INTEGRATIVE NEGOTIATION AMONG AUTONOMOUS AGENTS

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ABSTRACT

Autonomous agents generate plans towards the achievement of their goals and, over time, situations arise in which their plans conflict with the plans of other agents. Negotiation is the predominant process for resolving conflicts. This paper presents the key features of a negotiation model for autonomous agents that handles multi-party, multi-issue and repeated rounds. The model acknowledges the role of conflict as a driving force of negotiation, formalizes a set of human negotiation procedures, allows the dynamic addition and removal of issues, and accounts for a tight integration of the individual capability of planning and the social capability of negotiation. This paper also describes an experiment conducted to evaluate a version of the model that handles two-party, multi-issue negotiation. The results confirmed a number of conclusions about human negotiation.

INTRODUCTION

Autonomous agents generate plans towards the achievement of their goals. The agents operate in complex environments and situations often arise in which their plans conflict with the plans of other agents. The predominant process for resolving conflicts is negotiation. Recent growing interest in electronic commerce and supply chain management has given increased importance to negotiation.

This paper presents the key features of a generic model of negotiation that handles multi-party, multi-issue and repeated rounds. The main components of the model are: (i) a prenegotiation model, (ii) a multilateral negotiation protocol, (iii) an individual model of the negotiation process, (iv) a set of negotiation strategies, and (v) a set of negotiation tactics. The model accounts for a tight integration of individual and social behavior. Also, the model acknowledges the role of conflict as a driving force of negotiation, formalizes a set of human negotiation procedures, and allows the dynamic addition and removal of issues.

The model is currently being evaluated. This paper describes an experiment conducted to: (i) assess the feasibility of building autonomous negotiating agents equipped with a version of the model that handles two-party, multi-issue negotiation (integrative negotiation), (ii) investigate the behavior of integrative strategies and their associated tactics, and (iii) evaluate the effect of these strategies and tactics both on the process and on the outcome of negotiation.

This paper builds on our previous work in the area of negotiation (Lopes et al. 2002; Lopes et al. 2004). The remainder of the paper is structured as follows. A generic model of individual behavior for autonomous agents is presented first, followed by the key features of a generic model of negotiation. Next, the experimental work is reported. Finally, related work and concluding remarks are presented in the last two sections.

AUTONOMOUS AGENTS

This section presents a model of individual behavior that captures some important features of a wide range of autonomous agents. Let *Agents* be a set of agents. A brief description of the key features of every agent $ag_i \in Agents$ follows (see also Lopes et al. 2002).

The agent ag_i has a set $B_i=\{b_{i1},\ldots\}$ of beliefs, a set $G_i=\{g_{i1},\ldots\}$ of goals, and a library $PL_i=\{pt_{i1},\ldots\}$ of plan templates. *Beliefs* represent information about the world and the agent himself, *goals* represent world states to be achieved, and *plan templates* are procedures for achieving goals. Every plan template $pt_{ij} \in PL_i$ is a 6-tuple that includes a header, a type, a list of conditions, a body, a list a constraints, and a list of statements. The library PL_i has *composite* plan templates specifying the decomposition of goals into more detailed subgoals, and *primitive* plan templates specifying actions directly executable by ag_i.

The agent ag_i is able to generate complex plans from the simpler plan templates stored in the library. A *plan* p_{ik} for achieving a goal g_{ik} is a 3-tuple that includes a list $PT_{ik} \subseteq PL_i$ of plan templates, a binary relation that establishes a hierarchy on PT_{ik}, and another binary relation that establishes a temporal order on PT_{ik}. The plan p_{ik} is represented as a hierarchical and temporally constrained And-tree denoted by $Pstruct_{ik}$.

At any instant, the agent ag_i has a number of plans for execution. These plans are the plans adopted by ag_i and are stored in the *intention structure* $IS_i=[p_{i1},\ldots]$. For each plan $p_{ij} \in IS_i$, the header of every plan template pt_{ijm} in p_{ij}, is referred as *intention* int_{ijm}. The agent ag_i often has information about the other agents in *Agents*. This information is stored in the *social description* $SD_i=\{SD_i(ag_1),\ldots\}$.

The agent ag_i checks regularly its adopted plans in order to detect any potential conflict of interests. To this end, ag_i has a library of *conflict detection axioms* $CL_i=\{ax_{i1},\ldots\}$. The axioms state which intentions cannot be satisfied together.

THE NEGOTIATION MODEL

Let $Ag=\{ag_1,\ldots,ag_n\}$, $Ag \subseteq Agents$, be a set of autonomous agents. Let $P_{Ag}=\{p_{1k},\ldots,p_{nk}\}$ be a set of plans of the agents in Ag including intentions $I_{Ag}=\{int_{1kl},\ldots,int_{nkl}\}$, respectively for agents $ag_1,\ldots,ag_n$. Let the intentions in I_{Ag} represent commitments to achieve exclusive world states. In this situation, there is a conflict $Conf_{Ag}$ among the agents in Ag. This section presents the key features of a negotiation model (see our earlier work for an in-depth discussion (Lopes et al. 2002; Lopes et al. 2004)).

Preparing and Planning for Negotiation

The prenegotiation model defines the main tasks that each agent $ag_i \in Ag$ must attend to in order to prepare for negotiation. A description of these tasks follows.

Generation of the Negotiation Problem Structure. A negotiation problem NP_{ik} from the perspective of ag_i is a 6-tuple that includes a goal g_{ik}, a plan p_{ik} for achieving g_{ik}, an intention int_{ikl} of p_{ik}, the set $A_i=Ag-\{ag_i\}$ of agents negotiating with ag_i, and the set of intentions $I_{A_i}=I_{Ag}-\{int_{ikl}\}$. The problem NP_{ik} has a *structure* $NPstruct_{ik}$ consisting of a hierarchical And-Or tree. The nodes of the And-Or tree are plan templates. The header of the root node describes the *negotiation goal* g_{ik}. The structure $NPstruct_{ik}$ defines all the solutions of NP_{ik} currently known by ag_i. A *solution* is a plan that can achieve the negotiation goal g_{ik}.

Issue Identification and Prioritization. The negotiation issues of ag_i are obtained from the leaves of $NPstruct_{ik}$. Let $L_{ik}=[pt_{ika},\ldots]$ be the collection of plan templates constituting the leaves of $NPstruct_{ik}$. The header of every plan template $pt_{ikj} \in L_{ik}$ is called a *fact* and denoted by f_{ikj}. Formally, a *fact* f_{ikj} is as 3-tuple that includes a *negotiation issue* is_{ikj} and a value $v[is_{ikj}]$ of is_{ikj}. Let $F_{ik}=\{f_{ika}, \ldots, f_{ikz}\}$ be the set of facts of $NPstruct_{ik}$. The *negotiating agenda* of ag_i is the set of issues $I_{ik}=\{is_{ika}, \ldots, is_{ikz}\}$ associated with the facts in F_{ik}. The interval of legal values for each issue $is_{ikj} \in I_{ik}$ is represented by $D_{ikj}=[min_{ikj},max_{ikj}]$. The *priority* of is_{ikj} is a number that represents its order of preference. The *weight* of is_{ikj} is a number that represents its relative importance. The sets of priorities and normalized weights of the issues in I_{ik} are represented by $PR_{ik}=\{pr_{ika},\ldots,pr_{ikz}\}$ and $W_{ik}=\{w_{ika},\ldots,w_{ikz}\}$, respectively.

Limits and Aspirations Formulation. The *limit* or *reservation value* is the value beyond which a bargainer is unwilling to concede. The *aspiration* is the value sought at any particular time. The limit for each issue is_{ikj} in I_{ik} is represented by lim_{ikj} and the initial aspiration by asp_{ikj}^{t1}.

Negotiation Constraints Definition. Negotiation constraints bound the possible values for the issues in I_{ik}. *Hard constraints* are linear constraints that specify threshold values for the issues. *Soft constraints* are linear constraints that specify minimum acceptable values for the issues.

Negotiation Strategy Selection. The agent ag_i has a library $SL_i=\{str_{i1},\ldots\}$ of negotiation strategies and a library $TL_i=\{tact_{i1},\ldots\}$ of negotiation tactics. The selection of a strategy is an important task and must be carefully planned (Pruitt and Kim 2004). In this paper, we just assume that ag_i selects a strategy $str_{ik} \in SL_i$ that it considers appropriate according to its experience.

The Multilateral Negotiation Protocol

The protocol specifies the set of possible tasks that the agents in Ag can perform during the negotiation process. A *global* description of this process follows.

The negotiation process starts with an agent, say ag_i, communicating a negotiation proposal $prop_{ikm}^{t1}$ to all the agents in A_i. A *negotiation proposal* is a set of facts (see next subsection). Each agent $ag_j \in A_i$ receives $prop_{ikm}^{t1}$ and may decide either: (i) to accept $prop_{ikm}^{t1}$, (ii) to reject $prop_{ikm}^{t1}$ without making a critique, or (iii) to reject $prop_{ikm}^{t1}$ and making a critique. A *critique* is a comment on which parts of a proposal are acceptable and unacceptable or a statement about relevant aspects of the negotiation process.

The process continues with ag_i receiving the responses of all the agents in A_i. Next, ag_i checks whether a negotiation agreement was reached. If the proposal $prop_{ikm}^{t1}$ was accepted by all the agents in A_i, the negotiation process ends successfully. In this case, ag_i just informs the agents in A_i that an agreement was reached. Otherwise, ag_i can act either: (i) by communicating a new proposal $prop_{ikn}^{t3}$, or (ii) by acknowledging the receipt of all the responses.

The process proceeds with the agents in A_i receiving the response of ag_i. If ag_i decides to communicate a new proposal $prop_{ikn}^{t3}$, each agent ag_j in A_i may again perform the tasks just specified. If ag_i decides to acknowledge the receipt of all the responses, the process proceeds to a new round in which another agent $ag_k \in Ag$ communicates a proposal to all the agents in $A_k=Ag-\{ag_k\}$. This is repeated for other agents in Ag.

The Negotiation Process: Individual Perspective

The individual model of the negotiation process defines the tasks that each agent $ag_i \in Ag$ can perform during the negotiation process. A brief description of these tasks follows (for simplicity, we omit the time).

Negotiation Proposal Generation. This process generates the set of initial proposals NPS_{ik} satisfying the requirements imposed by $NPstruct_{ik}$. The generation of NPS_{ik} is performed through an iterative procedure involving: (i) problem interpretation, (ii) proposal preparation, and (iii) proposal addition. Problem interpretation consists of searching $NPstruct_{ik}$ for any solution sol_{ikm} of NP_{ik} and selecting the primitive plan templates $PPT_{ikm}=\{pt_{ika},\ldots,pt_{ikp}\}$ of sol_{ikm}. Proposal preparation consists of determining a *negotiation proposal* $prop_{ikm}=\{f_{ika},\ldots,f_{ikp}\}$, *i.e.*, a set of facts corresponding to the headers of the plans in PPT_{ikm}. Proposal addition consists of adding $prop_{ikm}$ to NPS_{ik}.

Feasible and Acceptable Proposal Preparation. This process generates the set of feasible proposals FPS_{ik}, $FPS_{ik} \subseteq NPS_{ik}$, and the set of acceptable proposals APS_{ik}, $APS_{ik} \subseteq FPS_{ik}$. Let $Iprop_{ikm} = \{is_{ika},\ldots,is_{ikp}\}$ be the issues associated with the facts in $prop_{ikm} = \{f_{ika},\ldots,f_{ikp}\}$. Also, let $HCprop_{ikm} = \{hc_{ika},\ldots,hc_{ikp}\}$ and $SCprop_{ikm} = \{sc_{ika}, \ldots, sc_{ikp}\}$ be the sets of hard and soft constraints for the issues in $Iprop_{ikm}$, respectively. A negotiation proposal $prop_{ikm}$ is *feasible* if the issues in $Iprop_{ikm}$ satisfy the set $HCprop_{ikm}$ of hard constraints. A feasible proposal $prop_{ikm}$ is *acceptable* if the issues in $Iprop_{ikm}$ satisfy the set $SCprop_{ikm}$ of soft constraints.

Feasible Proposal Evaluation. This process computes a score for each proposal in FPS_{ik}. In this paper, we consider that the score of $prop_{ikm}$ is given by an *additive scoring function* (Raiffa 1982).

Feasible Proposal Selection. This process selects a feasible proposal $prop_{ikm} \in FPS_{ik}$. The strategy str_{ik} of ag_i defines a tactic $tact_{ik} \in TL_i$ to use. The tactic $tact_{ik}$ specifies a particular proposal $prop_{ikm}$ (see the next two subsections).

Feasible Proposal Modification. This process computes a new proposal from a rejected proposal $prop_{ikm}$. The strategy str_{ik} defines one or more tactics to use. The tactics modify $prop_{ikm}$ to make it more acceptable. The modification can be done either: (i) by making a concession, or (ii) without making a concession (see again the next two subsections).

Negotiation Strategies

Negotiation strategies are functions that define the tactics to be used at the beginning and during the course of negotiation. This subsection describes two classes of strategies, called concession and problem solving (or integrative) strategies.

Concession strategies. These strategies are functions that model well-known concession patterns (Lewicki et al 2003; Carnevale and Pruitt 1992). In this paper, we consider the following three sub-classes of strategies:

1. *starting high and conceding slowly* – model an optimistic opening attitude and successive small concessions;
2. *starting reasonable and conceding moderately* – model a realistic opening attitude and successive moderate concessions;
3. *starting low and conceding rapidly* – model a pessimistic opening attitude and successive large concessions.

The "starting high and conceding slowly" strategies are formalized by similar functions. For instance, a strategy *shslw*_01 is formalized by the following function:

$shslw\_01(TL_i) = (class, tact_{ik}) \mid$
if: $state$ = "*initial*" then:
$class$ = "*opening_negotiation*" $\wedge$
$tact_{ik}$ = "*starting_optimistic*"
else:
$class$ = "*constant_concession_factor*" $\wedge$
$tact_{ik}$ = "*tough*"

where *state* is the current state of the negotiation, *class* denotes the class of the tactic $tact_{ik}$ specified by the strategy, and *starting_optimistic* and *tough* are tactics (see next subsection). The strategies in the other two-subclasses are formalized by similar functions.

Problem solving or integrative strategies. These strategies are functions that model negotiation procedures leading to integrative agreements. *Integrative or win-win agreements* are agreements that provide high joint benefit (Pruitt and Kim, 2004; Lewicki et al 2003). In this paper, we consider the following two sub-classes of strategies:

1. *low priority concession making* – model small concessions on issues of high priority and large concessions on issues of low priority;
2. *modified logrolling* – model large concessions both on issues of low priority for ag_i and on issues of high priority for the other agents;

The strategies in these sub-classes partition a set of issues, say $Iprop_{ikm}$, into: (i) subset $Iprop^{+}_{ikm}$, corresponding to higher priority issues, (ii) subset $Iprop^{-}_{ikm}$, corresponding to lower priority issues, and (iii) subset $Iprop^{\pm}_{ikm}$, corresponding to remaining issues.

The "low priority concession making" strategies are similar. For instance, a strategy *srmlp*_01 that specifies a realistic opening attitude, small concessions on issues of high priority, large concessions on issues of low priority, and moderate concessions on the remaining issues, is formalized by the following function:

$srmlp\_01(Iprop_{ikm}, PR_{ik}, TL_i) = (class, tact_{ik}, Iprop^{+}_{ikm}, tact_{ik+1}, Iprop^{\pm}_{ikm}, tact_{ik+2}, Iprop^{-}_{ikm}) \mid$
if: $state$ = "*initial*" then:
$class$ = "*opening_negotiation*" $\wedge$
$tact_{ik}$ = "*starting_realistic*" $\wedge tact_{ik+1} = tact_{ik+2}$ = "*nil*"
else:
$class$ = "*constant_concession_factor*" $\wedge$
$Iprop_{ikm} = Iprop^{+}_{ikm} + Iprop^{\pm}_{ikm} + Iprop^{-}_{ikm}$ $\wedge$
$\forall is_{ikj} \in Iprop^{+}_{ikm}, tact_{ik}$ = "*tough*" $\wedge$
$\forall is_{ikj} \in Iprop^{\pm}_{ikm}, tact_{ik+1}$ = "*moderate*" $\wedge$
$\forall is_{ikj} \in Iprop^{-}_{ikm}, tact_{ik+2}$ = "*soft*"

where $tact_{ik}$, $tact_{ik+1}$ and $tact_{ik+2}$ denote the tactics specified by the strategy, and *starting_realistic*, *moderate* and *soft* are tactics (see subsection "Negotiation Tactics").

The "modified_logrolling" strategies are also similar. Lopes et al. (2004) present a formal description of a strategy *srsml*_01 that specifies an optimistic opening attitude, small concessions on issues of high priority, large concessions on issues of low priority, large concession on issues of moderate priority for ag_i (and high priority for the other agents), and small concessions on the remaining issues of moderate priority.

Negotiation Tactics

Negotiation tactics are functions that define the moves to be made at each point of the negotiation process.

Opening negotiation tactics. These tactics are functions that specify a proposal to submit at the beginning of negotiation. Let $FPS_{ik}=\{prop_{ik1},\ldots,prop_{ikw}\}$ and $APS_{ik}=\{prop_{ik1},\ldots,prop_{ikh}\}$ be the ordered sets of feasible and acceptable proposals of ag_i, respectively. Let $NAPS_{ik}=FPS_{ik}-APS_{ik}$. In this paper, we consider three tactics (for simplicity, we omit the time):

1. *starting optimistic* – specifies the proposal $prop_{ik1}$ with the highest score $Vprop_{ik1}$;
2. *starting realistic* – specifies either: (i) proposal $prop_{ikh}\in APS_{ik}$ with the lowest score, or (ii) proposal $prop_{ikh+1}\in NAPS_{ik}$ with the highest score;
3. *starting pessimistic* – specifies the proposal $prop_{ikw}$ with the lowest score $Vprop_{ikw}$.

Concession tactics. These tactics are functions that compute new values for each issue during the negotiation process. Let $is_{ikl}\in I_{ik}$ be an issue at stake in negotiation. In this paper, we consider a *constant concession factor* sub-class of tactics. In this sub-class, we consider five tactics:

1. *stalemate* – models a *null* concession on is_{ikl};
2. *tough* – models a *small* concession on is_{ikl};
3. *moderate* – models a *moderate* concession on is_{ikl};
4. *soft* – models a *large* concession on is_{ikl};
5. *compromise* – models a *total* concession on is_{ikl}.

EXPERIMENTAL ANALYSIS

This section describes an experiment aiming at: (i) assessing the feasibility of building autonomous agents equipped with a version of the negotiation model that handles two-party, multi-issue negotiation, and (ii) evaluating the integrative strategies and their associated tactics by confirming a number of basic conclusions about human negotiation.

Empirical Research on Human Negotiation

Negotiation is a rich research area. Most studies are laboratory experiments on bilateral negotiation about two or more issues of different priority (integrative negotiation). Experimental evidence supports the following two conclusions (Lewicki et al 2003; Carnevale and Pruitt 1992):

1. systematic trial and error, in which one or both parties frequently make new proposals, or concede systematically (*i.e.*, explore various options at each profit level before proceeding to a lower level), or make large concessions on low priority issues, promotes the development of integrative agreements;
2. information exchange, in which one or both parties provide information about their priorities or the interests underlying their positions, promotes the development of integrative agreements.

The Experimental System

The experimental system consists of two autonomous agents and an environment. Let $Ag=\{ag_s, ag_b\}$ be the set of agents. The agent ag_s plays the role of a seller and the agent ag_b the role of a buyer. The agents negotiate the price, down payment, financing terms and delivery date of a commodity denoted by $prod_X$. A description of the agents and the environment follows.

Autonomous negotiating agents. Every agent $ag_i\in Ag$ is equipped with the model of individual behavior described in section "Autonomous Agents". We consider the following (for simplicity, we drop the subscripts *k* and *j*):

- the set G_i of every agent $ag_i\in Ag$ contains the goal g_i of selling (or buying) $prod_X$;
- the library PL_i contains thirteen plan templates;
- the intention structure IS_i contains the plan p_i for achieving the goal g_i;
- the library CL_i contains one axiom.

Every agent ag_i is also equipped with a simplified version of the negotiation model described in the section "The Negotiation Model". The process of preparing and planning for negotiation involves the tasks just specified, except the task "negotiation strategy selection"'. This task is performed directly by the experimenter. The protocol is a bilateral negotiation protocol. The negotiation process also involves the five tasks just specified. We consider the following:

- the first agent to submit a proposal is decided by coin-tossing;
- the acceptability of a proposal is determined by a *negotiation threshold* – $ag_j\in Ag$ accepts a proposal $prop_i^{tn}$, submitted by ag_i at an instant t_n, when the difference between the benefit provided by the proposal $prop_j^{tn+1}$ that ag_j is ready to send at t_{n+1} is lower than or equal to the negotiation threshold of ag_j;
- the agents are allowed to exchange only a maximum number of proposals max_{prop} – failure to reach agreement after max_{prop} proposals results in a deadlock.

The strategies and tactics are shown in Fig. 1. The first part of the figure presents the three strategies used by both the seller and the buyer. The last part of the figure shows the five strategies used only by the buyer.

The Environment. The environment contains information about prior negotiations and market characteristics. This information is grouped into four parameters: $bfpr_X$ (base fair market value for price), $bfdp_X$ (base fair market value for down payment), $bfft_X$ (base fair market value for financing terms), and $bfdd_X$ (base fair market value for delivery date). We consider the following: (i) the base fair market values are used to compute perceived market values, and (ii) the values to offer in the opening proposal are computed from the perceived market values.

Agent	Strategy Class	Strategy Key	Opening Negotiation Tactic	Concession Tactics
Seller and Buyer	Starting reasonable and conceding moderately	SRMDT	Starting realistic	Moderate
	Low priority concession making	SRMLP	Starting realistic	Tough; Moderate; Soft
	Modified logrolling	SRMML	Starting realistic	Moderate; Soft
Buyer (only)	Starting reasonable and conceding slowly	SRSLW	Starting realistic	Tough
	Starting reasonable and conceding rapidly	SRRPD	Starting realistic	Soft
	Low priority concession making	SRSLP	Starting realistic	Tough; Soft
	Low priority concession making	SRRLP	Starting realistic	Tough; Soft
	Modified logrolling	SRSML	Starting realistic	Tough; Soft

Figure 1. Negotiation strategies and tactics.

Experimental Hypotheses

The first two hypotheses are based on the conclusions just presented. The last hypothesis is related to the process of negotiation. The hypotheses are stated as follows:

Hypothesis 1: The strategy SRMLP leads, on average, to agreements than provide higher joint benefit than the strategy SRMDT;

Hypothesis 2: The strategy SRMML leads, on average, to agreements than provide higher joint benefit than the strategy SRMDT;

Hypothesis 3: The strategy SRMLP leads, on average, to slower agreements than the strategy SRMDT.

The Experimental Method

The experimental method is controlled experimentation. A description of the experimental parameters, the independent variable, the dependent variables, and the experimental procedure follows.

Experimental Parameters. The base fair market values for price, down payment, financing terms and delivery date are set to 500, 125, 180 and 90, respectively. The perceived market values are generated by randomly choosing a value within 10% of the bases. The values to offer in the opening proposal are computed from the perceived market values. The negotiation threshold is set to 0.0 and the maximum number of proposals to 10.

The Independent Variable. The independent variable is the strategy of the seller. This variable has three levels, namely the three first strategies presented in Fig. 1.

The Dependent Variables. The first dependent variable is the joint benefit provided by the final agreement, *i.e.*, the sum of the two agents' benefits in the final agreement. Consider that the agents agree on a proposal *prop* (specifying price *pr*, down payment *pa*, financing terms *fn* and delivery date *dt*). The benefit of each agent ag_i for price *pr* is given by the following function:

$$Vpr_i = \left| \frac{pr - lim_i}{lim_i - lim_j} \right|$$

where lim_i and lim_j are the limits of ag_i and ag_j for price, respectively. The benefits for *pa*, *fn* and *dt* are given by similar functions. The benefit for *prop* is given by an additive scoring function (Raiffa 1982).

The second dependent variable is the time spent in negotiation. This variable is measured in terms of the total number of offers exchanged by the agents until either they found an agreement or reach a deadlock. If no deal is made in a particular negotiation, then this variable is set to max_{prop}.

The Experimental Procedure. The experiment involves three groups of trials. For each group of trials, the experimenter manipulates the independent variable, *i.e.*, assigns a strategy to the seller agent. For each trial in each group, the experimenter: (i) randomly determines the agent that starts the bidding process, and (ii) randomly determines a strategy for the buyer agent. The experimenter then allows the agents to negotiate using the strategies and measures the dependent variables.

Experimental Results

The experiment was conducted on a personal computer using Visual C^{++}. For each of the 3 groups, we conducted 30 trials. A pretest was performed to establish how many trials were needed to obtain significant averages on the measures taken. The results are shown in Fig. 2.

The main response measure was the sum of the two negotiator's benefits in the final agreement. It was predicted that the strategies SRMLP and SRMML

Group	Seller's Strategy	Seller's Benefit (mean)	Buyer's Benefit (mean)	Joint Benefit (mean)	Number of Proposals (mean)
$group_1$	*SRMDT*	0.536	0.462	$0.999^{*,\dagger}$	7.366^{**}
$group_2$	*SRMLP*	0.615	0.449	1.064^{*}	8.200^{**}
$group_3$	*SRMML*	0.511	0.561	$1.073^{\dagger}$	6.533

*(F=1996.07, p<0.01); †(F=1844.40, p<0.01); **(F=5.71, p<0.025)

Figure 2. Experimental results.

yielded superior outcomes. The experimental results indicate that the strategy SRMLP resulted in significantly higher joint benefits when compared to the joint benefits resulting from the strategy SRMDT (F=1996.07, p<0.01). The same is true for the strategies SRMML and SRMDT (F=1844.40, p<0.01). Hypothesis 1 and hypothesis 2 are supported.

The number of proposals exchanged by the agents was also recorded. The prediction was that the strategy SRMLP produced slower agreements. The results indicate that this prediction was confirmed. The strategy SRMLP resulted in significantly more proposals than the strategy SRMDT (F=5.71, p<0.025). Hypothesis 3 is also supported.

RELATED WORK

The design of autonomous agents with negotiation competence has been investigated from both a theoretical and a practical perspective.

Researchers following the theoretical perspective attempt mainly to develop formal models. Some researchers define the modalities of the mental state of the agents, develop a logical model of individual behavior, and then use the model as a basis for the development of a formal model of negotiation or argumentation (e.g. Kraus et al. 1998). However, most researchers are neutral with respect to the modalities of the mental state and just develop formal models of negotiation. These models are often based on game-theoretic techniques (e.g. Fatima et al. 2004; Kraus 2001). Generally speaking, most theoretical models are rich but restrictive. They make assumptions that severely limit their applicability to solve real problems.

Researchers following the practical perspective attempt mainly to develop computational models, *i.e.*, models defining the key data structures of the agents and the processes operating on these structures. Some researchers start with a model of individual behavior, develop or adopt a negotiation model, and then integrate both models (e.g., Muller 1996). Again, most researchers prefer to be neutral about the model of individual behavior and just develop negotiation models (e.g., Faratin et al. 2002). Broadly speaking, most computational models are rich but based on ad hoc principles. They lack a rigorous theoretical grounding. Despite these weaknesses, some researchers, including the authors, believe that it is necessary to develop computational models in order to successfully use agents in real-world applications. Accordingly, this paper presented a computational model of negotiation.

As noted, most researchers have paid little attention to the problem of integrating models of individual behavior with negotiation models. However, it is one of the costliest lessons of computer science that independently developed components resist subsequent integration in a smoothly functioning whole. Components need to be designed for integration right from the start. Accordingly, this paper presented the key features of a model that accounts for a tight integration of the individual capability of planning and the social capability of negotiation.

CONCLUSION

This paper presented the key features of a negotiation model for autonomous agents. The model handles multi-party and multi-issue negotiation, acknowledges the role of conflict as a driving force of negotiation, formalizes a set of human negotiation procedures from management and social psychology and combines them with AI techniques, and accounts for a tight integration of individual and social behavior.

This paper also described an experiment performed to empirically evaluate a version of the model that handles two-party, multi-issue negotiation. The experimental results showed that: (i) the "low priority concession making" and "modified logrolling" strategies lead, on average, to superior outcomes, and (ii) the "low priority concession making" strategies lead, on average, to slower agreements. The results confirmed two conclusions about human negotiation. Our aim for the future is: (i) to extend the negotiation model, and (ii) to continue the experimental validation of the model.

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