Negotiation Among Autonomous Computational Agents

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Abstract. Autonomous agents are being increasingly used in a wide range of applications. Most applications involve or require multiple agents operating in complex environments and, over time, conflicts inevitably occur among them. Negotiation is the predominant process for resolving conflicts. Recent 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 repeated rounds. The model is based on computationally tractable assumptions.

1 Introduction

Autonomous agents operate in complex environments and, over time, conflicts inevitably occur among them. Conflict resolution is crucial for achieving coordination. The predominant process for resolving conflicts is negotiation. Recent 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 repeated rounds. The 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.

This paper builds on our previous work [7, 8, 9, 10]. In these papers, we presented the prenegotiation model, introduced the individual model of the negotiation process, and defined a number of negotiation tactics. In this paper, we present a multilateral negotiation protocol, continue the description of the individual model and introduce a set of negotiation strategies.

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. Finally, related work and concluding remarks are presented in sections 4 and 5, respectively.

2 Autonomous Agents

Let *Agents* be a set of autonomous agents. This section briefly describes the features of every agent $ag_i \in Agents$ (see [7, 8] for an in-depth discussion).

The agent ag_i has a set $B_i=\{b_{i1},\ldots\}$ of beliefs and a set $G_i=\{g_{i1},\ldots\}$ of goals. Beliefs represent information about the world and the agent himself. Goals represent world states to be achieved.

The agent ag_i has a library $PL_i=\{pt_{i11},\ldots\}$ of plan templates representing simple procedures for achieving goals. A plan template $pt_{ikl} \in PL_i$ 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 [8]. The header is a 2-tuple: $header_{ikl}=\langle pname_{ikl},pvars_{ikl}\rangle$, where $pname_{ikl}$ is the name of pt_{ikl} and $pvars_{ikl}$ 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: $p_{ik}=\langle PT_{ik},\leq_h,\leq_t\rangle$, where $PT_{ik} \subseteq PL_i$ is a list of plan templates, $\leq_h$ is a binary relation establishing a hierarchy on PT_{ik}, and $\leq_t$ is another binary relation establishing a temporal order on PT_{ik}. The plan p_{ik} is represented as a hierarchical and temporally constrained And-tree. Plan generation is an iterative procedure of: (i) plan retrieval, (ii) plan selection, (iii) plan addition, and (iv) plan interpretation [8].

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 template pt_{ikl} in p_{ik}, the header of pt_{ikl} is referred as *intention* int_{ikl}.

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

3 The Negotiation Model

Let $Ag=\{ag_1,\ldots,ag_i,\ldots,ag_n\}$, $Ag \subseteq Agents$, be a set of autonomous agents. Let $P_{Ag}=\{p_{11},\ldots,p_{ik},\ldots,p_{nn}\}$ be a set of plans of the agents in *Ag* including intentions $I_{Ag}=\{int_{111},\ldots,int_{ikm},\ldots,int_{nnn}\}$, respectively. Let the intentions in I_{Ag} represent commitments to achieve exclusive world states. In this situation, there is a conflict 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 and plan for negotiation. A brief description of these tasks follows (see [9] for an in-depth discussion).

Negotiation Problem Structure Generation. A negotiation problem NP_{ik} from the perspective of ag_i is a 6-tuple: $NP_{ik}=<ag_i,B_i,g_{ik},int_{ikm},A,I_A>$, where B_i is a set of beliefs, $g_{ik}\in G_i$ is a goal, $p_{ik}\in P_{Ag}$ is a plan of ag_i for achieving g_{ik}, $int_{ikm}\in I_{Ag}$ is an intention of p_{ik}, $A=Ag-\{ag_i\}$ and $I_A=I_{Ag}-\{int_{ikm}\}$. The problem NP_{ik} has a *structure* $NPstruct_{ik}$ consisting of a hierarchical And-Or tree. Formally, $NPstruct_{ik}$ is a 4-tuple: $NPstruct_{ik}=<NPT_{ik},\leq_h,\leq_t,\leq_a>$, where $NPT_{ik}\subseteq PL_i$ is a list of plan templates, $\leq_h$ and $\leq_t$ have the meaning just specified, and $\leq_a$ 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) problem structure interpretation, (ii) plan decomposition, (iii) goal selection, (iv) plan retrieval, and (v) plan addition [9]. $NPstruct_{ik}$ 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 ($pname_{ikl}$ and $pvars_{ikl}$) of every plan template $pt_{ikl}\in L_{ik}$ is called a fact and denoted by f_{ikl}. Formally, a *fact* f_{ikl} is a 3-tuple: $f_{ikl}=<is_{ikl},v[is_{ikl}],r_{ikl}>$, where is_{ikl} is a *negotiation issue* (corresponding to $pname_{ikl}$), $v[is_{ikl}]$ is a value of is_{ikl} (corresponding to an element of $pvars_{ikl}$), and r_{ikl} is a list of arguments (corresponding to the remaining elements of $pvars_{ikl}$). 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 $is_{ikl}\in I_{ik}$ is represented by $D_{ikl}=[min_{ikl},max_{ikl}]$.

For each issue is_{ikl}, let w_{ikl} be a number called *importance weight* that represents its importance. Let $W_{ik}=\{w_{ika},\ldots,w_{ikz}\}$ be the set of normalized importance weights of the issues in I_{ik}. The *priority* of the issues in I_{ik} is defined as their importance.

Limits and Aspirations Formulation. Limits and aspirations are formulated for each issue. The *limit* for issue is_{ikl} is represented by lim_{ikl} and the initial *aspiration* by asp^0_{ikl}, with $lim_{ikl},asp^o_{ikl}\in D_{ikl}$ and $lim_{ikl}\leq asp^0_{ikl}$.

Negotiation Constraints Definition. Constraints are defined for each issue $is_{ikl}\in I_{ik}$. *Hard constraints* are linear constraints that specify threshold values for issues. They cannot be relaxed. The hard constraint hc_{ikl} for is_{ikl} has the form: $hc_{ikl}=(is_{ikl} \geq lim_{ikl}, flex=0)$, where $flex=0$ represents null flexibility (inflexibility). *Soft constraints* are linear constraints that specify minimum acceptable values for issues. They can be relaxed. The soft constraint sc_{ikl} for is_{ikl} has the form: $sc_{ikl}=(is_{ikl} \geq asp^0_{ikl}, flex=n)$, where $flex=n$, $n \in N$, represents the degree of flexibility of sc_{ikl}.

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 [3, 12, 13]. In this paper, we assume that ag_i selects a strategy $str_{ik} \in SL_i$ accordingly to his experience.

3.2 A Multilateral Negotiation Protocol

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

The process starts with ag_i communicating a negotiation proposal $prop_{ikm}$ to all the agents in $A=Ag-\{ag_i\}$. A *negotiation proposal* is a set of facts (see subsection 3.3). Each agent $ag_j \in A$ receives $prop_{ikm}$ and may decide either: (i) to accept $prop_{ikm}$, (ii) to reject $prop_{ikm}$ without making a critique, or (iii) to reject $prop_{ikm}$ and making a critique. A *critique* is a statement about issue priorities.

The process of negotiation proceeds with ag_i receiving the responses of all the agents in A. Next, ag_i checks whether a negotiation agreement was reached. If the proposal $prop_{ikm}$ was accepted by all the agents in A, the negotiation process ends successfully. In this case, ag_i informs the agents in A that an agreement was reached. Otherwise, ag_i can act either: (i) by communicating a new proposal $prop_{ikm+1}$, or (ii) by acknowledging the receipt of all the responses.

The process continues with the agents in A receiving the response of ag_i. If ag_i decides to communicate a new proposal $prop_{ikm+1}$, each agent $ag_j \in A$ may again decide: (i) to accept $prop_{ikm+1}$, or (ii) to reject $prop_{ikm+1}$ without making a critique, or (iii) to reject $prop_{ikm+1}$ and making a critique. If ag_i decides to acknowledge the receipt of the responses, the process continues 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 in order to negotiate in a competent way. These tasks (or processes) are shown in Fig. 1 for the specific case of an agent $ag_i \in Ag$ that communicates a negotiation proposal. Let NP_{ik} represent ag_i's perspective of a negotiation problem and $NPstruct_{ik}$ be the structure of NP_{ik}. A description of the main processes follows.

Negotiation Proposal Generation. This process generates the set of initial negotiation proposals $INPS_{ik}$ satisfying the requirements imposed by $NPstruct_{ik}$. The generation of $INPS_{ik}$ is performed through an iterative procedure involving: (i) problem interpretation, (ii) proposal preparation, and (iii) proposal addition [10]. In brief, problem interpretation consists of searching $NPstruct_{ik}$ for any solution p_{ik} of NP_{ik} and selecting the primitive plan templates $ppt_{ik}=\{pt_{ika},\ldots,pt_{ikp}\}$ of p_{ik}. 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 plan templates in ppt_{ik}. Proposal addition consists of adding $prop_{ikm}$ to $INPS_{ik}$.

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

Feasible and Acceptable Proposal Preparation. This process generates the set of feasible proposals $IFPS_{ik}$, $IFPS_{ik} \subseteq INPS_{ik}$, and the set of acceptable proposals $IAPS_{ik}$, $IAPS_{ik} \subseteq IFPS_{ik}$. Let $prop_{ikm}=\{f_{ika},\ldots,f_{ikp}\}$ be a negotiation proposal. Let $Iprop_{ikm}=\{is_{ika},\ldots,is_{ikp}\}$ be the set of issues associated with the facts in $prop_{ikm}$. 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 $prop_{ikm} \in INPS_{ik}$ 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 $IFPS_{ik}$ using an *additive scoring function* and orders the proposals in descending order of preference. Let $W_{ik}=\{w_{ika},\ldots,w_{ikp}\}$ be the set of importance weights of the issues in $Iprop_{ikm}$. 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 $v[is_{ikl}] \in D_{ikj}$ of is_{ikl}. The score for contract C_{ikm} is given by [13]: $V(C_{ikm})= \sum_{j=a}^{p} w_{ikj} V_{ikj} (v[is_{ikj}])$. 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 $prop_{ikm} \in IFPS_{ik}$. The negotiation strategy str_{ik} of ag_i dictates a tactic $tact_{ik} \in TL_i$ to use. The tactic $tact_{ik}$ specifies a particular proposal $prop_{ikm}$.

Feasible Proposal Modification. This process computes a new proposal $prop_{ikm+1}$ from a rejected proposal $prop_{ikm}$. The strategy str_{ik} defines one or two tactics $tact_{ik}, tact_{ik+1} \in TL_i$. The tactics modify $prop_{ikm}$ to make it more acceptable.

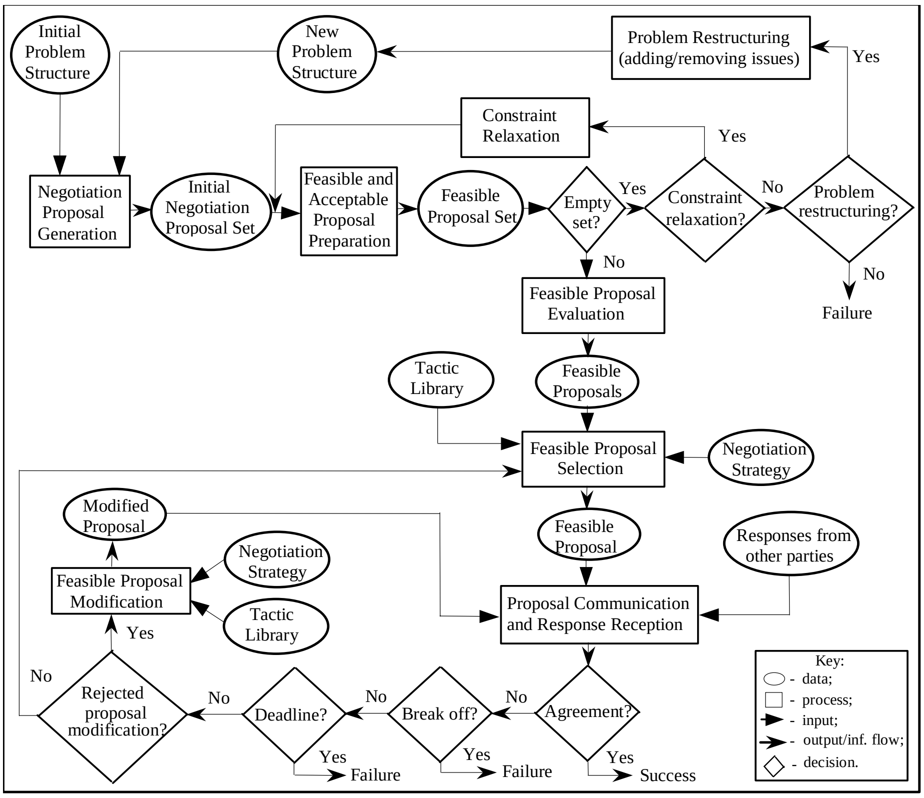

Fig. 1. The negotiation process (perspective of every agent that communicates a proposal)

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. In this paper, we consider 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 analogous functions. For instance, a strategy *SH01* is formalized by a function:

$sh\_strategy\_01(state, TL_i, F) = tact_{ik} \mid$

`if`: $state$ =“*initial*” `then`: $tact_{ik}$=“*starting_optimistic*”

`else`: $tact_{ik}$=”*const_factor_tact*” $\wedge F=0.1$

where *state* is the state of the negotiation, $F \in [0,1]$ is the *concession factor*, $tact_{ik}$ is the tactic specified by the strategy, *starting_optimistic* is an opening negotiation tactic, and *const_factor_tact* is a constant concession factor tactic (see subsection 3.5). The strategies in the other subclasses are formalized by similar functions.

Problem solving strategies define the opening negotiation, concession and compensation tactics. In this paper, we consider two sub-classes of strategies:

1. *low priority concession making* – model a realistic opening attitude, large concessions on issues of low priority and small concessions on other issues;
2. *low priority concession making with compensation* – these strategies are similar to previous strategies; however, concessions are interleaved with compensations.

Low priority concession making strategies partition the set I_{ik} of issues into: (i) subset I_{ik+}, corresponding to higher priority issues, and (ii) subset I_{ik-}, corresponding to the remaining issues. Again, the strategies in this sub-class are formalized by analogous functions. For instance, a strategy *LP01* is formalized by a function:

$lp\_strategy\_01(state, TL_i, I_{ik}, F_1, F_2) = (tact_{ik}, I_{ik+}, tact_{ik+1}, I_{ik-}) \mid$

`if`: $state$ =”*initial*” `then`: $tact_{ik}$=“*starting_realistic*” $\wedge$ $tact_{ik+1}$=”*nil*”

`else`: $I_{ik} = I_{ik+} + I_{ik-} \wedge \forall it_{ikj} \in I_{ik+}$, $tact_{ik}$=”*const_factor_tact*” $\wedge F_1 = 0.10 \wedge$

$\forall it_{ikj} \in I_{ik-}$, $tact_{ik+1}$=”*const_factor_tact*” $\wedge F_2 = 0.35$

where *state* and *const_factor_tact* have the meaning just specified, F_1 and F_2 are constants, $tact_{ik}$ and $tact_{ik+1}$ are the tactics defined by the strategy, and *starting_realistic* is an opening negotiation tactic (see subsection 3.5). The formalization of the strategies in the other sub-class is essentially identical to that.

3.5 Negotiation Tactics

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

Opening negotiation tactics specify a proposal to submit at the beginning of negotiation. Let $IFPS_{ik}$ and $IAPS_{ik}$ be the sets of feasible and acceptable proposals of ag_i, respectively. Let $INAPS_{ik}=IFPS_{ik}-IAPS_{ik}$. Let $Vprop_{ikh}$ be the score of proposal $prop_{ikh}\in IAPS_{ik}$. Let $Aprop^0_{ikh}$ be the set of initial aspirations of ag_i for issues in $prop_{ikh}$ and $VAprop^0_{ikh}$ be the score of $Aprop^0_{ikh}$. Let $Dif_{ikh}=|Vprop_{ikh}-VAprop^0_{ikh}|$. Similarly, let $Vprop_{ikh+1}$ be the score of proposal $prop_{ikh+1}\in INAPS_{ik}$. Let $Aprop^0_{ikh+1}$ be the set of initial aspirations of ag_i for issues in $prop_{ikh+1}$ and $VAprop^0_{ikh+1}$ be the score of $Aprop^0_{ikh+1}$. Let $Dif_{ikh+1}=|Vprop_{ikh+1}-VAprop^0_{ikh+1}|$. We consider three tactics:

1. *starting optimistic* – specifies the proposal $prop_{ik1}$ with the highest score;
2. *starting realistic* – specifies either: (i) proposal $prop_{ikh}$ with the lowest score, if $Dif_{ikh}\leq Dif_{ikh+1}$, or (ii) proposal $prop_{ikh+1}$ with the highest score, if $Dif_{ikh}>Dif_{ikh+1}$;
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:

$$starting\_optimistic(IFPS_{ik})=prop_{ik1}\,|\,\forall prop_{ikj}\in IFPS_{ik},\ Vprop_{ik1}\geq Vprop_{ikj}$$

Concession tactics are functions that compute new values for each issue. In this paper, we consider two sub-classes of tactics: (i) *constant concession factor tactics*, and (ii) *total concession dependent tactics*. In each 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 $prop_{ikm}$ be a proposal submitted by ag_i and rejected. Let $v[is_{ikj}]_m$ be the value of is_{ikj} offered in $prop_{ikm}$. Let lim_{ikj} be the limit for is_{ikj}. Let $v[is_{ikj}]_{m+1}$ be the new value of is_{ikj} to be offered in a new proposal $prop_{ikm+1}$. Let V_{ikj} be the component scoring function for is_{ikj}. The *constant concession factor tactics* are formalized by a function *const_factor_tact* which takes $v[is_{ikj}]_m$, a constant w, lim_{ikj} and another constant cte as input and returns $v[is_{ikj}]_{m+1}$, *i.e.*,

$const\_factor\_tact(v[is_{ikj}]_m, w, lim_{ikj}, cte) = v[is_{ikj}]_{m+1} |$

$$v[is_{ikj}]_{m+1} = v[is_{ikj}]_m + (-1)^w F \, |lim_{ikj} - v[is_{ikj}]_m| \wedge F = cte$$

where w=0 if V_{ikj} is monotonically decreasing or w=1 if V_{ikj} is monotonically increasing and F is the concession factor. The five tactics are defined as follows: the stalemate tactic by F=0, the tough tactic by $F \in]0,0.2]$, the moderate tactic by $F \in]0.2,0.3]$, the soft tactic by $F \in]0.3,0.4]$, and the compromise tactic by F=1.

The *total concession dependent tactics* are similar to the previous tactics, but F is a function of the total concession. Let $v[is_{ikj}]_0, \ldots, v[is_{ikj}]_m$, be the values of is_{ikj} successively offered by ag_i, with $V_{ikj}(v[is_{ikj}]_{h-1}) \geq V_{ikj}(v[is_{ikj}]_h)$, $0 \leq h \leq m$. The *total concession Ctotal* made by ag_i on is_{ikj} is: $Ctotal = |v[is_{ikj}]_0 - v[is_{ikj}]_m|$. These tactics are formalized by a function *tcd_tactics* which takes $v[is_{ikj}]_m$, w, lim_{ikj}, a constant $\lambda \in R^+$, $Ctotal$ and $v[is_{ikj}]_0$ as input and returns $v[is_{ikj}]_{m+1}$, *i.e.*,

$tcd\_tactics(v[is_{ikj}]_m, w, lim_{ikj}, \lambda, Ctotal, v[is_{ikj}]_0) = v[is_{ikj}]_{m+1} |$

$$v[is_{ikj}]_{m+1} = v[is_{ikj}]_m + (-1)^w F \, |lim_{ikj} - v[is_{ikj}]_m| \wedge$$
$$F = 1 - \lambda \, Ctotal \, / \, |lim_{ikj} - v[is_{ikj}]_0|$$

4 Related Work

The design of 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., [6]). However, most researchers are neutral with respect to the modalities of the mental state and just develop formal models of negotiation (e.g., [5]). Generally speaking, most theoretical models are rich but restrictive. They made 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 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., [11]). 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 based on ad hoc principles. They lack a rigorous theoretical grounding. Despite these, some researchers believe that it is necessary to develop computational models in order to use agents in real-world applications [14]. Accordingly, we developed a computational negotiation model.

As noted, most researchers have paid little attention to the problem of how to integrate 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 [2]. Accordingly, we developed 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 self-motivated and cooperative agents. Our structure for representing negotiation problems is similar to decision trees and goal representation trees [4], but there are important differences. Our approach does not require the quantitative measures typical of decision analysis. Also, our approach is based on plan templates and plan expansion, and not on production rules and forward or backward chaining. In addition, our formulae for modeling concession tactics are similar to the formulae used by Faratin *et al.* [1]. Again, there are important differences. The total concession criterion is not used by other researchers and our formulae: (i) assure that the agents do not negotiate in bad faith, and (ii) model important experimental conclusions about human negotiation.

5 Discussion and Future Work

This article has introduced 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 [3, 12]. Our aim for the future is: (i) to extend the model, and (ii) to finish the experimental validation of the model.

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