisions on bids. This style is characterized by $t_{EA} > t_{LB}$, as shown in Figure 3.

This style has two major variations, one in which $t_{EB} \ge t_{LB}$, allowing Vickrey and sealed-bid auctions, and one in which $t_{EB} < t_{LB}$. It is expected to be used in situations where the customer needs a significant amount of time to reason over the bids during which all bids must remain valid. This can occur for two reasons. First, if the plan is complex or contains many alternative branches, the search required to map bids to a near-optimal plan may require a significant amount of time and computational resources. Second, if the scope of the plan and the number of alternative branches available is so large that it is infeasible to enumerate all "reasonable" alternatives, then it may be advantageous for the customer to use the bidding process itself to prune the search space as the plan is built. In this case, multiple bid cycles would have to be run before bids could be accepted, and possibly even before the customer would know whether a feasible plan exists for the goal. This implies that before setting the value of t_{EA}, the customer must reason about the amount of time it wants to reserve for its reasoning process.

The primary disadvantage to extending the time interval during which bids must be "held open" is that suppliers must reserve resources to meet the commitments represented by their outstanding bids. This will likely lead to higher prices or fewer bids, because the supplier must expect to forgo other business opportunities while those

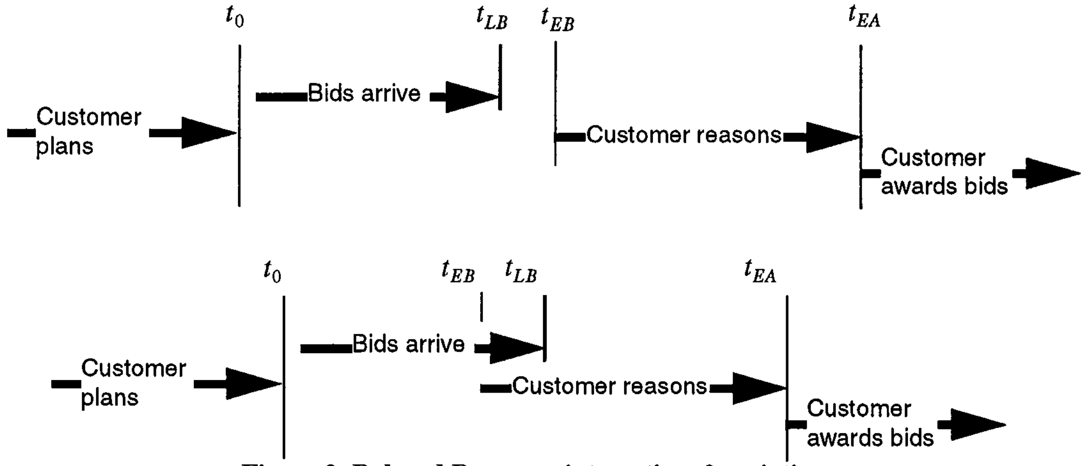

Figure 3: Delayed Response interaction, 2 variations

commitments are in place. In order to determine the bid price, the supplier must factor in an expected cost composed of the fixed cost of the resources required to perform the work, the probability of failing to win the bid, and the probability that the resources could have been allocated to other work had they not been reserved during the time the bid was outstanding. Customers can reduce this cost by making t_{SD0}, the time before which the supplier can decommit without cost, later than t_{EA}. The risk of doing this is that if a supplier does back out, replanning and rebidding becomes necessary, and the customer may have to pay decommitment penalties on previously awarded bids if the plan becomes infeasible.

If the customer sets $t_{EB} < t_{LB}$, perhaps in order to shorten the duration of the overall cycle, the supplier gains an opportunity to speculate on the limits of the customer's reasoning process and thereby gain advantage, and possibly charge a higher price, by bidding earlier. This can occur if the customer's search process is constrained enough that not all bids can be fully considered. If the supplier calculates that the probability of its bid being considered by the customer increases as the bid becomes earlier, then it gains an opportunity to be awarded the contract at a higher price than a bid submitted later. Conversely, if the supplier calculates that the customer will only consider later bids if they contain lower prices, then the value of a bid to the customer will decrease with time over the interval $[t_{EB}, t_{LB}]$.

Conclusions and Directions for Future Work

In recent years researchers have studied how the static structure of contracting and negotiation protocols in multi-agent virtual markets can affect the strategic behavior of participating agents. In this paper, we have shown that the timing of various protocol components can also lead to or curtail counterspeculation. We have presented a general and flexible protocol that supports planning by contracting over a set of agent capabilities available in a market of heterogeneous agents. We have provided a temporal analysis of agent strategies in the context of our proposed protocol. In particular, we have identified two classes of time-based counterspeculation opportunities in this domain that can be controlled by the settings of certain timing parameters. One of these situations occurs when the supplier agents are allowed to expire their bids before the customer's call-for-bids expires, and the other situation occurs when customers are perceived by suppliers to be considering bids and formulating plans before bidding is closed.

There are a number of open questions and issues raised by this work which are the subjects of our continuing investigation. Below we list some of these outstanding issues:

- Decommitment Penalties: exploring the role of decommitment penalties in time-based counterspeculation, including the timing of various decommitment stages by suppliers and customers.
- Game-Theoretic Analysis: studying the trade-offs and possible equilibria resulting from timing of protocol elements, and whether there are dominant strategies for suppliers and customers under various timing scenarios.
- Role of the Market: exploring the role of the market itself in planning by contracting, and in particular, how the market can play a role in reducing time-based counterspeculation among participants.
- Planning: formulating the specific details of how plans can be instantiated from bids and how the planning and bidding stages can be interleaved.

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