Negotiation Strategies for Autonomous Computational Agents

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Abstract. Autonomous agents operate in complex environments and, over time, conflicts inevitably occur among them. Negotiation is the predominant process for resolving conflicts. This paper presents a generic negotiation model for autonomous agents that handles multi-party, multi-issue and repeated rounds. The model is based on computationally tractable assumptions, accounts for a tight integration of the individual capability of planning and the social capability of negotiation, and formalizes a set of human negotiation procedures.

1 INTRODUCTION

Autonomous agents are being used in an increasing number of applications. The agents operate in complex environments and, over time, conflicts inevitably occur among them. The predominant process for resolving conflicts is negotiation. Recent growing interest in electronic commerce has also given increased importance to negotiation.

This paper presents a generic negotiation model for autonomous agents that handles multi-party, multi-issue, and single or 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 is based on computationally tractable assumptions, accounts for a tight integration of the individual capability of planning and the social capability of negotiation, and formalizes a set of human negotiation procedures.

This paper builds on our theoretical and experimental work in the area of negotiation [7]. In particular, this paper extends our negotiation model by both continuing the description of the individual model of the negotiation process and introducing a number of negotiation strategies and tactics. The new strategies and tactics are motivated by human procedures typical of integrative negotiation [6, 9, 10]. This paper also lays the foundation for extending our experimental work, namely for performing a new experiment aiming at validating a version of the model that handles two-party, multi-issue negotiation (integrative negotiation).

The remainder of the paper is structured as follows. Section 2 presents a generic model of individual behavior for autonomous agents. The model forms a basis for the development of negotiating agents. Section 3 presents a generic model of negotiation for autonomous agents. Section 4 situates the present work within the related literature. Finally, section 5 concludes and outlines future avenues of research.

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2 AUTONOMOUS AGENTS

Let $Agents$ be a set of autonomous agents. This section briefly describes the key features of every agent $ag_i \in Agents$.

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 of constraints, and a list of statements. The header is a 2-tuple: $header_{ij} = <pname_{ij}, pvars_{ij}>$, where $pname_{ij}$ is the name of pt_{ij} and $pvars_{ij}$ is a set of variables. 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 $g_{ik} \in G_i$ is a 3-tuple: $p_{ik} = < PT_{ik}, \preceq_h, \preceq_t >$, where $PT_{ik} \subseteq PL_i$ is a list of plan templates, $\preceq_h$ is a binary relation establishing a hierarchy on PT_{ik}, and $\preceq_t$ is another binary relation establishing a temporal order on PT_{ik}. The plan p_{ik} is represented by a hierarchical And-tree denoted by $Pstruct_{ik}$. Plan generation is an iterative procedure of: (i) plan retrieval, (ii) plan selection, (iii) plan addition, and (iv) plan interpretation.

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 often has information about other agents in $Agents$. This information is stored in the *social description* $SD_i = \{SD_i(ag_1), \ldots\}$. Each entry $SD_i(ag_j) = <B_i(ag_j), G_i(ag_j), I_i(ag_j)>$, contains the beliefs, goals and intentions that ag_i believes ag_j has.

3 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 $Conf_{Ag}$ be a conflict of interests among the agents in Ag. This section presents a domain-independent description of a computational model of negotiation.

3.1 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.

Negotiation problem structure generation. A negotiation problem NP_{ik} from the perspective of ag_i is a 6-tuple: $NP_{ik} = < ag_i, g_{ik}, p_{ik}, int_{ikl}, A_i, I_{Ai} >$, where $g_{ik} \in G_i$ is a goal, $p_{ik} \in P_{Ag}$ is a plan of ag_i for achieving g_{ik}, $int_{ikl} \in I_{Ag}$ is an intention of p_{ik}, $A_i = Ag - \{ag_i\}$ and $I_{Ai} = I_{Ag} - \{int_{ikl}\}$. The problem NP_{ik} has a *structure* $NPstruct_{ik}$ consisting of a hierarchical And-Or tree. Formally, $NPstruct_{ik}$ is a 4-tuple: $NPstruct_{ik} = <NPT_{ik}, \preceq_h^+, \preceq_t^+, \preceq_a>$, where $NPT_{ik} \subseteq PL_i$ is a list of plan templates, $\preceq_h^+$ and $\preceq_t^+$ are relations similar to $\preceq_h$ and $\preceq_t$, and $\preceq_a$ is a binary relation establishing alternatives among the plan templates in NPT_{ik}. The nodes of the And-Or tree are plan templates. The header of the root node describes the *negotiation goal* g_{ik}.

The structure $NPstruct_{ik}$ is generated from plan p_{ik} by an iterative procedure involving: (i) plan interpretation, (ii) plan retrieval, (iii) plan selection, and (iv) plan addition. $NPstruct_{ik}$ defines all the solutions of NP_{ik} currently known by ag_i. A *solution* is a plan that can achieve 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 a 3-tuple: $f_{ikj} = <is_{ikj}, v[is_{ikj}], r_{ikj}>$, where is_{ikj} is a *negotiation issue* (corresponding to $pname_{ikj}$), $v[is_{ikj}]$ is a value of is_{ikj} (corresponding to an element of $pvars_{ikj}$), and r_{ikj} is a list of arguments (corresponding to the remaining elements of $pvars_{ikj}$). 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 $D_{ikj} = [min_{ikj}, max_{ikj}]$.

For each issue $is_{ikj} \in I_{ik}$, let pr_{ikj} be its *priority* and w_{ikj} its *importance weight*. Let $PR_{ik} = \{pr_{ika}, \ldots, pr_{ikz}\}$ and $W_{ik} = \{w_{ika}, \ldots, w_{ikz}\}$ be the sets of priorities and normalized importance weights of the issues in I_{ik}, respectively.

Limits and aspirations formulation. Limits and aspirations are formulated for each issue at stake in negotiation. The *limit* for issue $is_{ikj} \in I_{ik}$ is represented by lim_{ikj} and the initial *aspiration* by asp_{ikj}^{t1}, with $lim_{ikj} \in D_{ikj}$ and $asp_{ikj}^{t1} \in D_{ikj}$.

Negotiation constraints definition. Constraints are defined for each issue $is_{ikj} \in I_{ik}$. Without loss of generality, consider that ag_i wants to maximize is_{ikj}. *Hard constraints* are linear constraints that specify threshold values for the issues. They cannot be relaxed. The hard constraint hc_{ikj} for is_{ikj} has the form: $hc_{ikj} = (is_{ikj} \geq lim_{ikj}, flex = 0)$, where $flex = 0$ represents null flexibility (inflexibility). *Soft constraints* are linear constraints that specify minimum acceptable values for the issues. They can be relaxed. The soft constraint sc_{ikj} for is_{ikj} has the form: $sc_{ikj} = (is_{ikj} \geq asp_{ikj}^{t1}, flex = n)$, where $flex = n$, $n \in N$, represents the degree of flexibility of sc_{ikj}.

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. *Negotiation strategies* are functions that define the tactics to be used at the beginning and during the course of negotiation (see subsection 3.4). *Negotiation tactics* are functions that define the moves to be made at each point of the negotiation process (see subsection 3.5). Strategy selection is an important task and must be carefully planned [6, 9]. In this paper, we just assume that ag_i selects a strategy $str_{ik} \in SL_i$ that he considers appropriate according to his experience.

3.2 The multilateral negotiation protocol

The protocol defines the set of possible tasks that each agent $ag_i \in Ag$ can perform at each point of the negotiation process. A negotiation strategy specifies a particular task to perform from the set of possible tasks. A *global* description of the negotiation process follows.

The 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* $prop_{ikm}^{t1}$ is a set of facts (see subsection 3.3). 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, for instance, a statement about issue priorities.

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 and the agreement $prop_{ikm}^{t1}$ is implemented. 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 decide: (i) to accept $prop_{ikn}^{t3}$, or (ii) to reject $prop_{ikn}^{t3}$ without making a critique, or (iii) to reject $prop_{ikn}^{t3}$ and making a critique. 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.

3.3 The negotiation process: individual perspective

The individual model of the negotiation process specifies the tasks that each agent must perform. These tasks (or processes) are shown in Figure 1 for the specific case of an agent $ag_i \in Ag$ that communicates a negotiation proposal. A description of the main processes follows (for clarity, we omit the representation of time).

Negotiation proposal generation. This process generates the set of negotiation proposals NPS_{ik} satisfying the requirements imposed by the structure $NPstruct_{ik}$. 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 possible 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 primitive plan templates in PPT_{ikm}. Proposal addition consists of adding the negotiation proposal $prop_{ikm}$ to the set NPS_{ik}.

The preparation of a proposal $prop_{ikm}$ partitions the set F_{ik} of facts into: (i) subset $prop_{ikm}$, and (ii) subset $comp_{ikm} = \{f_{ikp+1}, \ldots, f_{ikz}\}$, called *proposal complement* of $prop_{ikm}$, and corresponding to the remaining facts of F_{ik}. The facts in $prop_{ikm}$ are fundamental for achieving the negotiation goal g_{ik}. They are the *inflexible facts* of negotiation, for $prop_{ikm}$. The negotiation issues $Iprop_{ikm} = \{is_{ika}, \ldots, is_{ikp}\}$ associated with these facts are the *inflexible issues*. On the other hand, the facts in $comp_{ikm}$ are not important for achieving g_{ik}. They are the *flexible facts* of negotiation, for $prop_{ikm}$. The issues $Icomp_{ikm} = \{is_{ikp+1}, \ldots, is_{ikz}\}$ associated with these facts are the *flexible issues*.

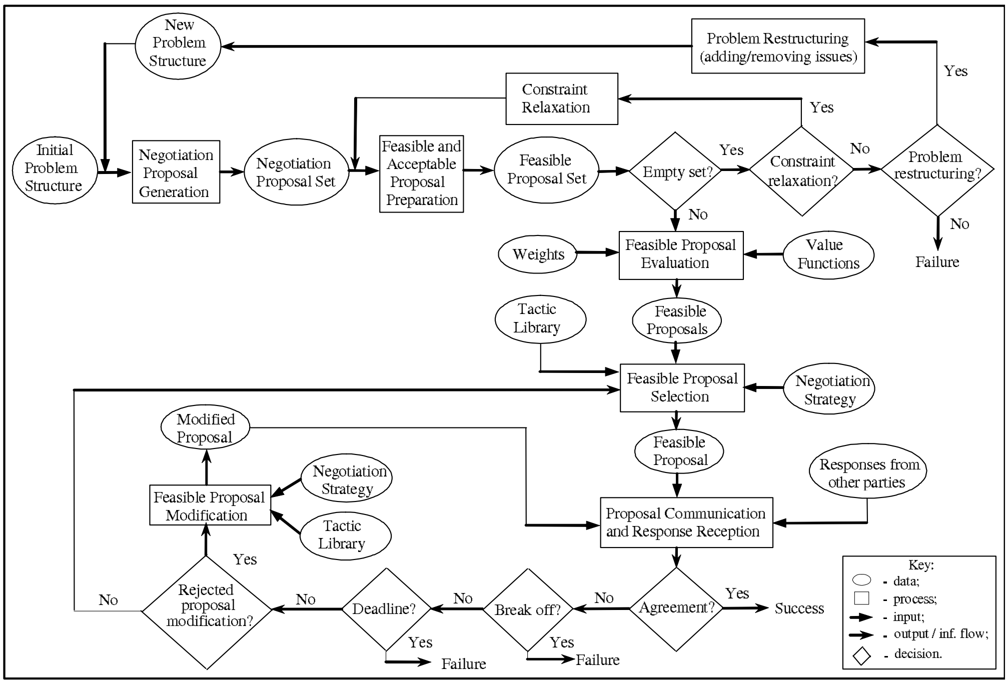

Figure 1. The negotiation process (perspective of every agent that communicates a proposal).

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 $HCprop_{ikm} = \{hc_{ika}, \ldots, hc_{ikp}\}$ and $SCprop_{ikm} = \{sc_{ika}, \ldots, sc_{ikp}\}$ be the sets of hard and soft constraints for issues in $Iprop_{ikm}$, respectively. A negotiation proposal $prop_{ikm} \in NPS_{ik}$ 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} using an *additive scoring function* [10] and orders the proposals in descending order of preference. Let $C_{ikm} = (v[is_{ika}], \ldots, v[is_{ikp}])$ be the values of the issues in $Iprop_{ikm}$ (C_{ikm} is called a *contract*). For each issue $is_{ikl} \in Iprop_{ikm}$ defined over the interval $D_{ikl} = [min_{ikl}, max_{ikl}]$, let V_{ikl} be a *component scoring function* that gives the score that ag_i assigns to a value $v[is_{ikl}] \in D_{ikl}$ of is_{ikl}. The score for contract C_{ikm} is given by a function V:

$$V(C_{ikm}) = \sum_{j=a}^{p} w_{ikj} \times V_{ikj}(v[is_{ikj}])$$

The proposal $prop_{ikm}$ is identified with contract C_{ikm} and both have the same score.

Feasible proposal selection. This process selects a feasible proposal $prop_{ikm} \in FPS_{ik}$. The negotiation strategy str_{ik} of ag_i dictates a tactic $tact_{ik} \in TL_i$ to use (see subsection 3.4). The tactic $tact_{ik}$ specifies a particular proposal $prop_{ikm}$ (see subsection 3.5).

Feasible proposal modification. This process computes a new proposal from a rejected proposal $prop_{ikm}$. The strategy str_{ik} defines one or more tactics. The tactics modify $prop_{ikm}$ to make it more acceptable (see subsections 3.4 and 3.5).

3.4 Negotiation strategies

This subsection describes two classes of strategies, called concession and problem solving strategies.

Concession strategies are functions that define the opening negotiation and concession tactics. These strategies model well-known concession patterns. In this paper, we consider the following three subclasses 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 analogous functions. For instance, a strategy $shcs\_01$ is formalized by a function which takes a set of issues, say $Iprop_{ikm}$, as input and specifies a tactic $tact_{ik}$ of a particular class denoted by $class$:

$$\begin{aligned} shcs\_01(Iprop_{ikm}) = (class, tact_{ik}) \ | \\ \text{if: } state = initial \text{ then:} \\ class = opening\_negotiation \wedge \\ tact_{ik} = starting\_optimistic \\ \text{else:} \\ class = constant\_concession\_factor \wedge \\ tact_{ik} = tough \end{aligned}$$

where $state$ is the current state of the negotiation, and $starting\_optimistic$ and $tough$ are tactics (see subsection 3.5). The strategies in the other two-subclasses are formalized by similar functions.

Problem solving strategies are functions that define the opening negotiation, concession and compensation tactics. These strategies often lead to integrative solutions, $i.e.$, solutions providing high joint benefit [6, 9]. In this paper, we consider the following three 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 high priority for other agents and on issues of low priority for ag_i;
3. *compensation* − model concession patterns similar to the previous ones until a specific point of the negotiation process; then, model a partial or total attitude of toughness and compensations to indemnify for the losses resulting from that attitude.

The strategies in these sub-classes partition a set of issues, say again $Iprop_{ikm}$, 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 $lpcm\_01$ that specifies an optimistic 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:

$$
\begin{aligned}
&lpcm\_01(Iprop_{ikm}, PR_{ik}) = (class, tact_{ik}, Iprop^{+}_{ikm},\\
&\qquad tact_{ik+1}, Iprop^{\pm}_{ikm}, tact_{ik+2}, Iprop^{-}_{ikm}) \ \mid\\
&\text{if: } state = initial \text{ then:}\\
&\quad class = opening\_negotiation \wedge\\
&\quad tact_{ik} = starting\_optimistic \wedge tact_{ik+j} = nil,\ 1 \leq j \leq 2\\
&\text{else: } class = constant\_concession\_factor \wedge\\
&\quad Iprop_{ikm} = Iprop^{+}_{ikm} + Iprop^{\pm}_{ikm} + Iprop^{-}_{ikm} \wedge\\
&\quad \forall is_{ikj} \in Iprop^{+}_{ikm}, tact_{ik} = tough \wedge\\
&\quad \forall is_{ikj} \in Iprop^{\pm}_{ikm}, tact_{ik+1} = moderate \wedge\\
&\quad \forall is_{ikj} \in Iprop^{-}_{ikm}, tact_{ik+2} = soft
\end{aligned}
$$

where $tact_{ik}$, $tact_{ik+1}$ and $tact_{ik+2}$ are the tactics specified by the strategy, and $moderate$ and $soft$ are tactics (see subsection 3.5).

The logrolling strategies are also similar. For instance, a strategy $mlgr\_01$ that specifies a realistic 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 other agents, and small concessions on the remaining issues of moderate priority, is formalized by the following function:

$$
\begin{aligned}
&mlgr\_01(Iprop_{ikm}, PR_{ik}, PR) = (class, tact_{ik}, Iprop^{+}_{ikm},\\
&\quad tact_{ik+1}, Iprop^{\oplus}_{ikm}, tact_{ik+2}, Iprop^{\ominus}_{ikm}, tact_{ik+3}, Iprop^{-}_{ikm}) \ \mid\\
&\text{if: } state = initial \text{ then:}\\
&\quad class = opening\_negotiation \wedge\\
&\quad tact_{ik} = starting\_realistic \wedge tact_{ik+j} = nil,\ 1 \leq j \leq 3\\
&\text{else: } class = constant\_concession\_factor \wedge\\
&\quad Iprop_{ikm} = Iprop^{+}_{ikm} + Iprop^{\oplus}_{ikm} + Iprop^{\ominus}_{ikm} + Iprop^{-}_{ikm} \wedge\\
&\qquad \forall is_{ikj} \in Iprop^{+}_{ikm}, tact_{ik} = tough \wedge\\
&\qquad \forall is_{ikj} \in Iprop^{\oplus}_{ikm}, tact_{ik+1} = soft \wedge\\
&\qquad \forall is_{ikj} \in Iprop^{\ominus}_{ikm}, tact_{ik+2} = tough \wedge\\
&\qquad \forall is_{ikj} \in Iprop^{-}_{ikm}, tact_{ik+3} = soft
\end{aligned}
$$

where $Iprop^{\oplus}_{ikm}$ contains the issues of moderate priority for ag_i and high priority for other agents, $Iprop^{\ominus}_{ikm}$ contains the remaining issues of moderate priority for ag_i, PR contains the priorities that other agents assign to negotiation issues, and $starting\_realistic$ is a tactic (see subsection 3.5).

The compensation strategies are again similar. For instance, a strategy cmp_1 that specifies a realistic opening attitude, a concession pattern until a pre-defined score, and a general compensation, is formalized by the following function:

$$
\begin{aligned}
&cmp\_1(Iprop_{ikm}, comp_{ikm}, PR_{ik}) = (class, tact_{ik}, Iprop^{+}_{ikm},\\
&\quad tact_{ik+1}, Iprop^{\pm}_{ikm}, tact_{ik+2}, Iprop^{-}_{ikm}, tact_{ik+3}, comp_{ikm}) \ \mid\\
&\text{if: } state = initial \text{ then:}\\
&\quad class = opening\_negotiation \wedge\\
&\quad tact_{ik} = starting\_realistic \wedge tact_{ik+j} = nil,\ 1 \leq j \leq 3\\
&\text{else if: } Vprop_{ikm} \geq Vlim_{ik} \text{ then:}\\
&\qquad class = constant\_concession\_factor \wedge\\
&\qquad Iprop_{ikm} = Iprop^{+}_{ikm} + Iprop^{\pm}_{ikm} + Iprop^{-}_{ikm} \wedge\\
&\qquad \forall is_{ikj} \in Iprop^{+}_{ikm}, tact_{ik} = moderate \wedge\\
&\qquad \forall is_{ikj} \in Iprop^{\pm}_{ikm}, tact_{ik+1} = moderate \wedge\\
&\qquad \forall is_{ikj} \in Iprop^{-}_{ikm}, tact_{ik+2} = moderate \wedge\\
&\quad \text{else: } class = compensation \wedge tact_{ik+j} = nil,\ 0 \leq j \leq 2 \wedge\\
&\qquad \forall f_{ikj} \in comp_{ikm}, tact_{ik+3} = general\_compensation
\end{aligned}
$$

where $Vprop_{ikm}$ is the score for $prop_{ikm}$, $Vlim_{ik}$ is a pre-defined score, and $general\_compensation$ is a tactic (see subsection 3.5).

3.5 Negotiation tactics

This section describes three classes of tactics, called opening negotiation, concession and compensation tactics.

Opening negotiation tactics specify a proposal to submit at the beginning of negotiation. Let $NAPS_{ik} = FPS_{ik} - APS_{ik}$. In this paper, we consider three tactics (for clarity, we omit the time):

1. *starting optimistic* − specifies the proposal $prop_{ik1}$ with the highest score;
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 $prop_{ikn}$ with the lowest score.

The three tactics are formalized by similar functions. For instance, the tactic starting optimistic is formalized by the following function:

$$
\begin{aligned}
&starting\_optimistic(FPS_{ik}) = prop_{ik1} \ \mid\\
&\qquad \forall prop_{ikj} \in FPS_{ik}, Vprop_{ik1} \geq Vprop_{ikj}
\end{aligned}
$$

Concession tactics are functions that compute new values for each issue is_{ikj}. 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_{ikj};
2. *tough* − models a *small* concession on is_{ikj};
3. *moderate* − models a *moderate* concession on is_{ikj};
4. *soft* − models a *large* concession on is_{ikj};
5. *compromise* − models a *complete* concession on is_{ikj}.

Let $prop^{tn}_{ikn}$ be a proposal submitted by ag_i at an instant t_n and rejected. Let $v[is_{ikj}]^{tn}$ be the value of is_{ikj} offered in $prop^{tn}_{ikn}$. Let lim_{ikj} be the limit for is_{ikj}. Let $v[is_{ikj}]^{tn+2}$ be the new value of is_{ikj} to be offered in a new proposal. Let V_{ikj} be the component scoring function for is_{ikj}. The *constant concession factor tactics* are formalized by the following function:

$$const\_factor\_tact(v[is_{ikj}]^{tn}, lim_{ikj}, w, cte) = v[is_{ikj}]^{tn+2} \ \mid$$
$$v[is_{ikj}]^{tn+2} = v[is_{ikj}]^{tn} + (-1)^w \times$$
$$Fc \times \mid lim_{ikj} - v[is_{ikj}]^{tn} \mid \ \wedge \ Fc = cte$$

where $w = 0$ if V_{ikj} is monotonically decreasing or $w = 1$ if V_{ikj} is monotonically increasing, $Fc \in [0, 1]$ is the concession factor, and cte is a constant. The five tactics are defined as follows: the stalemate tactic by $Fc = 0$, the tough tactic by $Fc \in]0, 0.15]$, the moderate tactic by $Fc \in]0.15, 0.30]$, the soft tactic by $Fc \in]0.30, 0.45]$, and the compromise tactic by $Fc = 1$.

Compensation tactics are functions that allow ag_i to "improve" rejected proposals in order to indemnify other agents for the losses resulting from his demands. Successful negotiators often add to the negotiation agenda issues that they do not really care about, in the hope that the other parties will feel strong about these issues − strong enough to be willing to make concessions [10]. In this paper, we consider the following tactic (again, we omit the representation of time):

1. *general compensation or flexible fact manipulation* − allows ag_i to "improve" a rejected proposal $prop_{ikn}$ by adding a flexible fact $f_{ikx} \in comp_{ikn}$ to $prop_{ikn}$.

This tactic is formalized by the following function:

$$general\_compensation(prop_{ikn}, f_{ikx}) = prop_{ikn} \ \mid$$
$$prop_{ikn} = prop_{ikn} + \{f_{ikx}\}$$

4 RELATED WORK

The design of autonomous negotiating agents 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., [5]). 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-theoretical techniques (e.g., [4]). 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 specifying the key data structures of the agents and the processes operating on these structures. Some researchers start with a particular model of individual behavior, develop or adopt a negotiation model, and then integrate both models (e.g., [8]). Again, most researchers prefer to be neutral about the model of individual behavior and just develop negotiation models (e.g., [1]). 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 presents a computational negotiation model.

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 [2]. Accordingly, this paper presents a model that accounts for a tight integration of the individual capability of planning and the social capability of negotiation.

We are interested in negotiation among both competitive and cooperative agents. Our structure for representing negotiation problems is similar to decision trees and goal representation trees [3], but there are important differences. In particular, our approach is based on plan templates and plan expansion, and not on production rules and forward or backward chaining.

Our negotiation model defines and formalizes a number of negotiation strategies and tactics. Our formulae for modeling concession tactics are similar to the formulae used by other researchers [1]. However, our formulae assure that agents do not negotiate in bad faith and model typical concession magnitudes of human negotiation.

5 CONCLUSION

This article presented a computational negotiation model for autonomous agents. There are several features of our work that should be highlighted. First, the model is generic and can be used in a wide range of domains. Second, the structure of a negotiation problem allows the direct integration of planning and negotiation. Also, this structure defines the set of negotiation issues. Third, the model supports problem restructuring ensuring a high degree of flexibility. Problem restructuring allows the dynamic addition of negotiation issues. Finally, the negotiation strategies are motivated by human negotiation procedures. Our aim for the future is: (i) to extend the model, and (ii) to continue the experimental validation of the model, namely to perform an experiment aiming at validating a version of the model that handles two-party, multi-issue negotiation.

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