

# Automated Formal Analysis of Human Multi-Issue Negotiation Processes

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**Abstract.** This paper reports on experiments in (human) multi-issue negotiation and their analysis, and presents a generic software environment supporting such an analysis. First, the paper presents a System for Analysis of Multi-Issue Negotiation (SAMIN). SAMIN is designed to analyse multi-issue negotiation processes between human negotiators, between human and software agents, and between software agents. The agents conduct one-to-one negotiations, in which the values across multiple issues are negotiated on simultaneously. To analyse such negotiation processes, the user can enter any formal property deemed useful into the system and use the system to automatically check this property in given negotiation traces. The paper presents the results of applying SAMIN in the analysis of empirical traces obtained from an experiment in multi-issue negotiation about second hand cars. In the experiment the efforts of 74 humans negotiating against each other have been analysed using SAMIN.

## 1. Introduction

Negotiation is a process by which a joint decision is made by two or more parties [19]. Typically each party starts a negotiation by offering the most preferred solution from the individual area of interest. If an offer is not acceptable by the other parties they make counter-offers in order to move them closer to an agreement. The field of negotiation can be split into different categories, e.g. along the following lines:

- one-to-one versus more than two parties

- single- versus multi-issues
- closed versus open
- mediator-based versus mediator-free

The research reported in this article concerns one-to-one, multi-issue, closed, mediator-free negotiation. For more information on negotiations between more than two parties (e.g., in auctions), the reader is referred to, e.g., [23]. In single-issue negotiation, the negotiation focuses on one aspect only (typically price) of the concept under negotiation. Multi-issue negotiation (also called multi-attribute negotiation) is often seen a more cooperative form of negotiation, since often an outcome exists that brings joint gains for both parties, see [21].

Closed negotiation means that no information regarding preferences is exchanged between the negotiators. The only information exchanged is formed by the bids. In partially open negotiation some information regarding preferences is exchanged, and in completely open negotiation all information is exchanged. More information about (partially) open negotiations can be found, e.g., in [17] and [21]. However, the trust necessary for open negotiations is not always available.

The use of mediators is a well-recognised tool to help the parties in their negotiations, see e.g., [6, 10]. The mediator aims for a deal that is fair to all parties. Reasons for negotiating without a mediator can be the lack of a trusted mediator, the costs of a mediator, and the hope of doing better than fair with respect to personal gain.

The literature on closed, multi-issue, one-to-one negotiation without mediators covers both systems to (partially) automate the negotiation process, and more analytic research focused on properties of the negotiation process and negotiation space. Based on a literature study and on our own analysis, a number of properties are presented here that focus largely on the dynamics of the negotiation process itself and on the results of the negotiation.

The SAMIN system presented in this paper has been developed to support and formally analyse such negotiation processes, i.e., multi-issue, (partially) closed, one-to-one negotiations without mediators. The system requires three types of input:

- (1) a negotiation *trace* (or a set of traces)
- (2) a set of *dynamic properties* considered relevant for the negotiation process
- (3) the *negotiation profiles* of the participants

A *trace* is a sequence of bids by the negotiators. A *dynamic property* is an (informal, semi-formal or formal) expression that might or might not hold for a certain trace. An example of a simple dynamic property is bid-alternation, i.e., after communicating a bid to another agent, the agent remains silent until it has received a new bid from the other agent. A *negotiation profile* is a description of the preferences of the agent within the particular negotiation domain. The profiles

together define the space of possible and efficient outcomes and are, therefore, essential for the creation of a complete analysis of the performance of a negotiator.

The most important measure of efficiency in bilateral negotiations, cf. [20], is Pareto-efficiency. An outcome is said to be Pareto-efficient if the utility of any party cannot be improved without a loss of utility for another. The set of all Pareto-efficient outcomes form the Pareto-efficient frontier. The distance of an outcome to the Pareto frontier gives a measure of efficiency of a bid.

The SAMIN system consists of three components: an *Acquisition Component*, an *Analysis Component* and a *Presentation Component*. The Acquisition Component is used to acquire the input necessary for analysis. The Analysis Component performs the actual analysis, and the Presentation Component presents the results of the analysis in a user-friendly format.

SAMIN can check automatically whether selected properties hold for the traces under analysis. Such an analysis provides a means to improve bidding strategies and bidding protocols, both for human negotiators and for software agents in automated negotiation systems. Beside introduction of the SAMIN system, a subgoal of this paper is to report some results of such analyses, focusing on human negotiators. The results are presented of applying SAMIN in the analysis of empirical traces obtained from an experiment in multi-issue negotiation about second hand cars. In the experiment the efforts of 74 humans negotiating against each other have been analysed using SAMIN.

In Section 2 formalisation of negotiation process dynamics will be discussed in terms of negotiation states, transitions, and traces. Section 3 explains the formal specification of dynamic properties and presents example dynamic properties relevant for (partially) closed multi-issue one-to-one negotiations. The architecture of the SAMIN system is presented in Section 4. Section 5 illustrates how SAMIN can be used to analyse human negotiation processes. Some experiments in human multi-issue negotiation are described and analysed, and the results of the analysis are discussed. Finally, Section 6 discusses related work, and Section 7 provides conclusions and some planned future work.

## 2. Formalising Negotiation Process Dynamics

Negotiation is essentially a dynamic process. To analyse those dynamics, it is, therefore, relevant to formalise and study dynamic properties of such processes. For example, how does a bid at a certain point in time compare to bids at previous time points? The formalisation introduced in this section is based on the notion of negotiation process state, negotiation transition and negotiation trace.

## 2.1 Formalising States of a Negotiation Process

The state of a (one-to-one) negotiation process at a certain time point can be described as a combined state consisting of two states for each of the negotiating agents:

$$S = \langle S1, S2 \rangle$$

where  $S1$  is the state of agent  $A$ , and  $S2$  is the state of agent  $B$ .

Each of these states include:

- the agent's own most recent bid
- its evaluation of its own most recent bid
- its evaluation of the other agent's most recent bid
- the history of bids from both sides and evaluations

To describe negotiation states a state ontology  $Ont$  is used. Example elements of this ontology are a sort  $BID$  for bids, and relations such as  $utility(A, b, v)$  expressing that  $A$ 's overall evaluation of bid  $b$  is a real number  $v$  between 0 and 1. Based on this ontology the set of ground atoms  $At(Ont)$  can be defined. A state is formalised as any truth assignment:  $At(Ont) \rightarrow \{t, f\}$  to this set of ground atoms. The set of all states described by this ontology is denoted by  $States(Ont)$ .

## 2.2 Negotiation Transitions

A particular negotiation process shows a sequence of transitions from one state  $S$  from  $States(Ont)$  to another (next) state  $S'$  from  $States(Ont)$ . A transition  $S \rightarrow S'$  from a state  $S$  to  $S'$  can be classified according to which agents are involved. During such a transition each of the main state components ( $S1, S2$ ) of the overall state  $S$  may change. The simplest types of transition involve a single component transition. For example, when one agent generates a bid, while the other agents is just waiting: a transition of type  $S1 \rightarrow S1$  or  $S2 \rightarrow S2$ . Next come transition types where both components are involved. For example, when a communication from agent  $A$  to agent  $B$  takes place, changing the state  $S2$  of agent  $B$ : a transition of type  $S1 \times S2 \rightarrow S2$ . Notice that in principle, also more complex transition types are possible, involving changes of both state components at the same time, i.e.,  $S1 \times S2 \rightarrow S1 \times S2$ . In organised cooperations between multiple agents the complexity of the types of transitions is often limited by regulation of the organisation. For example, in organised negotiation processes, usually it is assumed in the protocol that after communicating a bid to the other agent, the agent remains silent until it has received a new bid from the other agent (see the dynamic property 'bid alternation' in Sections 3 and further

below). Such an assumption about the protocol implies that the transitions involved in the negotiation are only of the simpler types mentioned above.

### 2.3 Negotiation Traces

Negotiation traces are time-indexed sequences of negotiation states, where each successive pair of states is a negotiation transition. To describe such sequences a fixed *time frame*  $\mathcal{T}$  is assumed which is linearly ordered. A *trace*  $\mathcal{T}$  over a state ontology  $\text{Ont}$  and time frame  $\mathcal{T}$  is a mapping  $\mathcal{T}: \mathcal{T} \rightarrow \text{STATES}(\text{Ont})$ , i.e., a sequence of states  $\mathcal{T}_t$  ( $t \in \mathcal{T}$ ) in  $\text{STATES}(\text{Ont})$ . The set of all traces over state ontology  $\text{Ont}$  is denoted by  $\text{TRACES}(\text{Ont})$ . Depending on the application, the time frame  $\mathcal{T}$  may be dense (e.g., the real numbers), or discrete (e.g., the set of integers or natural numbers or a finite initial segment of the natural numbers), or any other form, as long as it has a linear ordering.

## 3. Dynamic Properties of Negotiation Processes

This section presents a classification of dynamic properties of negotiation processes along with examples of each class. Before presenting the classification and the specific dynamic properties of negotiation, the formal method for specifying those properties is presented.

### 3.1 Specification of Dynamic Properties

Specification of dynamic properties of a negotiation process can be done in order to *analyse* its dynamics, for example to find out how certain properties of a negotiation process as a whole relate to properties of a certain subprocess, or to verify or evaluate a negotiation model. To formally specify dynamic properties that express characteristics of dynamic processes (such as negotiation) from a temporal perspective an expressive language is needed. To this end the *Temporal Trace Language* TTL is used as a tool; cf. [5]. This language can be classified as a reified predicate-logic-based temporal logic (see, e.g., Galton, 2003, 2006), in contrast to, for example, modal-logic-based temporal logics as the ones discussed in, e.g., (Fisher, 2005). The language is briefly introduced here. For more details, see (Bosse, Jonker, Meij, Sharpanskykh and Treur, 2006).

The set of *dynamic properties*  $\text{DYNPROP}(\text{Ont})$  is the set of temporal statements that can be formulated with respect to traces based on the state ontology  $\text{Ont}$  in the following manner. Given a trace  $\mathcal{T}$  over state ontology  $\text{Ont}$ , a certain state of the agent  $A$  during a negotiation process at time point  $t$  is indicated by  $\text{state}(\mathcal{T}, t, A)$ . In the third argument, instead of  $A$  also specific parts of  $A$  can be used, such as  $\text{input}(A)$ , or  $\text{output}(A)$ , which refer to observations and actions by  $A$ , or communications. These state indicators can be related to state properties via the formally defined satisfaction relation denoted by the infix predicate  $\models$ , comparable to the  $\text{Holds}$ -predicate in the Situation Calculus:

$\text{state}(\mathcal{T}, t, A) \models p$  denotes that state property  $p$  holds in trace  $\mathcal{T}$  at time  $t$  in the state of agent  $A$ . Here state properties are considered objects and denoted by term expressions in the TTL language. The infix predicate  $\models$  is alternatively written in prefix form as holds:  $\text{holds}(s, p)$  means  $s \models p$ . Based on these atomic TTL-statements, dynamic properties can be formulated in a formal manner in a sorted first-order predicate logic with sorts  $T$  for time points,  $\text{Traces}$  for traces and  $F$  for state formulae, using quantifiers and the usual first-order logical connectives such as  $\neg$ ,  $\&$ ,  $\vee$ ,  $\Rightarrow$ ,  $\forall$ ,  $\exists$ .

In some more detail, both  $\text{state}(\gamma, t, \text{output}(A))$  and  $p$  are terms of the TTL language. TTL terms are constructed by induction in a standard way for sorted predicate logic from variables, constants and functional symbols typed with TTL sorts. Dynamic properties are expressed by TTL-formulae inductively defined by:

- (1) If  $v_1$  is a term of sort  $\text{STATE}$ , and  $u_1$  is a term of the sort  $\text{STATPROP}$ , then  $\text{holds}(v_1, u_1)$  is an atomic TTL formula.
- (2) If  $\tau_1, \tau_2$  are terms of any TTL sort, then  $\tau_1 = \tau_2$  is an atomic TTL formula.
- (3) If  $t_1, t_2$  are terms of sort  $\text{TIME}$ , then  $t_1 < t_2$  is an atomic TTL formula.
- (4) The set of well-formed TTL-formulae is defined inductively in a standard way based on atomic TTL-formulae using boolean connectives and quantifiers.

For example, the dynamic property

‘in any trace  $\gamma$ , if at any point in time  $t_1$  agent  $A$  observes that it is dark in the room, whereas earlier a light was on in this room, then there exists a point in time  $t_2$  after  $t_1$  such that at  $t_2$  in the trace  $\gamma$  agent  $A$  switches on a lamp’

is expressed in formalized form in TTL as:

$$\begin{aligned} & \forall t_1 [ [ \text{state}(\gamma, t_1, \text{input}(A)) \models \text{observed}(\text{dark\_in\_room}) \& \\ & \exists t_0 < t_1 [ \text{state}(\gamma, t_0, \text{input}(A)) \models \text{observed}(\text{light\_on}) ] \\ & \Rightarrow \exists t_2 \geq t_1 \text{state}(\gamma, t_2, \text{output}(A)) \models \text{performing\_action}(\text{switch\_on\_light}) ] \end{aligned}$$

As another example, consider the dynamic property bid alternation, which states that for all two different moments in time  $t_1, t_3$ , that  $A$  generates a bid, there is a moment in time  $t_2$ , with  $t_1 < t_2 < t_3$ , such that  $A$  received a bid generated by  $B$ . In formal TTL-format, this property is expressed as:

$$\begin{aligned} & \mathbf{bid\_alternation}(\gamma:\text{TRACE}) \equiv \\ & \forall A, B: \text{AGENT}, \forall b_1, b_3: \text{BID}, \forall t_1, t_3: \text{time} : \\ & \quad t_1 < t_3 \& \\ & \quad \text{state}(\gamma, t_1, \text{output}(A)) \models \text{to\_be\_communicated\_to\_by}(b_1, B, A) \& \\ & \quad \text{state}(\gamma, t_3, \text{output}(A)) \models \text{to\_be\_communicated\_to\_by}(b_3, B, A) \\ & \Rightarrow \exists b_2: \text{BID}, \exists t_2: \text{time} : t_1 < t_2 < t_3 \& \\ & \quad \text{state}(\gamma, t_2, \text{input}(A)) \models \text{communicated\_to\_by}(b_2, A, B) \end{aligned}$$

Often for reasons of presentation dynamic properties are expressed in informal or semi-formal forms.

### 3.2 Classes and Examples of Dynamic Properties of Negotiation

The properties relevant for analysing the dynamics of (partially) closed multi-issue one-to-one negotiation, can be divided into the following types:

- **Bid properties** give some information about a specific bid. They are usually defined in terms of the negotiation space and the profiles of the negotiators. Bid properties concern, for example, the Pareto efficiency of a bid.
- **Result properties** are a subset of the set of bid properties, concerning only the last bid of a negotiation process (i.e., the final agreement).
- **Bid comparison properties** compare two arbitrary bids with each other. An example is domination: a bid  $b_1$  dominates a bid  $b_2$  with respect to agents A and B iff both agents prefer bid  $b_1$  over bid  $b_2$ ; see below for a formalisation
- **Step properties** are a subset of the set of bid comparison properties, concerning only the transitions between successive bids. Hence, they are restricted to the combinations of bids of one party that directly follow each other.
- **Limited interval properties** concern parts of traces. Basically, they state that each step in a certain interval satisfies a certain step property. For instance: a negotiation process is Pareto-monotonous for the interval  $[t_1, t_2]$  iff for all successive bids  $b_1, b_2$  in the interval  $b_2$  dominates  $b_1$  (see below).
- **Trace properties** are a subset of the set of limited interval properties, concerning whole traces.
- **Multi-trace properties** compare the dynamics observed in more than one trace. An example is Better Negotiator: agent A is a better negotiator than agent B iff in more than 60% of the negotiations between A and B, the deal reached is more to the advantage of agent A than of agent B.
- **Protocol properties** specify certain constraints on the negotiation protocol. A specific instance is: over time the bids of negotiators A and B alternate.

Note that the first two types are basically *static properties*, whereas the other types are *dynamic properties*: they specify behaviour over time. In [3] for each of these types a number of properties are described in detail, both in informal and in formal notation. In this paper, only a small selection of relevant properties is presented. See Appendix A for a more extensive overview of these properties.

**configuration\_differs(b1: *BID*, b2: *BID*)**  $\equiv$

$\exists a: \text{ISSUE}, \exists v1, v2: \text{VALUE} :$

$\text{value\_of}(b1, a, v1) \ \& \ \text{value\_of}(b2, a, v2) \ \& \ v1 \neq v2$

This bid comparison property states that two bids *b1* and *b2* differ in configuration iff there is an issue that has a different value in both bids. For example, in bid *b1* the value of the issue “color” is “red”, whereas in bid *b2* this value is “blue”. Similar properties can be defined stating that two bids differ in configuration in at least *x* issues. This property can also be used as a building block to specify a step property, e.g. “in the view of agent *A*, agent *B* varies the configuration, but not the utility”. Such a property are useful to find out what kind of opponent the negotiator is dealing with.

**strictly\_dominates(b1: *BID*, b2: *BID*, A: *AGENT*, B: *AGENT*)**  $\equiv$

$\forall vA1, vA2, vB1, vB2 : \text{real} :$

$\text{util}(A, b1, vA1) \ \& \ \text{util}(A, b2, vA2) \ \& \ \text{util}(B, b1, vB1) \ \& \ \text{util}(B, b2, vB2) \Rightarrow vA1 > vA2 \ \& \ vB1 > vB2$

This bid comparison property states that a bid *b1* dominates a bid *b2* with respect to agents *A* and *B* iff both agents prefer bid *b1* over bid *b2*. This notion is related to Pareto Efficiency, see e.g., [21]. The property could also be changed to *weakly\_dominates* by changing the  $>$  sign into the  $\geq$  sign. Moreover, it can be used as a building block to specify step properties, limited interval properties (see the next property), and trace properties.

**strict\_pareto\_monotony( $\gamma$ : *trace*, *tb*: *time*, *te*: *time*)**  $\equiv$

$\forall t1, t2: \text{time}, \forall A, B: \text{AGENT}, \forall b1, b2: \text{BID} :$

$[ \text{tb} \leq t1 < t2 \leq \text{te} \ \& \ \text{is\_followed\_by}(\gamma, A, t1, b1, B, t2, b2) ]$

$\Rightarrow \text{state}(\gamma, t2) \models \text{strictly\_dominates}(b2, b1, A, B)$

This limited interval property makes use of the previous property. It states that a negotiation process  $\gamma$  is strictly Pareto-monotonous for the interval  $[t1, t2]$  iff for all successive bids *b1*, *b2* in the interval *b2* dominates *b1*. By choosing for *tb* and *te* respectively the start and end time of the process, the property can be transformed into a trace property. Generally, traces that satisfy this property are not abundant in (human) real world multi-issue negotiations, since if the profiles of the two parties are strongly opposed (with emphasis on the same issues), even in multi-issue situations a gain for the one often implies a loss for the other. If, however, the profiles are less opposed, Pareto-monotony may occur.

**pareto\_inefficiency( $\gamma$ : *trace* *b*: *BID*, A: *AGENT*, B: *AGENT*,  $\epsilon$ : *real*)**  $\equiv$

$\forall vA, vB : \text{real} :$

$\text{util}(A, b, vA) \ \& \ \text{util}(B, b, vB) \Rightarrow \text{pareto\_distance}(vA, vB) = \epsilon$

This bid property informally states that with respect to agents *A* and *B*, the Pareto inefficiency of a bid *b* is the number  $\epsilon$  that indicates the distance to the Pareto Efficient Frontier according to some distance measure *d* in utilities. Here,  $d(b_1, b_2)$  is the distance between the bids *b*<sub>1</sub> and *b*<sub>2</sub> when viewed as points in the plane of utilities. The function to measure the distance in the plane can still be filled in, e.g., the sum of absolute differences of coordinates, or the square root of the sum of squares of the differences, or the maximum of the differences of the coordinates. The Pareto Efficient Frontier is the set of all bids *b* for which there is no other bid *b'* that dominates *b*. Hence, in case the Pareto Inefficiency of a bid is 0, there is no other bid that dominates it. By filling in the resulting agreement of a negotiation for bid *b*, the property is transformed into a result property. In general, determining the number  $\epsilon$  for which this property holds is a good measure for checking the success of the negotiation process. In a similar way, the property *nash\_inefficiency* can be formulated, which calculates the distance from a certain bid to the Nash Point. This is the point (on the Pareto Efficient Frontier) for which the product of both utilities is maximal, see e.g., [21].

#### 4. The SAMIN Architecture

SAMIN is a Prolog-based software environment that has been designed at the Vrije Universiteit Amsterdam for the analysis of multi-issue negotiation processes. Section 4.1 describes the role SAMIN can take in an analysis setting of negotiation processes. Next, Section 4.2 presents a top level overview of the SAMIN architecture. Basically, the system consists of three components: an *Acquisition Component*, an *Analysis Component* and a *Presentation Component*. These components are described in more detail in Sections 4.3, 4.4, and 4.5, respectively.

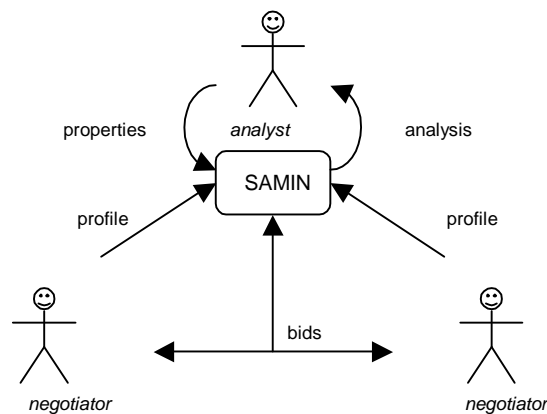
##### 4.1 SAMIN in its Environment

The SAMIN system has been designed to work together in interaction with a human analyst and either human or software agent negotiators. As depicted in Figure 1, the analyst determines the properties that SAMIN is to use in the analysis of negotiation processes. He or she can select (and if necessary adapt) properties from SAMIN's library, or can construct new properties with the help of SAMIN's special dynamic property editor. SAMIN can only analyse a negotiation process if it has access to the profiles used by the different parties, and the bids exchanged between the parties. SAMIN does not influence the negotiation while it is being carried out, it only observes either during the negotiation, or afterwards.

The analysis result of one or more negotiations is presented to the human analyst. The analyst can use that result for purposes within Cognitive Science (e.g., to analyse human negotiation processes and train human negotiators) or Artificial Intelligence (e.g., to improve the strategies of

software agents). Interesting for the future might be to present the results directly after the conclusion of the negotiation to a software agent negotiator that is capable of learning so that the agent can use the result to improve its negotiation skill by itself. A negotiation process can be monitored directly by SAMIN (if the agents allow interfacing), or the negotiation trace can be written to a file and be analysed in hindsight by SAMIN. The current version of SAMIN is developed especially for closed multi-issue one-to-one negotiations, entailing that the only information exchanged between the negotiators are the bids.

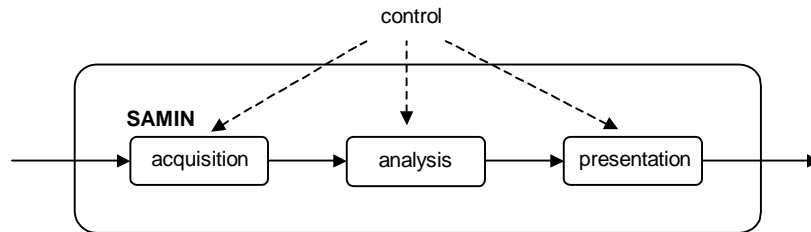
The input required by SAMIN (see Figure 1) consists of properties, profiles, and traces of bids. Its output consists of an analysis that can be presented in a user-friendly format (see Section 4.4 and 4.5). As mentioned before, SAMIN offers the user both a library of properties to choose from and a dynamic property editor to create new properties. Profiles can be obtained in two ways. Either the negotiator presents a pre-specified profile to SAMIN or the negotiator can use SAMIN's interactive profile editor to create it in SAMIN. Pre-specified profiles have to be in a format recognised by SAMIN. The trace of bids required by SAMIN can be obtained by SAMIN monitoring the bids exchanged between the negotiators during the negotiation process. This only requires the bids to be in a format recognised by SAMIN and the possibility to "overhear" the communication between the negotiators. Another possibility is that the bids exchanged during a negotiation process are stored in a special file. If the bid-traces are in the right format, SAMIN can perform analysis on one or on a combination of such traces after the negotiation has been completed. If the negotiators wish to do so, they can use SAMIN's bid ontology editor to define what a bid should look like, before entering the negotiation phase. Construction of bid ontology and the profiles is part of the pre-negotiation phase [21].



**Figure 1.** SAMIN in its environment

## 4.2 Top Level

At the top level, SAMIN consists of three components: an Acquisition Component, an Analysis Component and a Presentation Component, see Figure 2. Here, the solid arrows indicate data flow. The dotted arrows indicate that each component can be controlled separately by the analyst. The Acquisition Component is used to acquire the input necessary for analysis. The Analysis Component is used to perform the actual analysis (i.e., checking which properties hold for the negotiation process under analysis). Finally, the Presentation Component is used to present the results of the analysis in a user-friendly format. Furthermore, SAMIN maintains a library of properties, templates of properties, bid ontologies, and profile ontologies (not shown in Figure 2). The working of the three components will be described in detail in the next sections.



**Figure 2.** Global Overview of the SAMIN architecture

## 4.3 The Acquisition Component

The acquisition component is used to obtain the required input for the analysis. It consists of an *ontology editor*, a *dynamic property editor* and a *trace determinator*.

The ontology editor is used for the construction of bid ontologies and profile ontologies necessary to automatically interpret the bids exchanged by the negotiators, and to automatically interpret the profiles of the negotiators. The ontology editor is typically used to construct a bid ontology and a profile ontology, thus allowing the user to identify the issues to be negotiated, the values that each of these issues can take, and the structure of bids, in the bid ontology. Furthermore, in specifying the profile ontology the user identifies the possible evaluations that can be given to values, and the utility functions of bids.

The dynamic property editor supports the gradual formalisation of dynamic properties in TTL format. The editor offers a user interface that allows the analyst to construct dynamic properties, represented in a tree-like format.

The trace determinator can be used interactively with the analyst to determine what traces to use in the analysis. The user can interactively locate the files containing the traces to be checked. The traces themselves can be of three categories: (human) empirical traces, simulated traces, and mixed traces. An empirical trace is the result of an existing human negotiation process. A simulated trace is the result of an automated negotiation process. A mixed trace is the result of a human negotiating with a software agent. To support the acquisition of traces of all three types, a dedicated interface has been created for SAMIN.

#### 4.4 The Analysis Component

The analysis component currently consists of a *logical analyser* that is capable of checking properties against traces. To this end, the tool takes a dynamic property in TTL format and one or more traces as input, and checks whether the dynamic property holds for the traces .

Traces are represented by sets of Prolog facts of the form  $holds(state(m1, t(2)), a, true)$  where  $m1$  is the trace name,  $t(2)$  time point 2, and  $a$  is a state property as introduced in Section 3.1. The above example indicates that state formula  $a$  is true in trace  $m1$  at time point 2. The Analysis Component basically uses Prolog rules for the predicate  $sat$  that reduce the satisfaction of the temporal formula finally to the satisfaction of atomic state formulae at certain time points, which can be read from the trace representation. Examples of such reduction rules are:

```
sat(and(F,G)) :- sat(F), sat(G).
sat(not(and(F,G))) :- sat(or(not(F), not(G))).
sat(or(F,G)) :- sat(F).
sat(or(F,G)) :- sat(G).
sat(not(or(F,G))) :- sat(and(not(F), not(G))).
```

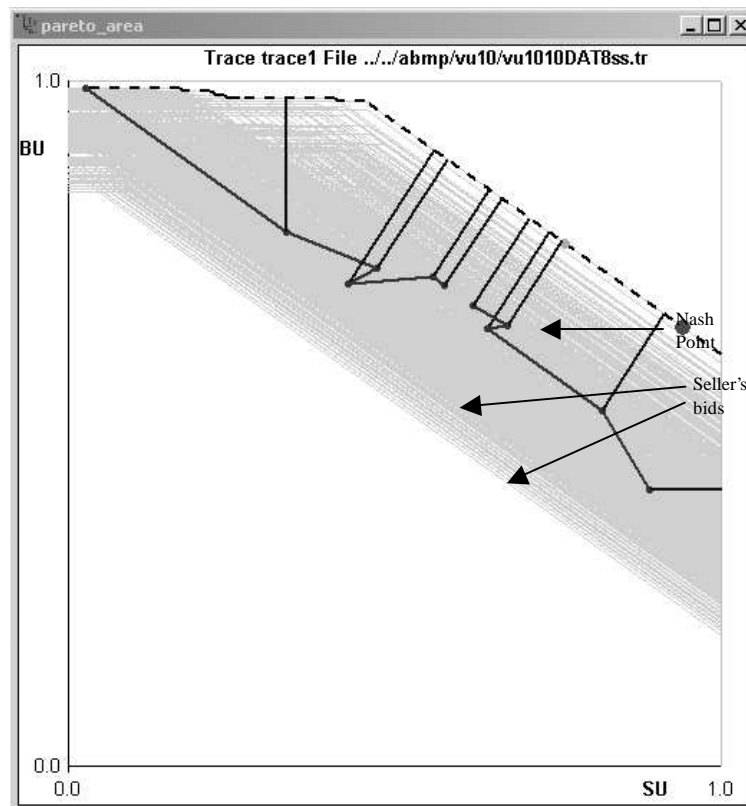
In addition, if a dynamic property does not hold in a trace, then the software reports the places in the trace where the property failed.

#### 4.5 The Presentation Component

The presentation component currently includes a tool that visualises the negotiation space in terms of the utilities of both negotiators. This *visualisation tool* plots the bid trajectory in a 2-dimensional plane, see Figure 3. The utilities are real values that indicate how a particular bid is evaluated by a negotiator. Details about the calculation of utilities are provided in the next Section.

In Figure 3, the seller's utility of a bid is on the horizontal axis, and the buyer's utility is on the vertical axis. The light area corresponds to the space of possible bids. In this area, each curve is a continuous line, corresponding to a different combination of discrete issues. The specific position on the line is determined by the continuous issue 'price'. Since in this particular domain 4 discrete issues with 5 possible values occur (see next section), there are already  $625 (= 5^4)$  different curves.

In this Figure, the sequences of actual bids made by both buyer (left) and seller (right) are indicated by the dark points that are connected by the two angular lines. The upper-left point indicates the buyer's first bid, and the lower-right point indicates the seller's first bid. The dotted line indicates the Pareto Efficient Frontier according to the profiles of the negotiating agents, and the short dark lines show the distance from each bid to this frontier. The small dot that is plotted on the Pareto Efficient Frontier (on the right) corresponds to the Nash Point. From this picture, it is clear that both negotiators make more and more concessions (their bids converge towards each other). Eventually, they reach a point that does not lie on the Pareto Efficient Frontier, but is rather close to it anyhow.



**Figure 3.** Visualisation Tool

## 5. Human Multi-Issue Negotiation Experiments

To illustrate the use of analysing human multi-issue negotiation processes, SAMIN has been applied in a case study. As mentioned in Section 4, the analysis component of SAMIN takes traces and formally specified dynamic properties as input and checks whether a property holds for a trace. Using automatic checks of this kind, some of the properties provided in Section 3 have been checked against empirical traces generated by students during practical sessions in multi-issue negotiation. The domain of the case study, a negotiation about second hand cars, is presented in detail in Section 5.1. Section 5.2 describes the setup of the experiments performed in the case study. The analytical results of the acquired traces will be shown in Section 5.3.

### 5.1 Domain: second hand cars

The protocol used in the experiments is an alternating-offers protocol. In this type of negotiation, a bid has the form of values assigned to a number of issues of the object under negotiation. Here, the object of negotiation is a particular second hand car. Within this domain, the relevant issues are *cd\_player*, *extra\_speakers*, *airco*, *tow\_hook* and *price*. Consequently, a bid consists of an indication of which CD player is meant, which extra speakers, airco and tow hook, and what the price of the bid is. The goal of the negotiators is to find agreement upon the values of the four accessories and the price. Here, the price issue has a continuous value, whilst the other four issues have a discrete value from the set {good, fairly\_good, standard, meager, none}. These values are assumed to be objective indicators from a consumer organisation, so there can be no discussion about whether a certain CD player is good or fairly good.

Before the negotiation starts, both parties specify their *negotiation profile*: for all issues with discrete values they have to assign a number to each value, indicating how satisfied they would be with that particular value for the issue (e.g. “I would be very happy to buy/sell a good CD player, a bit less happy with a fairly good CD player, ...” and so on). The buyer also has to indicate what is the maximum amount of money (s)he would be willing to spend. Moreover, both parties have to assign a number to each of the issues, indicating how important they judge that issue (e.g. “I don’t care that much which CD player I will buy/sell”). Notice that this does not conflict with the above statements. An example negotiation profile for a buyer is shown in Figure 4. In addition to this negotiation profile, the seller is provided with a *financial profile*. This is a list of all issues, where for each issue it is indicated how much it costs, both to buy it and to build it into the car. Since we focus on closed negotiation, none of the profiles will be available for the other party. However, SAMIN has access to both profiles.

When both parties have completed their profiles, the negotiation starts. To help human negotiators generating their bids, the system offers a special tool that calculates the utility of a bid before it is passed to the opponent.

The utility  $U_B$  of a bid  $B$  is defined by the weighted sum over the issue evaluation values  $E_{B,j}$  for the different issues denoted by:  $U_B = \sum_j w_j E_{B,j}$ . The weight factors  $w_j$  are based on the issue importance factors. Here scaling takes place (the sum of weight factors is made 1, and the evaluation values  $E_{B,j}$  are between 0 and 1) so that the utility is indeed is between 0 and 1; for more details, see [14]. Since the negotiators have individual negotiation profiles, for each bid the seller's utility of the bid is different from the buyer's utility of the bid.

The screenshot shows a software window titled "human\_buyer\_interface accessoire". It contains several sections for configuring a buyer's negotiation profile:

- cd\_player:** Sliders for Good (100), Fairly good (80), Standard (75), Meager (70), and None (20).
- extra\_speakers:** Sliders for Good (100), Fairly good (95), Standard (90), Meager (20), and None (20).
- airco:** Sliders for Good (97), Fairly good (98), Standard (99), Meager (100), and None (0).
- tow\_hook:** Sliders for Good (97), Fairly good (98), Standard (99), Meager (100), and None (0).
- attribute\_importance:** Sliders for Cd player (80), Extra speakers (80), Airco (20), Tow hook (30), and Price (50).
- Price:** A text input field containing "18000".
- Buttons:** "Accept" and "Stop" buttons at the bottom right.

**Figure 4.** Example Buyer's Negotiation Profile

Besides for facilitating the bidding process, the profiles are used by SAMIN to analyse the resulting traces. For example, to check whether the property Pareto-Monotony holds (i.e., "For each combination of successive bids  $b_1$ ,  $b_2$  in the trace, both agents prefer bid  $b_2$  over bid  $b_1$ "), the software must have a means to determine when an agent "prefers" one bid over another.

## 5.2 Experimental setup

**Participants.** 74 subjects participated in the experiment, in three different sessions. All sessions took place during a master class for students of the final classes of the VWO (a particular type of Dutch High School). The age of the students mostly was 17 years, but varied between 14 and 18 years. Most of them were males. In the first session, in March 2002, 30 students participated. In the second, in March 2003, 28 students participated. In the third session, in November 2003, 16 students participated.

External Bidding buyer						
<b>Own Bids:</b>						
round	cd_player	extra speakers	airco	tow hook	price	utility
1	good	good	meager	meager	15000	1
2	good	good	meager	standard	16000	0.999752
3	good	fairly good	meager	standard	19000	0.913802
4	good	fairly good	meager	standard	19400	0.880744
<b>Others Bids:</b>						
round	cd_player	extra speakers	airco	tow hook	price	utility
1	none	standard	good	standard	20013	0.773388
2	good	good	meager	standard	20077	0.828099
3	good	fairly good	meager	standard	19593	0.864793
4	good	fairly good	meager	standard	19567	0.866942
<b>Round:</b> 5						
<b>Cd player:</b>	<input type="button" value="Good"/>	<input type="button" value="Fairly good"/>	<input type="button" value="Standard"/>	<input type="button" value="Meager"/>	<input type="button" value="None"/>	
<b>Extra speakers:</b>	<input type="button" value="Good"/>	<input type="button" value="Fairly good"/>	<input type="button" value="Standard"/>	<input type="button" value="Meager"/>	<input type="button" value="None"/>	
<b>Airco:</b>	<input type="button" value="Good"/>	<input type="button" value="Fairly good"/>	<input type="button" value="Standard"/>	<input type="button" value="Meager"/>	<input type="button" value="None"/>	
<b>Tow hook:</b>	<input type="button" value="Good"/>	<input type="button" value="Fairly good"/>	<input type="button" value="Standard"/>	<input type="button" value="Meager"/>	<input type="button" value="None"/>	
<b>Price:</b>	<input type="text" value="19400"/>					
<b>Utility:</b>	<input type="text" value="0.880744"/>					
<input type="button" value="Pass on bid"/> <input type="button" value="Accept others last bid"/> <input type="button" value="No deal"/> <input type="button" value="Recalculate utility"/> <input type="button" value="Utility settings..."/>						

**Figure 5.** Example Negotiation Trace

**Method.** Before starting the experiment, the participants were provided some background information on negotiation, and in particular about multi-issue negotiation. Some basic negotiation strategies were discussed. In addition, the second hand car example was explained. Then they were asked to start negotiating, thereby taking a profile in mind (that had to be specified first) aiming at

obtaining the best possible deal, without showing their own profile to the opponent. The negotiation process was performed using different terminals over a network, which allowed each participant to negotiate with another anonymous participant. All negotiators could input their bids within a special interface. The resulting negotiation traces were logged by the system, so that they could be re-used for the purpose of analysis. A screenshot of an example negotiation trace is depicted in Figure 5. This trace is shown from the perspective of the buyer. In the upper part of the window, the buyer's own bids are displayed, including the buyer's utility for each bid. In the middle part, the bids of the seller are displayed, including the buyer's utility for each bid. The lower part consists of the bidding interface, which allows the buyer to input his bid and pass it to the seller.

### 5.3 Results of the Human Experiments

Using the SAMIN prototype, a number of relevant dynamic properties for multi-issue negotiation (also see Section 3) have been checked against the traces that resulted from the experiments. The results indicate that humans find it hard to guess where the Pareto Efficient Frontier is located. Due to space limitations, the detailed results are not shown in this paper. The interested reader is referred to [3].

## 6 Related Work

This section discusses the literature on the analysis of negotiation processes. Moreover, it reviews automated negotiation systems that use incomplete information described in the literature and compares them to our own.

In the literature on negotiation a number of systems are described. Sometimes it is stated what properties these systems have, sometimes not. If properties are mentioned they can be of different types, and also the justifications of them can be of different degree or type. This section discusses the literature on properties of negotiation and analytical results of implemented systems and of human case studies.

Faratin, Sierra, and Jennings [6] concentrate on many parties, many-issues, single-encounter closed negotiations with an environment of limited resources (time among them). Agents negotiating using the model are guaranteed to converge on a solution in a number of situations. The authors do not compare the solutions found to fair solutions (Nash Equilibrium, Maximal Social Welfare, Maximal Equitability), nor whether the solutions are Pareto Efficient.

Klein, Faratin, Sayama, and Bar-Yam [16] developed a mediator-based negotiation system to show that conceding early (by both parties) often is the key to achieving good solutions. Hyder, Prietula, and Weingart [12] showed that substantiation (providing rationale for your position to persuade the other person to change their mind) interferes with the discovery of optimal agreements.

Weingart et al. [24] found that the Pareto efficiency of agreements between naïve negotiators could be significantly improved by simply providing negotiators with descriptions of both integrative and distributive tactics. Although Pareto *efficiency* was positively influenced by the tactics, Pareto *optimality* was only minimally affected. Compared to [8, 11, 12], the properties identified in this paper are geared towards the analysis of the dynamics of the negotiation process, whereas theirs are more oriented towards the negotiation outcome, rationality and use of resources.

In [8], a model for bilateral multi-issue negotiation is presented, where issues are negotiated sequentially. The issue studied is the optimal agenda for such a negotiation under both incomplete information and time constraints. However a central mediator is used and the issues all have continuous values. The effect of time on the negotiation equilibrium is the main feature studied, from both a game-theoretic and empirical perspective. In earlier research [7] a slightly different model is proposed, but the focus of the research is still on time constraints and the effect of deadlines on the agents' strategies. This contrast with our model, where efficiency of the outcome and not time is the main issue studied. This is because we found that, due to our cooperative assumption, a deal is usually reached in maximum 10-15 steps, if the negotiation speed and tolerance parameters are suitably calibrated.

A direction of work directly related to guessing heuristic is represented by [5], [2] and [5]. Like [5] we start from the perspective of distributed negotiation, which eliminates the need of a central planner. As in [5], in [2] we also take the heuristic approach and we model agents that are able to jointly explore the space of possible outcomes with a limited (incomplete) information assumption. In [5], this is done through a trade-off mechanism, in which the agent selects the value of its next offer based on a similarity degree with previous bids of the opponent. In our design, we do not explicitly model trade-offs, yet the same effect is achieved through the asymmetric concessions mechanism. An advantage of our model over [5] is that we allow agents to take into account not only their own weights, but also those of the opponent in order to compute the next bid. In this way agents may exchange partial preference information for those issues for which their owners feel this does not violate their privacy. Also the initial domain information for the issues with discrete ("qualitative") values is different. In [5], this consists of fuzzy values, while in our model it is a partial ordering of issue weights.

## 7 Conclusions and Future Work

The contribution of this work consists of a systematic approach to the analysis of the negotiation process. Different types of properties are identified and for each class a number of properties are defined. The System for Analysis of Multi-Issue Negotiation (SAMIN) is presented and applied in two ways: to analyse human negotiation in a case study and to analyse the effectiveness of guessing and limited information exchange as implemented in a number of software agents. SAMIN consists

of three components: an Acquisition Component to acquire the input necessary for analysis, an Analysis Component to perform the actual analysis, and a Presentation Component to presents the results of the analysis in a user-friendly format.

The system has proved to be a valuable tool to analyse the dynamics of human-human closed negotiation against a number of dynamic properties. Our analysis shows that humans find it difficult to guess where the Pareto Efficient Frontier is located, making it difficult for them to accept a proposal. Although humans apparently do not negotiate in a strictly Pareto-monotonous way, when considering larger intervals, a weak monotony can be discovered. Such analysis results can be useful in two different ways: to train human negotiators, or to improve the strategies of software agents.

Currently, SAMIN is being used to analyse the dynamics of humans negotiating against software agents (with and without guessing strategy, also in setting in which limited preference information is shared; e.g. [13]). Future research is to analyse the dynamics of other types of (e.g., more experienced) human negotiators. Furthermore, the system needs to allow heterogeneous agents, so that a competition of negotiating agents can be set up and the results of that competition formally analysed. In future, SAMIN will be extended with training facilities for human negotiators, allowing to test the effectiveness of training methods for negotiation. As a simple extension, for example, if a dynamic property checked in a trace turns out to fail, a more detailed analysis can be given of the part(s) of the formula that cause(s) the failure. Finally, we plan to extend SAMIN to provide feedback to a negotiator who is in the middle of a negotiation process, where SAMIN only has access to the same information as the negotiator.

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## Appendix A - Dynamic Properties of Negotiation Processes

### **bid\_alternation( $\gamma$ :trace)**

Over time the bids of A and B alternate: thus for all two different moments in time  $t_1, t_3$ , that A generated a bid, there is a moment in time  $t_2$ , with  $t_1 < t_2 < t_3$ , such that A received a bid generated by B.

$\forall A, B: \text{AGENT}, \forall b_1, b_3: \text{BID}, \forall t_1, t_3:$

$$\begin{aligned} & t_1 < t_3 \ \& \\ & \text{state}(\gamma, t_1, \text{output}(A)) \models \text{to\_be\_communicated\_to\_by}(b_1, B, A) \ \& \\ & \text{state}(\gamma, t_3, \text{output}(A)) \models \text{to\_be\_communicated\_to\_by}(b_3, B, A) \ \Rightarrow \\ & \quad \exists b_2, \exists t_2: t_1 < t_2 < t_3 \ \& \\ & \quad \text{state}(\gamma, t_2, \text{input}(A)) \models \text{communicated\_to\_by}(b_2, A, B) \end{aligned}$$

### **is\_followed\_by( $\gamma$ :trace, A:AGENT, t1:time, b1:BID, B:AGENT, t2:time, b2:BID)**

In a negotiation process  $\gamma$  bid  $b_1$  at time  $t_1$  is followed by a bid  $b_2$  at time  $t_2$  iff bids  $b_1$  and  $b_2$  are subsequent bids in  $\gamma$ .

$$\begin{aligned} & \text{state}(\gamma, t_1, \text{output}(A)) \models \text{to\_be\_communicated\_to\_by}(b_1, A, B) \ \& \\ & \text{state}(\gamma, t_2, \text{output}(B)) \models \text{to\_be\_communicated\_to\_by}(b_2, B, A) \ \& \\ & t_1 < t_2 \ \& \\ & [ \forall t_3, \forall C, D: \text{AGENT}, \forall b_3: \text{BID}: \\ & \quad t_1 < t_3 < t_2 \Rightarrow \text{state}(\gamma, t_3, \text{output}(C)) \not\models \text{to\_be\_communicated\_to\_by}(b_3, C, D) ] \end{aligned}$$

### **agent\_consecutively\_bids\_to( $\gamma$ :trace, A:AGENT, t1:time, b1:BID, t2:time, b2:BID, B:AGENT)**

In a negotiation process  $\gamma$  agent A consecutively bids  $b_1$  at time  $t_1$  and then  $b_2$  at time  $t_2$  to agent B.

$$\begin{aligned} & \text{state}(\gamma, t_1, \text{output}(A)) \models \text{to\_be\_communicated\_to\_by}(b_1, A, B) \ \& \\ & \text{state}(\gamma, t_2, \text{output}(A)) \models \text{to\_be\_communicated\_to\_by}(b_2, A, B) \ \& \\ & t_1 < t_2 \ \& \\ & [ \forall t_3, \forall b_3: \text{BID}: t_1 < t_3 < t_2 \Rightarrow \text{state}(\gamma, t_3, \text{output}(A)) \not\models \text{to\_be\_communicated\_to\_by}(b_3, A, B) ] \end{aligned}$$

### **stop\_criterion( $\gamma$ :trace, A:AGENT, t2:time)**

The stop criterion holds for agent A at time  $t$ , if at time  $t$  agent A receives a bid by negotiation partner B that is at least as good as the last bid made by A.

$$\begin{aligned} & \exists t_1, \exists B: \text{AGENT}, \exists b_1, b_2: \text{BID}: \\ & \quad \text{state}(\gamma, t_2, \text{input}(A)) \models \text{communicated\_to\_by}(b_2, A, B) \ \& \\ & \quad \text{state}(\gamma, t_1, \text{output}(A)) \models \text{to\_be\_communicated\_to\_by}(b_1, B, A) \ \& \\ & \quad \text{is\_followed\_by}(\gamma, t_1, b_1, t_2, b_2) \ \& \\ & \quad \text{util}(\gamma, A, b_1) \leq \text{util}(\gamma, A, b_2) \end{aligned}$$

### **negotiation\_continuation( $\gamma$ :trace)**

For both A and B, unless the stop criterion holds, a new proposal is generated by A upon receipt of a proposal by B.

$\forall t, \forall A, B: \text{AGENT}, \forall b1: \text{BID}$ :

$\neg \text{stop\_criterion}(\gamma, A, t) \ \&$

$\text{state}(\gamma, t, \text{input}(A)) \models \text{communicated\_to\_by}(b1, A, B) \Rightarrow$

$[ \exists b2: \text{BID} \exists t2: t2 > t \ \& \ \text{state}(\gamma, t2, \text{output}(A)) \models \text{to\_be\_communicated\_to\_by}(b2, B, A) ]$

**strictly\_dominates(b1: BID, b2: BID, A: AGENT, B: AGENT)**

A bid b1 dominates a bid b2 with respect to agents A and B iff both agents prefer bid b1 over bid b2.

$\forall vA1, vA2, vB1, vB2 : \text{real} :$

$\text{util}(A, b1, vA1) \ \& \ \text{util}(A, b2, vA2) \ \& \ \text{util}(B, b1, vB1) \ \& \ \text{util}(B, b2, vB2) \Rightarrow$

$vA1 > vA2 \ \& \ vB1 > vB2$

**weakly\_dominates(b1: BID, b2: BID, A: AGENT, B: AGENT)**

A bid b1 dominates a bid b2 with respect to agents A and B iff both agents prefer bid b1 over bid b2.

$\forall vA1, vA2, vB1, vB2 : \text{real} :$

$\text{util}(A, b1, vA1) \ \& \ \text{util}(A, b2, vA2) \ \& \ \text{util}(B, b1, vB1) \ \& \ \text{util}(B, b2, vB2) \Rightarrow vA1 \geq vA2 \ \& \ vB1 \geq vB2$

**strictly\_better\_social\_welfare(b1: BID, b2: BID, A: AGENT, B: AGENT)**

The social welfare of bid b1 is better than that of bid b2 with respect to agents A and B iff the sum of the utility values of bid b1 is bigger than the sum of the utility values of bid b2. See also [6,10].

$\forall vA1, vA2, vB1, vB2 : \text{real} :$

$\text{util}(A, b1, vA1) \ \& \ \text{util}(A, b2, vA2) \ \& \ \text{util}(B, b1, vB1) \ \& \ \text{util}(B, b2, vB2) \Rightarrow vA1 + vB1 > vA2 + vB2$

**strictly\_better\_equitability(b1: BID, b2: BID, A: AGENT, B: AGENT)**

A bid b1 has a better equitability than bid b2 with respect to agents A and B iff the difference in the utility values of bid b1 is less than the difference in utility values of bid b2.

$\forall vA1, vA2, vB1, vB2 : \text{real} :$

$\text{util}(A, b1, vA1) \ \& \ \text{util}(A, b2, vA2) \ \& \ \text{util}(B, b1, vB1) \ \& \ \text{util}(B, b2, vB2) \Rightarrow |vA1 - vB1| < |vA2 - vB2|$

**$\epsilon$ -equitability(b: BID, A: AGENT, B: AGENT,  $\epsilon$ : real)**

A bid b has  $\epsilon$ -equitability with respect to agents A and B iff the difference in the utility values of bid b is less than  $\epsilon$ . Thus, a bid that has an equitability of 0 has a maximum equitability. This definition corresponds to the idea of Raiffa to maximize the minimum utility [21].

$\forall vA, vB : \text{real} :$

$\text{util}(A, b, vA) \ \& \ \text{util}(B, b, vB) \Rightarrow |vA - vB| \leq \epsilon$

**pareto\_inefficiency(b: BID, A: AGENT, B: AGENT,  $\epsilon$ : real)**

With respect to agents A and B, the Pareto inefficiency of a bid b is the number  $\epsilon$  that indicates the distance to the Pareto Efficient Frontier according to some distance measure d in utilities. Here  $d(b1, b2)$  is the distance between the bids b1 and b2 when viewed as points in the plane of utilities.

$\forall vA, vB : \text{real} :$

$\text{util}(A, b, vA) \ \& \ \text{util}(B, b, vB) \Rightarrow \text{pareto\_distance}(vA, vB) = \epsilon$

**making\_global\_concession( $\gamma$ :trace, A:AGENT, t1:time, b1: BID, t2:time, b2: BID, B:AGENT)**

In a negotiation process  $\gamma$  agent B makes a global concession to agent B with respect to bid b1 at time t1 and bid b2 at time t2 iff both bids are consecutive, and b2 has a lower utility than b1, from A's perspective. A similar property could be defined stating that an agent receives a global concession from another agent.

agent\_consecutively\_bids\_to( $\gamma$ , A, t1, b1, t2, b2, B) &

$\forall vA1, vA2 : \text{real} :$

$$\text{util}(A, b1, vA1) \ \& \ \text{util}(A, b2, vA2) \Rightarrow vA1 > vA2$$

**configuration\_differs(b1: BID, b2: BID)**

Two bids b1 and b2 differ in configuration iff there is an issue that has a different value in both bids. Similar properties could be defined stating that two bids differ in configuration in at least x issues.

$\exists a: \text{ISSUE}, \exists v1, v2: \text{VALUE}:$

$$\text{value\_of}(b1, a, v1) \ \& \ \text{value\_of}(b2, a, v2) \ \& \ v1 \neq v2$$

**agent\_views\_agent\_makes\_config\_variation( $\gamma$ :trace, A:AGENT, B:AGENT, t1:time, b1: BID, t2:time, b2: BID)**

In the view of agent A, agent B varies the configuration, but not the utility. Note that one agent can both be agent A and B, or A and B can refer to different agents.

agent\_consecutively\_bids\_to( $\gamma$ , A, t1, b1, t2, b2, B) &

configuration\_differs(b1, b2) &

$\forall vA1, vA2 : \text{real} :$

$$\text{util}(A, b1, vA1) \ \& \ \text{util}(A, b2, vA2) \Rightarrow vA1 = vA2$$

**agent\_views\_agent\_makes\_strict\_ε-progression( $\gamma$ :trace, A:AGENT, B:AGENT, t1:time, b1: BID, t2:time, b2: BID, ε:real)**

In the view of agent A, the two consecutive bids b1 and b2 made at times t1 and t2 by agent B show minimum  $\epsilon$ -progression in utility iff the second bid is at least  $\epsilon$  higher than the first bid. Note that one agent can both be agent A and B, or A and B can refer to different agents.

agent\_consecutively\_bids\_to( $\gamma$ , A, t1, b1, t2, b2, B) &

$\forall vA1, vA2 : \text{real} :$

$$\text{util}(A, b1, vA1) \ \& \ \text{util}(A, b2, vA2) \Rightarrow vA2 - vA1 > \epsilon$$

**strict\_pareto\_monotony( $\gamma$ :trace, tb:time, te:time)**

A negotiation process  $\gamma$  is Strictly Pareto-monotonous for the interval [t1, t2] iff for all subsequent bids b1, b2 in the interval b2 dominates b1:

$\forall t1, t2, \forall A, B: \text{AGENT}, \forall b1, b2: \text{BID}$

$$[ \text{tb} \leq t1 < t2 \leq \text{te} \ \& \ \text{is\_followed\_by}(\gamma, A, t1, b1, B, t2, b2) ]$$

$$\Rightarrow \text{strictly\_dominates}(\gamma, b2, b1, A, B)$$

**weak\_pareto\_monotony( $\gamma$ :trace,  $t_b$ :time,  $t_e$ :time)**

A negotiation process  $\gamma$  is Weakly Pareto-monotonous for the interval  $[t_1, t_2]$  iff for all subsequent bids  $b_1$ ,  $b_2$  in the interval  $b_2$  weakly dominates  $b_1$ :

$\forall t_1, t_2, \forall A, B: \text{AGENT}, \forall b_1, b_2: \text{BID}$

[  $t_b \leq t_1 < t_2 \leq t_e$  &  $\text{is\_followed\_by}(\gamma, A, t_1, b_1, B, t_2, b_2)$  ]

$\Rightarrow \text{weakly\_dominates}(\gamma, b_2, b_1, A, B)$

Internet address for download:

<http://www.few.vu.nl/~wai/samin>

Contact point for questions about the software:

see <http://www.few.vu.nl/~wai/samin>