Negotiation Among Autonomous Computational Agents

Fernando Lopes[1], Nuno Mamede[2], A. Q. Novais[1] and Helder Coelho[3]

[1]INETI, DMS, Est. Paço do Lumiar, 1649-038 Lisboa, Portugal
{fernando.lopes, augusto.novais}@ineti.pt
[2]IST, Avenida Rovisco Pais, 1049-001 Lisboa, Portugal
Nuno.Mamede@acm.org
[3]UL/FC/DI, Campo Grande, 1700 Lisboa, Portugal
hcoelho@di.fc.ul.pt

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 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 repeated rounds. The model is based on computationally tractable assumptions The paper also introduces the types of application domains we are interested in, by describing a multi-agent supply chain system.

Key Words: Autonomous Agents, Conflict of Interests, Multi-Agent Negotiation, Supply Chain management.

Track: Paper Track.

Topics: Multi-Agent Systems and Distributed AI.

1 Introduction

Autonomous agents operate in complex environments and, over time, conflicts inevitably occur among them. Conflict resolution is crucial for achieving multi-agent coordination. 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 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 [8, 9, 10, 11]. 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. We also describe a complex and, we believe, important application domain, namely a multi-agent supply chain system.

The remainder of the paper is structured as follows. Section 2 describes a multi-agent supply chain system. Section 3 presents a generic model of individual behavior for autonomous agents. The model forms a basis for the development of negotiating agents. Section 4 presents a generic model of negotiation for autonomous agents. Finally, related work and concluding remarks are presented in sections 5 and 6, respectively.

2 Multi-Agent Supply Chain System

A *supply chain* is a network of facilities that performs the functions of procurement of raw materials from suppliers, transformation of these materials into intermediate goods and finished products, and the distribution of these products to customers. The *supply chain functions* range from the ordering and receipt of raw materials, to the distribution and delivery of final products, via the scheduling, production, warehousing, and inventory of intermediate goods and final products.

The *integration* of the multiple supply chain functions has received a great deal of attention in the recent years. However, most work addresses only single functions, such as scheduling or production. To date there exist little work that addresses the problem of integrating such isolated functions into a global supply chain. The *coordination* of the supply chain functions has been another active area of research. Also, most research addresses the coordination of two or more supply chain functions, such as production-distribution and buyer-vendor coordination. Despite the importance of the results obtained, the coordination of multiple supply chain functions is still an open problem [16].

We address the integration and coordination problems in this paper by organizing the supply chain as a collection of autonomous agents that are able to coordinate their activities through negotiation.

2.1 System Architecture

The architecture of a simplified multi-agent supply chain system is shown in Fig. 1. The system is composed by a set of autonomous agents, each responsible for performing one or more supply chain functions [2]. We are currently working on the following agents: logistics agent, scheduler, resource management agent, dispatcher, a number of suppliers, and a number of customers. A brief description of each agent follows.

The *logistics* agent manages the movement of raw materials from the suppliers, the manufacturing of intermediate goods and final products by the enterprise, and the distribution of the products to the customers. He receives customer orders, deviations in schedules which affects customer orders, and resource demands. He originates production requirements and supplier requests. He also notices the acquisition of resources. The *scheduler* is responsible for scheduling and rescheduling activities in the manufacturing enterprise. He receives production requests from the logistics agent, resource problems from the resource agent, and deviations of the current schedule from the dispatcher. He originates detailed schedules and sends them to the dispatcher and to the resource management agent. He also communicates the deviations of the current schedule to the logistics agent. The *resource management* agent is responsible for managing dynamically the availability of resources in order to execute the scheduled activities. He receives the schedule from the scheduler and the consumption of resources from the dispatcher. He also receives information about the acquisition of resources from the logistics agent. He estimates resource demands and identifies resource problems. He transmits resource availability to the dispatcher. The *dispatcher* is responsible for executing the scheduled activities. This agent controls the real time functions of the factory floor. He receives the schedule and the availability of resources. He notices deviations of the current schedule and the consumption of resources. The *suppliers* sell raw materials and the *customers* buy finished goods. The suppliers receive orders from the logistics agent and transmit their own alternative orders. The customers send orders to the logistics agent and receive alternative orders.

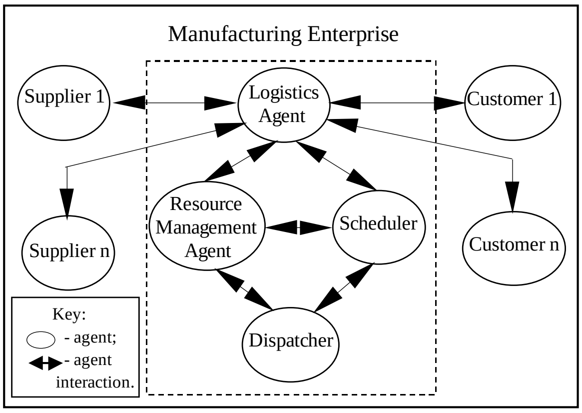

Fig. 1. Simplified multi-agent supply chain system

2.2 Multi-Agent Negotiation

The individual agents of the supply chain system must work in a tightly coordinated manner. Coordination is achieved through negotiation between one or more suppliers and the logistics agent, the agents within the manufacturing enterprise, and one or more customers and the logistics agent.

Negotiation between agents in the supply chain system and, we believe, a wide range of similar systems, exhibit the following characteristics:

1. *two or more parties* – negotiation may involve two parties (e.g., the logistics agent and a customer) or many parties (e.g., the logistics agent and the scheduler, the resource management agent, etc);
2. *multiple issue*s – negotiation ranges over a number of interrelated issues (e.g., price, quantity, quality, date, etc);.
3. *repeated rounds* (*encounters*) – more than one bargaining session may occur before reaching an agreement;
4. *cooperative or non-cooperative negotiation behavior* – negotiation may occur between agents within the same organization (e.g., between the logistics agent and the scheduler) or between inter-organizational agents (e.g., between the logistics agent and a customer). In the former case, negotiation is cooperative in nature. In the latter case, negotiation is purely competitive;
5. *time restrictions* – time is an important factor. The time needed to reach an agreement must be reasonable. Also, the mutually accepted due dates are often important.

3 Autonomous Agents

Let $Agents=\{ag_1,\ldots,ag_n\}$ be a set of autonomous agents. This section briefly describes the key features of every agent $ag_i \in Agents$ (see[8, 9] for an in-depth discussion).

The agent ag_i has a set $B_i=\{b_{i1},b_{i2},\ldots\}$ of beliefs and a set $G_i=\{g_{i1},g_{i2},\ldots\}$ 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 $PL_i=\{pt_{i11},pt_{i12},\ldots\}$ 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 [9]. The header is a 2-tuple: $header_{ikl}=<pname_{ikl},pvars_{ikl}>$, 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: $p_{ik}=<PT_{ik},\leq_h,\leq_t>$, 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 [9].

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* $IS_i=[p_{i1},p_{i2},\ldots]$. 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* $SD_i=\{SD_i(ag_1),\ldots,SD_i(ag_n)\}$. 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.

4 The Negotiation Model

This section presents a domain-independent description of a computational model of negotiation. 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.

4.1 Preparing and Planning for Negotiation

Prenegotiation is the process of 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 brief description of these tasks follows (see [10] 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 the 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 a goal g_{ik} (called *negotiation goal*).

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 and placement [10]. $NPstruct_{ik}$ defines all the possible solutions of NP_{ik} currently known by ag_i. A *possible 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 $L_{ik}=[pt_{ika},pt_{ikb},\ldots]$ 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 $is_{ikl} \in I_{ik}$, let w_{ikl} be a real number called *importance weight* that represents its relative importance. Let $W_{ik}=\{w_{ika},\ldots,w_{ikz}\}$ be the set of importance weights of the issues in I_{ik}. The importance weights are normalized, *i.e.*, $\sum_{j=a}^{z} w_{ikj} = 1$. The *priority* of the issues in I_{ik} is just defined as their relative importance.

Limits and Aspirations Formulation. Limits and aspirations are formulated for each issue at stake in negotiation. The *limit* for issue $is_{ikl} \in I_{ik}$ is represented by lim_{ikl} and the initial *aspiration* by asp^0_{ikl}, with $lim_{ikl}, asp^0_{ikl} \in D_{ikl}$ 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 the 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 the 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. *Negotiation tactics* are functions that define the moves to be made at each point of the negotiation process. Strategy selection is an important task and must be carefully planned [4, 13, 14]. In this paper, we just assume that ag_i selects a strategy $str_{ik} \in SL_i$ that he considers appropriate accordingly to his experience.

4.2 A 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 $prop_{ikm}$ to all the agents in $A=Ag-\{ag_i\}$. Broadly speaking, a *negotiation proposal* $prop_{ikm}$ is a set of facts (see subsection 4.3). 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. Broadly speaking, a *critique* is a statement about priorities of the issues.

The process continues 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 and the agreement $prop_{ikm}$ is implemented. In this case, ag_i just 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 of negotiation proceeds 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 all the responses, the process of negotiation 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.

4.3 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. 2 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 three main sub-tasks: (i) problem interpretation, (ii) proposal preparation, and (iii) proposal addition [11]. In brief, problem interpretation consists of searching $Npstruct_{ik}$ for any possible 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 primitive plan templates in ppt_{ik}. Proposal addition consists of adding the negotiation proposal $prop_{ikm}$ to the set $INPS_{ik}$.
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 $prop_{ikm}$, 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 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* ofnegotiation, for proposal $prop_{ikm}$. The issues $Icompl_{ikm}=\{is_{ikp+1},\ldots,is_{ikz}\}$ associated with these facts are the *flexible* or *bargaining 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 $IAPS_{ik}$,

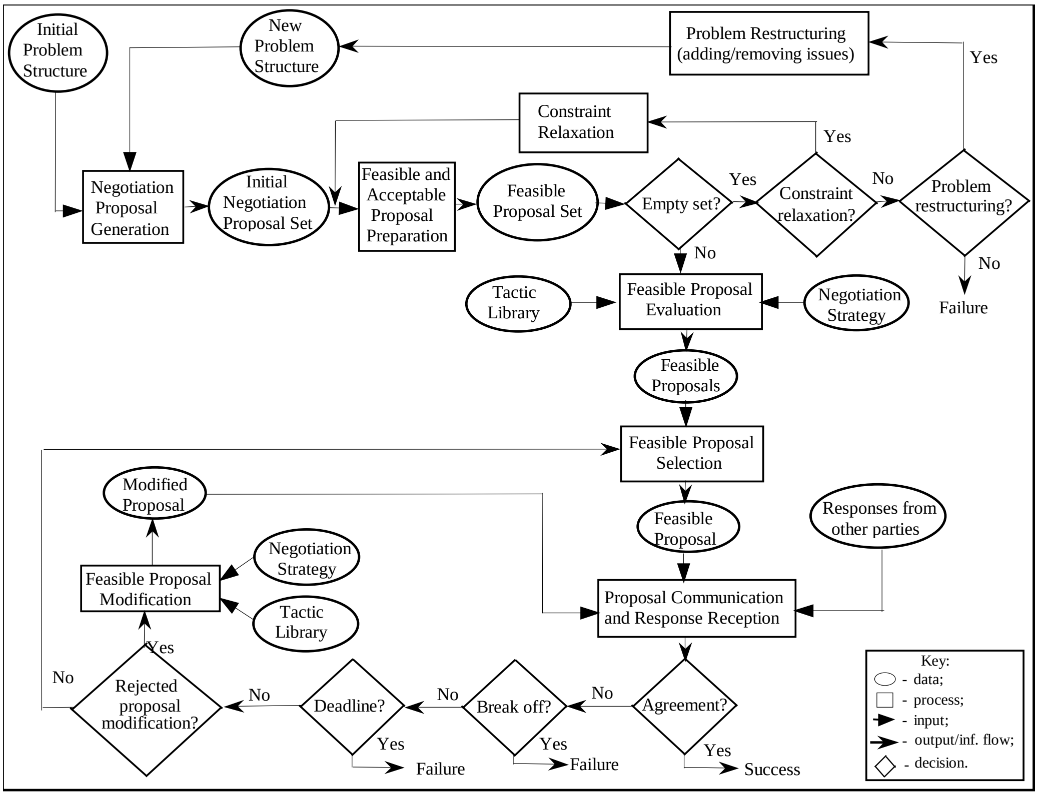

Fig. 2. The negotiation process (perspective of every agent that communicates a proposal)

$IAPS_{ik} \subseteq IFPS_{ik}$. 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* [14] 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 the following function: $V(C_{ikm}) = \sum_{j=1}^{p} w_{ikj} V_{ikj}(v[is_{ikj}])$. 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.

4.4 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 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 strategies in the sub-class starting high and conceding slowly are similar and formalized by analogous functions. For instance, a strategy *SH01* that specifies a high initial demand and very small concessions (constant, in percentage) is formalized by a function:

sh_strategy_01(*state*,TL_i,*F*)= $tact_{ik}$ |

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

`else`: $tact_{ik}$=”*const_factor_tact*” $\wedge$ F=0.05

where *state* is the current state of the negotiation, $F \in R^+$ is a constant, $tact_{ik}$ is the tactic specified by the strategy, *starting_optimistic* is an opening negotiation tactic, and *const_factor_tact* is a concession tactic, more specifically, a constant concession factor tactic (see subsection 4.5). The strategies in the other two-subclasses are formalized by functions essentially identical to that. These functions are, therefore, omitted.

Problem solving strategies are functions that define the opening negotiation, concession and compensation tactics. In this paper, we consider the following 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 issues of high priority;
2. *low priority concession making with compensation* – these strategies are similar to the previous strategies; they model the same opening attitude and concession pattern; 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 similar and formalized by analogous functions. For instance, a strategy *LP01* that specifies a moderate initial demand and large/small concessions (constant, in percentage) is formalized by a function:

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

`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*”$\wedge F=0.10 \wedge$

$\forall it_{ikj} \in I_{ik}^{-}$, $tact_{ik}$=”*const_factor_tact*”$\wedge F=0.40$

where *state*, *const_factor_tact* and F have the meaning just specified, $tact_{ik}$ and $tact_{ik+1}$ are the tactics defined by the strategy, and *starting_realistic* is an opening negotiation tactic (see subsection 4.5). The formalization of the *low priority concession making strategies with compensation* is essentially identical to that and is omitted.

4.5 Negotiation Tactics

This section describes two classes of tactics, called opening negotiation and concession tactics.
Opening negotiation tactics are functions that specify the proposal to submit at the beginning of negotiation. Let $IFPS_{ik}$ and $IAPS_{ik}$, $IAPS_{ik} \subseteq IFPS_{ik}$, be the sets of feasible and acceptable proposals of ag_i, respectively. These sets are ordered in a descending order of preference. Let $INAPS_{ik} = IFPS_{ik} - IAPS_{ik}$, $IAPS_{ik} \cap INAPS_{ik} = \emptyset$.

Let $Vprop_{ikh}$ be the score of proposal $prop_{ikh} \in IAPS_{ik}$. Let $Aprop0_{ikh}$ be the set of initial aspirations of ag_i for issues in $prop_{ikh}$ and $VAprop0_{ikh}$ be the score of $Aprop0_{ikh}$. Let $Dif_{ikh} = |Vprop_{ikh} - VAprop0_{ikh}|$. Similarly, let $Vprop_{ikh+1}$ be the score of proposal $prop_{ikh+1} \in INAPS_{ik}$. Let $Aprop0_{ikh+1}$ be the set of initial aspirations of ag_i for issues in $prop_{ikh+1}$ and $VAprop0_{ikh+1}$ be the score of $Aprop0_{ikh+1}$. Let $Dif_{ikh+1} = |Vprop_{ikh+1} - VAprop0_{ikh+1}|$. In this paper, we consider the following three tactics:

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

The tactic starting optimistic is formalized by a function *starting_optimistic* which takes $IFPS_{ik}$ as input and returns $prop_{ik1}$, *i.e.*,

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

The definition of the functions for the tactics starting realistic and starting pessimistic is similar to that and is omitted.

Concession tactics are functions that compute new values for each negotiation issue. Let I_{ik} be the set of negotiation issues. A *concession* on an issue $is_{ikj} \in I_{ik}$ is a change in the value of is_{ikj} that reduces the level of benefit sought. 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 the following 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 of ag_i for is_{ikj}.

The *constant concession factor tactics* are formalized by a function *const_factor_tact* which takes the value $v[is_{ikj}]_m$, a constant w, the limit lim_{ikj} and another constant *cte* as input and returns $v[is_{ikj}]_{m+1}$, *i.e.*,

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

where w=0 if V_{ikj} is monotonically decreasing or w=1 if V_{ikj} is monotonically increasing, and $F \in [0, 1]$ is the concession factor. $F=cte$ means that the concession factor is constant. The five tactics in this sub-class are defined as follows: the stalemate tactic by F=0, the tough tactic by $F \in]0,0.33]$, the moderate tactic by $F \in]0.33,0.66]$, the soft tactic by $F \in]0.66, 1]$, and the compromise tactic by F=1.

The *total concession dependent tactics* are similar to the constant concession factor tactics, but F is a function of the total concession made by ag_i on an issue is_{ikj}. Let $v[is_{ikj}]_0, v[is_{ikj}]_1, \ldots, v[is_{ikj}]_m$, be the values of is_{ikj} successively offered by ag_i, with $V_{ikj}(v[is_{ikj}]_{i-1}) \geq V_{ikj}(v[is_{ikj}]_i)$, $0 \leq i \leq m$. The *total concession Ctotal* made by ag_i on is_{ikj} is defined by: $Ctotal = \left| v[is_{ikj}]_0 - v[is_{ikj}]_m \right|$. These tactics are formalized by a function *tcd_tactics* which takes $v[is_{ikj}]_m$, w, lim_{ikj}, a constant λ, *Ctotal* and $v[is_{ikj}]_0$ as input and returns $v[is_{ikj}]_{m+1}$, *i.e.*,

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

where $\lambda \in R^+$. The five tactics in this class are defined as follows: the stalemate tactic by setting $\lambda = (|lim_{ikj} - [is_{ikj}]_0|)/Ctotal$, the tough tactic by λ=1.5, the moderate tactic by λ=1.0, the soft tactic by λ=0.5, and the compromise tactic by λ=0.0.

5 Related Work

The design of autonomous negotiating agents has been investigated by Artificial Intelligence researchers 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 (e.g., beliefs, desires and intentions), 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., [7]). 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., [6]). Generally speaking, most theoretical models are rich but restrictive. They made a number of 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. Again, some researchers start with a particular model of individual behavior (e.g., a belief-desire-intention model), develop a negotiation model or adopt an existing one, and then integrate both models into a unified model that accounts for both individual and social behavior (e.g., [12]). However, most researchers prefer to be neutral about the model of individual behavior and just develop models of negotiation (e.g., [1], [17]). Broadly speaking, most computational models are rich but based on ad hoc principles. They lack a rigorous theoretical grounding. However, despite these weaknesses, some researchers believe that it is necessary to develop computational models in order to implement and successfully use autonomous agents in real-world applications [15]. Accordingly, in this work we developed a computational negotiation model.

As noted above, most researchers following the practical perspective have paid little or no attention to the problem of how to integrate existing or new models of individual behavior with the 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 [3]. Accordingly, in this work we developed a unified 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 negotiation model is generic and supports problem restructuring. Our structure for representing negotiation problems allows the direct integration of planning and negotiation. This structure is similar to decision trees and goal representation trees [5], but there are important differences. Our approach does not require the quantitative measures typical of decision analysis. In addition, our approach is based on plan templates and plan expansion, and not on production rules and forward and backward chaining. Also, 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 criteria is not used by other researchers and our formulae: (i) assure that the new value of an issue ranges between the limit and the previous value of the issue, and (ii) model important experimental conclusions about demand, and concession.

6 Discussion and Future Work

This article has introduced a computational negotiation model for autonomous agents and a multi-agent supply chain system. 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 constraint relaxation and 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 [4, 13]. Our aim for the future is: (i) to extend the model, and (ii) to finish the ongoing experimental validation of the model.

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