A formal analysis of the role of argumentation in negotiation dialogues

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Abstract

This paper proposes an *abstract* framework for argumentation-based negotiation in which the impact of exchanging arguments on agents' theories is formally described, the different types of solutions in negotiation are investigated, and the added value of argumentation in negotiation dialogues is analyzed. We study when, how and to which extent an exchange of arguments can be beneficial in negotiation. The results show that argumentation can improve the quality of an outcome but never decrease it.

Key words: Negotiation, Argumentation

1 Introduction

1.1 What is negotiation?

Negotiation is a process that aims at finding some *compromise* or *consensus* on an issue between two or more agents having different *goals*. In the negotiation literature, the issue under negotiation is called the *negotiation object*. Examples of negotiation objects are: the price of a given product, the date and/or the place of a meeting and so on. In the seminal book by Walton and Krabbe [38], the object concerns the share of some goods or services.

Throughout the paper, $\mathcal{O}$ denotes a set of possible values, called *offers*, that can be assigned to a negotiation object. For instance, if agents negotiate about an allocation of a set of resources, $\mathcal{O}$ will contain all the possible allocations. Thus, negotiation amounts to find among elements of $\mathcal{O}$ the one that will be the solution.

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The main question is 'why do agents need to negotiate'? The answer is that each negotiating agent has a binary relation $\succeq$ on the set $\mathcal{O}$ (or on a finite subset of it) reflecting its goals. For two offers o_1 and o_2 of the set $\mathcal{O}$, $(o_1, o_2) \in \succeq$ (or equivalently $o_1 \succeq o_2$) means that o_1 is at least as good as o_2 for the agent. Unfortunately, the relations of the negotiating agents may not be the same. The most preferred element for an agent may be the worst one for another agent. Consequently, agents exchange offers and maybe other information in order to reach a final decision. They may even need to make *concessions*, i.e. to accept less preferred offers.

1.2 Main approaches to negotiation

A huge amount of work was done for modeling negotiation. In [22], the authors argued that there are three types of approaches for negotiation in MAS literature: *game-theoretic* approach, *heuristic-based* approach and finally *argumentation-based negotiation* (ABN). In what follows, we will briefly describe the two first approaches, whereas the third one will be discussed in the next section.

Game-theoretic approach is based on studying and developing strategic negotiation models based on game-theoretic precedents [33,37]. The basic idea is to see the interaction as a game in which each agent tries to maximize her utility. Given a protocol, most researchers in this line of work attempt to analyze the optimal strategy. While this approach is very powerful in terms of results analysis, it suffers from some drawbacks due to the assumptions upon which it is built. The most important ones are i) agents are only allowed to exchange offers, and ii) the preference relation $\succeq$ on $\mathcal{O}$ is fixed during a negotiation for an agent. These assumptions are not realistic since in everyday life, other information than offers may be exchanged. Moreover, it is very common that preferences on $\mathcal{O}$ may change. Let us illustrate this idea through the following example encountered in the academic world when new researchers are being recruited. Two professors, say Pr_1 and Pr_2, want to employ a new research assistant on a European project. Three candidates, Carla, John and Mary are interested in the position. Unfortunately, the two professors have conflicting preferences. Professor Pr_1 prefers Carla to John and John to Mary (i.e. Carla $\succeq_1$ John $\succeq_1$ Mary). However, professor Pr_2 prefers John to Carla and Carla to Mary (i.e. John $\succeq_2$ Carla $\succeq_2$ Mary). The following dialogue may take place between the two agents:

Pr_1: I suggest to recruit Carla
Pr_2: No, I prefer John. He is working on my research topic.
Pr_1: But, you know that Carla has a better publication record than John. Moreover, recently she did a very interesting work on your topic.
Pr_2: Really, I didn't know that. So let's give her the position then.

In this dialogue, Pr_2 received a strong argument in favor of Carla which leads him to change his preference between John and Carla.

The second category of approaches, i.e. the heuristic-based one, comes to cope with some limitations of the game-theoretic approach (e.g. [17,22]). Heuristics are rules of thumb that ensure good enough rather than optimal solutions. For that purpose, some strong assumptions made in game-theoretic approach are relaxed. Most of these assumptions concern the notion of rationality of agents as well as their resources. Unfortunately, this approach suffers from the drawback related to fixed preferences, i.e. the relation $\succeq$ remains the same during a negotiation.

1.3 Why arguing in negotiation?

Argumentation is considered as a reasoning model based on the construction and evaluation of interacting arguments. Those arguments are intended to support/attack statements that can be decisions, opinions, and so on. Let us recall below a definition given by philosophers in [36, page 5].

> *Argumentation is a verbal and social activity of reason aimed at increasing (or decreasing) the acceptability of a controversial standpoint for the listener or reader, by putting forward a constellation of propositions intended to justify (or refute) the standpoint before a rational judge.*

Argumentation has developed into an important area of study in artificial intelligence over the last eighteen years, especially in sub-fields such as non-monotonic reasoning (e.g. [13,29]), multiple-source information systems (e.g. [4]) and decision making (e.g. [8,12,18]). Moreover, it was shown that such an approach is general enough to capture some existing approaches for non-monotonic reasoning [15]. Argumentation has also been extensively used for modeling different kinds of dialogues, in particular persuasion (e.g. [5,19,27]), inquiry (e.g. [11,26]) and deliberation (e.g. [10,21]).

In the early nineties, Sycara emphasized the importance of using argumentation techniques even in negotiation [34]. Since then, several works were done including work by Parsons and Jennings [25], Reed [32], Kraus et al. [24], Tohmé [35], Amgoud et al. [2,6,7], and Kakas and Moraitis [23]. The basic idea behind an argumentation-based approach for negotiation is to allow agents not only to exchange offers but also reasons that support these offers in order to mutually influence their preference relation on the set of offers, and consequently the outcome of the dialogue. By exchanging arguments, the theories of the agents (i.e. their mental states) may evolve and thus, the *status* of offers may change. For instance, an agent may accept an offer (which was rejected) after receiving a strong argument in favor of this offer. Let us consider again the example of the two professors who want to recruit a new researcher. If these professors are only allowed to exchange offers (candidates in this case), then there is no way to change their preferences. Thus, there are three possibilities:

(1) One of the professors concedes, and accepts the offer of the other. In this case, that professor will not be fully satisfied, whereas the other is.
(2) No one agrees to make a concession, and they decide to recruit the worst candidate for both. In this case, both professors are fully unsatisfied.
(3) They decide to not recruit anyone.

However, if the previous dialogue takes place, then professor Pr_2 changes his preference between John and Carla in light of a new argument. Note that by making such a change, the solution is "optimal" for both professors.

1.4 Contribution of the paper

As said before, several proposals were made in the literature for modeling argumentation-based negotiation (see [31] for a survey). Most of them were interested in proposing protocols which show how arguments and offers can be generated, evaluated and exchanged in a negotiation dialogue. Unfortunately, except the termination of each dialogue generated under those protocols, nothing is said on their *quality*. In particular, it is not clear what kind of *solutions* (or *outcomes*) that are reached by their dialogues. Moreover, it is not clear whether an *optimal solution* (when it exists) can be reached by a dialogue under such protocols. The reason is simply that the notion of optimal solution is not defined for argument-based negotiations. Indeed, there is no study on the types of outcomes that may be reached in such rich negotiations. It is also worth mentioning that before the work done in [2], it was not even yet clear how new arguments may influence the preferences of an agent. In that paper, each agent is equipped with a *theory* which is an argumentation system that computes a preference relation on the set of offers. It was shown that the *theory* of an agent may evolve when new arguments are received, and consequently the initial preference relation may change. However, it is not clear how this evolution of agents' theories may have an impact on the outcome of a negotiation. In other words, is this theories' evolution always beneficial for a negotiation and for the agents?

The contribution of this paper is twofold. It characterizes for the first time the possible outcomes of ABN dialogues. Three kinds of outcomes (solutions) are identified: *local* solutions, Pareto optimal solutions and *ideal* solutions. Local and Pareto optimal solutions are the best outcomes at a given step of a dialogue while an ideal solution is the best solution in general and is time-independent. The second important contribution of this paper consists in studying to what extent argumentation may be beneficial in a negotiation dialogue. We show that arguing is always beneficial since it pushes towards discovering the ideal solution (when it exists). When such a solution does not exist, arguing allows agents to make better decisions (i.e. under more information). Our study is undertaken at an abstract level since we do not bother on dialogue protocols and strategical issues. Thus, our results are true under any protocol and using any strategy.

1.5 Outline of the paper

This paper is organized as follows: Section 2 presents the agent's theory, that is the argumentation system used by the agent for generating the preference relation over offers. Section 3 proposes a negotiation framework in which a very basic definition of a negotiation dialogue is provided. Section 4 defines different types of negotiation solutions while Section 5 investigates the added value of argumentation in ABN dialogues. Section 6 is devoted to related work while Section 7 concludes the paper by summarizing its contribution and by pointing out some possibilities for future work.

2 Agent Theory

The theory of a negotiating agent is an argumentation system that is used in order to generate and evaluate arguments, and for rank-ordering offers in a negotiation dialogue. It is thus a decision system based on argumentation. A decision problem amounts to defining a pre-ordering, usually a complete one, on a set of alternatives (offers in our case) on the basis of the different consequences of each alternative. In an argumentation-based approach, alternatives are compared on the basis of their arguments pros/cons. An argument pro highlights a positive consequence while an argument cons refers to a negative one. An argumentation-based decision process can be decomposed into the following steps:

(1) Constructing arguments *in favor/against* statements (pertaining to beliefs or options);
(2) Evaluating the strength of each argument;
(3) Determining the different conflicts among arguments
(4) Evaluating the acceptability of the arguments;
(5) Comparing decisions on the basis of the "accepted" arguments.

Throughout the paper, $\mathcal{L}$ denotes a logical language from which a set $\mathcal{O}(\mathcal{L})$ of distinct offers is identified. Two other sets are distinguished. The first set, denoted by $\texttt{Arg}_e(\mathcal{L})$, contains *epistemic arguments* while the second set, $\texttt{Arg}_p(\mathcal{L})$, gathers all *practical arguments*. An epistemic argument justifies a belief and is itself based only on beliefs, whereas a practical argument justifies an offer and is built from both beliefs and goals. Let us illustrate the two kinds of arguments on the following example borrowed from [18].

Example 1 (Having or not a surgery) *The example is about having a surgery (sg) or not ($\neg sg$), knowing that the patient has colonic polyps. The knowledge base contains the following information:*

- *not having surgery avoids having side-effects,*
- *when having a cancer, having a surgery avoids loss of life,*
- *the patient has colonic polyps,*
- *having colonic polyps may lead to cancer.*

In addition to the above knowledge, the patient has also some goals like: "no loss of life" and "no side effects". We assume that the first goal is more important for the patient than the second one.

In this example, α = ["the patient has colonic polyps", and "having colonic polyps may lead to cancer"] is considered as an argument for believing that the patient may have cancer. This epistemic argument involves only beliefs. While δ_1 = ["the patient may have a cancer", "when having a cancer, having a surgery avoids loss of life"] is an argument for choosing the options "having a surgery". This is a practical argument and it involves both beliefs and goals. Similarly, δ_2 = ["not having surgery avoids having side-effects"] is a practical argument in favor of "not having a surgery".

We assume that $\texttt{Arg}(\mathcal{L}) = \texttt{Arg}_e(\mathcal{L}) \cup \texttt{Arg}_p(\mathcal{L})$ and $\texttt{Arg}_e(\mathcal{L}) \cap \texttt{Arg}_p(\mathcal{L}) = \emptyset$. The structure and origin of the arguments are assumed to be unknown. Epistemic arguments will be denoted by variables $\alpha_1, \alpha_2, \ldots$, while practical arguments will be referred to by variables $\delta_1, \delta_2, \ldots$. When no distinction is necessary between arguments, we will use the variables $a, b, c, \ldots$.

Throughout the paper, we assume that arguments in $\texttt{Arg}_p(\mathcal{L})$ highlight *positive* features of the options they support, i.e. they are pro offers. The reason of this restriction is due to the fact that the decision rule that will be used for rank-ordering offers is the qualitative *optimistic* criterion defined and axiomatized in [14]. Moreover, in [8] it has been shown that such a criterion is captured by arguments pro meaning that arguments con options are not needed.

In the argumentation literature, it has been acknowledged that arguments may not have equal strength. Some arguments may be stronger than others for different reasons. For instance, because they are built from more certain information. In [3], three preference relations between arguments are defined. The first one, denoted by $\geq_e$, is a *partial preorder* (i.e. a *reflexive* and *transitive* binary relation) on the set $\mathtt{Arg}_e(\mathcal{L})$. The second relation, denoted by $\geq_p$, is a partial preorder on the set $\mathtt{Arg}_p(\mathcal{L})$. Finally, a third relation, denoted by $\geq_m$ (m stands for mixed relation), captures the idea that any epistemic argument is stronger than any practical argument. The role of epistemic arguments in a decision problem is to validate or to undermine the beliefs on which practical arguments are built. Indeed, decisions should be made under "certain" information. Thus, $\forall \alpha \in \mathtt{Arg}_e(\mathcal{L})$, $\forall \delta \in \mathtt{Arg}_p(\mathcal{L})$, $(\alpha, \delta) \in \geq_m$ and $(\delta, \alpha) \notin \geq_m$. Note that $(a, b) \in \geq_x$ (or equivalently $a \geq_x b$), with $x \in \{e, p, m\}$, means that a is *at least as good as* b. The symbol $>_x$ denotes the strict relation associated with $\geq_x$. It is defined as follows: $(a, b) \in >_x$ iff $(a, b) \in \geq_x$ and $(b, a) \notin \geq_x$. When $(a, b) \in \geq_x$ and $(b, a) \in \geq_x$, a and b are said to be *indifferent*. When $(a, b) \notin \geq_x$ and $(b, a) \notin \geq_x$, the two arguments are said to be *incomparable*. Let $\geq\, = \,\geq_e \cup \geq_p \cup \geq_m$.

Example 1 (Cont): From the definition of $\geq_m$, it follows that $\alpha >_m \delta_1$ and $\alpha >_m \delta_2$. Regarding $\geq_p$, one may assume that δ_1 is stronger than δ_2 since the goal satisfied by δ_1 (namely, not loss of life) is more important than the one satisfied by δ_2 (not having side effects). Thus, $\delta_1 >_p \delta_2$.

2.2 Attacks among arguments

Generally arguments may be conflicting. These conflicts are captured by a *binary relation* on the set of arguments. Three such relations are distinguished:

- The first relation, denoted by $\mathcal{R}_e(\mathcal{L})$, captures the different conflicts that may exist between epistemic arguments. Thus, $\mathcal{R}_e(\mathcal{L}) \subseteq \mathtt{Arg}_e(\mathcal{L}) \times \mathtt{Arg}_e(\mathcal{L})$.
- Practical arguments may also be conflicting. These conflicts are captured by the binary relation $\mathcal{R}_p(\mathcal{L}) \subseteq \mathtt{Arg}_p(\mathcal{L}) \times \mathtt{Arg}_p(\mathcal{L})$. Indeed, since options are distinct and competitive (i.e. only one option will be chosen), arguments in favor of different offers are assumed to be conflicting. However, arguments supporting the same offer are not since they are defending the same option. Formally: $\forall \delta, \delta' \in \mathtt{Arg}_p(\mathcal{L})$, $(\delta, \delta') \in \mathcal{R}_p(\mathcal{L})$ iff $\mathtt{Conc}(\delta) \neq \mathtt{Conc}(\delta')$.
- Finally, practical arguments may be attacked by epistemic ones. The idea is that an epistemic argument may undermine the beliefs part of a practical

argument. However, practical arguments are not allowed to attack epistemic ones. This avoids wishful thinking. This relation, denoted by $\mathcal{R}_m(\mathcal{L})$, contains pairs (α, δ) where $\alpha \in \mathtt{Arg}_e(\mathcal{L})$ and $\delta \in \mathtt{Arg}_p(\mathcal{L})$.

It is clear that relation $\mathcal{R}_p(\mathcal{L})$ is symmetric and $\mathcal{R}_m(\mathcal{L})$ is asymmetric. Let $\mathcal{R}(\mathcal{L}) = \mathcal{R}_e(\mathcal{L}) \cup \mathcal{R}_p(\mathcal{L}) \cup \mathcal{R}_m(\mathcal{L})$.

Example 1 (Cont): $\mathcal{R}_e = \emptyset$, $\mathcal{R}_m = \emptyset$, while $(\delta_1, \delta_2) \in \mathcal{R}_p(\mathcal{L})$ and $(\delta_2, \delta_1) \in \mathcal{R}_p(\mathcal{L})$.

2.3 Decision system

Now that the sets of arguments and the defeat relations are identified, we can define the decision system (or agent theory) as proposed in [3].

Definition 1 (Agent theory) *An* agent theory *is a tuple* $\mathtt{AF} = (\mathcal{O}, \mathcal{A}, \mathcal{R}, \geq, \mathcal{F})$ *where* $\mathcal{O}$ *is a finite subset of* $\mathcal{O}(\mathcal{L})$*,* $\mathcal{A}$ *is a finite subset of* $\mathtt{Arg}(\mathcal{L})$*,* $\mathcal{R} = \mathcal{R}(\mathcal{L})_{\downarrow \mathcal{A}}$ [1]*,* $\geq \subseteq \mathtt{Arg}(\mathcal{L}) \times \mathtt{Arg}(\mathcal{L})$ *with* $\geq$ *is a partial or total preorder, and* $\mathcal{F} : \mathcal{O} \rightarrow 2^{\mathcal{A} \cap \mathtt{Arg}_p(\mathcal{L})}$ *s.t.* $\mathcal{A} \cap \mathtt{Arg}_p(\mathcal{L}) = \bigcup \mathcal{F}(o_i)$ *with* $o_i \in \mathcal{O}$ *and* $\forall o_i, o_j \in \mathcal{O}$ *if* $o_i \neq o_j$*, then* $\mathcal{F}(o_i) \cap \mathcal{F}(o_j) = \emptyset$*.*
When $a \in \mathcal{F}(o)$*, we say that* o *is the* conclusion *of* a *and write* $\mathtt{Conc}(a) = o$*.*

Arguments are evaluated using any acceptability semantics. For an illustrative purpose, we recall below some of the semantics defined in [15]. They define sets of arguments that satisfy a consistency requirement and must defend all their elements.

Definition 2 (Conflict-free, Defence) *Let* $\mathtt{AF} = (\mathcal{O}, \mathcal{A}, \mathcal{R}, \geq, \mathcal{F})$ *be an agent theory,* $\mathcal{B} \subseteq \mathcal{A}$ *and* $a \in \mathcal{A}$*.*

- $\mathcal{B}$ *is* conflict-free *iff* $\nexists\, a, b \in \mathcal{B}$ *s.t.* $(a, b) \in \mathcal{R}$ *and* $(b, a) \notin >$*.*
- $\mathcal{B}$ defends a *iff* $\forall\, b \in \mathcal{A}$*, if* $(b, a) \in \mathcal{R}$ *and* $(a, b) \notin >$*, then* $\exists c \in \mathcal{B}$ *s.t.* $(c, b) \in \mathcal{R}$ *and* $(b, c) \notin >$*.*

The main semantics introduced by Dung are recalled below.

Definition 3 (Acceptability semantics) *Let* $\mathtt{AF} = (\mathcal{O}, \mathcal{A}, \mathcal{R}, \geq, \mathcal{F})$ *be an agent theory, and* $\mathcal{B}$ *a conflict-free set of arguments.*

- $\mathcal{B}$ *is an* admissible extension *iff it defends any element in* $\mathcal{B}$*.*
- $\mathcal{B}$ *is a* preferred extension *iff* $\mathcal{B}$ *is a maximal (w.r.t set* $\subseteq$*) admissible set.*

[1] $\mathcal{R}(\mathcal{L})_{\downarrow \mathcal{A}}$ is the restriction of $\mathcal{R}(\mathcal{L})$ to arguments in $\mathcal{A}$.

- $\mathcal{B}$ *is a* stable extension *iff it defeats any argument in* $\mathcal{A} \backslash \mathcal{B}$.

Using these semantics, the status of each argument can be defined as follows.

Definition 4 (Argument status) *Let* $\texttt{AF} = (\mathcal{O}, \mathcal{A}, \mathcal{R}, \geq, \mathcal{F})$ *be an agent theory, and* $\mathcal{E}_1, \ldots, \mathcal{E}_n$ *its extensions under a given semantics. Let* $a \in \mathcal{A}$.

- a *is* skeptically accepted *iff* $a \in \cap \mathcal{E}_i$, $i \in \{1, \ldots, n\}$.
- a *is* credulously accepted *iff* $\exists i, j \in \{1, \ldots, n\}$ *such that* $a \in \mathcal{E}_i$ *and* $a \notin \mathcal{E}_j$.
- a *is* rejected *iff* $a \notin \cup \mathcal{E}_i$, $i \in \{1, \ldots, n\}$.

Example 1 (Cont): In this example, $\mathcal{O} = \{sg, \neg sg\}$, $\mathcal{A} = \{\alpha, \delta_1, \delta_2\}$ and $\mathcal{R} = \{(\delta_1, \delta_2), (\delta_2, \delta_1)\}$. This theory has exactly one extension $\{\alpha, \delta_1\}$ which is both stable and preferred. Thus, the arguments α and δ_1 are skeptically accepted while δ_2 is rejected.

2.4 Comparing offers

Recall that the main objective in a decision problem consists of ordering a set $\mathcal{O}$ of offers. Such an ordering is defined on the basis of a *status* assigned to each offer. For the purpose of our paper, we only recall the statuses that produce a preordering on the set $\mathcal{O}$.

Definition 5 (Credulous offer) *Let* $\texttt{AF} = (\mathcal{O}, \mathcal{A}, \mathcal{R}, \geq, \mathcal{F})$ *be an agent theory and* $o \in \mathcal{O}$. *Offer* o *is* credulous *iff there exists an extension* $\mathcal{E}$ *of* AF *(under a given semantics) such that* $\exists \delta \in \mathcal{F}(o)$ *and* $\delta \in \mathcal{E}$. *Let* $\mathcal{O}_c(\texttt{AF})$ *denote the set of credulous offers of* AF.

Two other types of offers are defined: the ones that are not supported at all by arguments, and the ones whose arguments are all rejected in the theory.

Definition 6 (Rejected offer/Non-supported offer) *Let* $\texttt{AF} = (\mathcal{O}, \mathcal{A}, \mathcal{R}, \geq, \mathcal{F})$ *be an agent theory and* $o \in \mathcal{O}$. *Offer* o *is* rejected *iff* $\forall\ \delta \in \mathcal{F}(o)$, δ *is rejected in* AF. *It is* non-supported *iff* $\mathcal{F}(o) = \emptyset$. *Let* $\mathcal{O}_r(\texttt{AF})$ *(resp.* $\mathcal{O}_{ns}(\texttt{AF})$*) denote the set of rejected (resp. non-supported) offers of* AF.

Example 2 (Example 1 cont.) *Since the argument* δ_1 *is skeptically accepted and* δ_2 *is rejected, then the offer* sg *(having a surgery) is credulous while* $\neg sg$ *is rejected.*

It was shown that the set $\mathcal{O}$ of offers can be partitioned into three classes: credulous, rejected and non-supported offers.

Property 1 ([3]) *The following equality holds:* $\mathcal{O} = \mathcal{O}_c(\texttt{AF}) \cup \mathcal{O}_r(\texttt{AF}) \cup \mathcal{O}_{ns}(\texttt{AF})$.

In addition to the best offer which is an output of a decision system, a preference relation $\succeq$ on $\mathcal{O}$ ($\succeq \subseteq \mathcal{O} \times \mathcal{O}$) is also provided. For two offers o, o', $(o, o') \in \succeq$ (or $o \succeq o'$) means that o is at least as good as o'. Let $\succ$ denote the strict version of $\succeq$ (i.e. $(o, o') \in \succ$ iff $(o, o') \in \succeq$ and $(o', o) \notin \succeq$). The idea is that credulous offers are strictly preferred to any non-supported offer. A non-supported offer is better than a rejected one. For simplicity reasons, we will write $\mathcal{O}_x(\texttt{AF}) \succ \mathcal{O}_y(\texttt{AF})$ to denote that any offer in $\mathcal{O}_x(\texttt{AF})$ is strictly preferred to any offer in $\mathcal{O}_y(\texttt{AF})$. Offers of the same set $\mathcal{O}_x(\texttt{AF})$ with $x \in \{c, r, ns\}$ are equally preferred (i.e. $\forall o, o' \in \mathcal{O}_x(\texttt{AF})$, both (o, o') and (o', o) are in $\succeq$).

Definition 7 *Let* $\mathcal{O}$ *be a set of offers.* $\mathcal{O}_c(\texttt{AF}) \succ \mathcal{O}_{ns}(\texttt{AF}) \succ \mathcal{O}_r(\texttt{AF})$.

It is easy to show that the relation $\succeq$ is a total preorder. Moreover, it privileges the offer that is supported by the strongest argument in the sense of $\geq_p$.

Theorem 1 ([3]) *If* $\mathcal{R}_m = \emptyset$*, then an offer* o *is skeptical iff* $\exists \delta \in \mathcal{F}(o)$ *s.t.* $\forall \delta' \in \mathcal{F}(o')$ *with* $o \neq o'$*, then* $(\delta, \delta') \in >_p$.

3 Negotiation Framework

In a negotiation dialogue several agents may be involved. In what follows, we restrict ourselves to the case of only two agents denoted by i and $-i$. These agents are assumed to share some background in order to understand each other. They use the same logical language $\mathcal{L}$ and the same definition of an argument. Thus, both agents recognize any argument in the set $\texttt{Args}(\mathcal{L})$. Similarly, each agent recognizes any conflict in $\mathcal{R}(\mathcal{L})$ meaning that the agents use the same attack relation (for instance, 'assumption attack' developed in [16]). In addition, each negotiating agent i is equipped with a theory like the one developed in the previous section. This theory is used to build and evaluate arguments, to evaluate offers, to compare pairs of offers, and finally to select the best offer. Recall that an offer is a possible value of the negotiation object and elements of $\mathcal{O}$ represent the possible offers. Thus, the theory of agent i is $\texttt{AF}^i = (\mathcal{O}^i, \mathcal{A}^i, \mathcal{R}^i, \geq^i, \mathcal{F}^i)$ where $\mathcal{O}^i$ is a *finite* subset of $\mathcal{O}(\mathcal{L})$. In what follows, we assume that agents have the same set of offers, i.e. $\mathcal{O}^i = \mathcal{O}^{-i}$. We will use $\mathcal{O}$ to denote that set. $\mathcal{A}^i$ is a *finite* subset of $\texttt{Args}(\mathcal{L})$. The two agents may not necessarily have the same arguments in favor of an offer. $\mathcal{F}^i$: $\mathcal{O} \mapsto 2^{\mathcal{A}^i \cap \texttt{Args}_p(\mathcal{L})}$, $\mathcal{R}^i \subseteq \mathcal{A}^i \times \mathcal{A}^i$, where $\mathcal{R}^i$ is the restriction of $\mathcal{R}(\mathcal{L})$ on $\mathcal{A}^i$, and $\geq^i \subseteq \texttt{Args}(\mathcal{L}) \times \texttt{Args}(\mathcal{L})$ where $\geq^i$ is a (partial or total) preorder. Note that the preference relation between arguments is expressed on the whole set $\texttt{Args}(\mathcal{L})$. This means that an agent is *able* to express a preference between any pair of arguments. We denote by $\succeq^i$ the preference relation on $\mathcal{O}$ induced by the theory $\texttt{AF}^i$.

3.1 Negotiation dialogues

In order to analyze the role of argumentation in negotiation, we need a minimal definition of a negotiation dialogue, that is a definition that sheds light on the basic elements that are exchanged during such a dialogue. In order to stay as general as possible, we do not focus on protocols. Thus, the definition can be extended by rules of any possible protocol. The basic element of a negotiation dialogue is the notion of move through which agents exchange offers of $\mathcal{O}$ and/or arguments of $\texttt{Arg}(\mathcal{L})$.

Definition 8 (Move) *A* move *is a tuple $m = \langle p, a, o \rangle$ such that:*

(1) $p \in \{i, -i\}$,
(2) $a \in \mathcal{A}^i \cup \mathcal{A}^{-i} \cup \theta$ [2]*,*
(3) $o \in \mathcal{O} \cup \theta$, and
(4) $(a \neq \theta) \vee (o \neq \theta)$.

The function `Player` *(resp.* `Argument`*,* `Offer`*) returns the player (resp. the argument, the offer) of the move. Let $\mathcal{M}$ be the set of all moves that can be built from $\langle \{i, -i\}, \mathcal{A}^i \cup \mathcal{A}^{-i}, \mathcal{O} \rangle$.*

The fourth condition of the above definition states that at each step of the dialogue, an agent utters an argument, an offer or both. It can be shown that the set $\mathcal{M}$ is finite.

Property 2 *The set $\mathcal{M}$ is finite.*

A negotiation dialogue is a sequence of moves.

Definition 9 (Negotiation) *A* negotiation dialogue *d between two agents i and $-i$ is a finite and non-empty sequence $\langle m_1, \ldots, m_l \rangle$ of moves. d is* non-argumentative *iff $\forall i = 1, \ldots, l$, $\texttt{Argument}(m_i) = \theta$, otherwise d is* argumentative*.*

It is very common in negotiation dialogues that agents propose less preferred offers in case their best options are all rejected by the other party. Such offers are called *concessions*. For the purpose of our paper, we do not need to define this notion.

[2] θ is a symbol that denotes that no argument, or no offer is suggested.

So far, an abstract model for decision making has been presented. It takes as input a set of offers, a set of arguments (some of them support offers), an attack relation among arguments and a preference relation between arguments. The model computes a total preorder on the set of offers and thus, the best offer(s). An important question is how and why a new argument may change this preorder? In this section, we answer these questions by analyzing all the possible cases. Before that, let us introduce some notation.

Let $\mathtt{AF}_0^i$ be the *initial* theory of agent i, i.e. her theory before any dialogue $d = \langle m_1, \ldots, m_l \rangle$ starts. At each step t of d, a new theory $\mathtt{AF}_t^i$ is computed such that $\mathtt{AF}_t^i = \mathtt{AF}_{t-1}^i \oplus \mathtt{Argument}(m_t)$ if $\mathtt{Player}(m_t) = -i$ and $\mathtt{Argument}(m_t) \neq \theta$, otherwise $\mathtt{AF}_t^i = \mathtt{AF}_{t-1}^i$. Assume that $\mathtt{AF}_{t-1}^i = (\mathcal{O}_{t-1}^i, \mathcal{A}_{t-1}^i, \mathcal{R}_{t-1}^i, \geq_{t-1}^i, \mathcal{F}_{t-1}^i)$. The theory $\mathtt{AF}_{t-1}^i \oplus \mathtt{Argument}(m_t)$ is defined as $(\mathcal{O}_t^i, \mathcal{A}_t^i, \mathcal{R}_t^i, \geq_t^i, \mathcal{F}_t^i)$ where:

- $\mathcal{O}_t^i = \mathcal{O}_{t-1}^i = \mathcal{O}$,
- If $\mathtt{Argument}(m_t) \notin \mathcal{A}_{t-1}^i$, then $\mathcal{A}_t^i = \mathcal{A}_{t-1}^i \cup \{\mathtt{Argument}(m_t)\}$, otherwise $\mathcal{A}_t^i = \mathcal{A}_{t-1}^i$,
- If $\mathtt{Argument}(m_t) \notin \mathcal{A}_{t-1}^i$, then $\mathcal{R}_t^i = \mathcal{R}_{t-1}^i \cup \{(\mathtt{Argument}(m_t), x) \mid x \in \mathcal{A}_{t-1}^i$ and $(\mathtt{Argument}(m_t), x) \in \mathcal{R}(\mathcal{L})\} \cup \{(x, \mathtt{Argument}(m_t)) \mid x \in \mathcal{A}_{t-1}^i$ and $(x, \mathtt{Argument}(m_t)) \in \mathcal{R}(\mathcal{L})\}$, otherwise $\mathcal{R}_t^i = \mathcal{R}_{t-1}^i$,
- $\geq_t^i = \geq_{t-1}^i = \geq_0^i$,
- $\mathcal{F}_t^i : \mathcal{O}_t^i \mapsto 2^{\mathcal{A}_t^i \cap \mathtt{Arg}_p(\mathcal{L})}$ s.t. if $\mathtt{Argument}(m_t) \in \mathtt{Arg}_p(\mathcal{L})$, then $\mathcal{F}_t^i(\mathtt{Conc}(\mathtt{Argument}(m_t)))$ $= \mathcal{F}_{t-1}^i(\mathtt{Conc}(\mathtt{Argument}(m_t))) \cup \{\mathtt{Argument}(m_t)\}$ and $\forall o \neq \mathtt{Conc}(\mathtt{Argument}(m_t))$, $\mathcal{F}_t^i(o) = \mathcal{F}_{t-1}^i(o)$. If $\mathtt{Argument}(m_t) \in \mathtt{Arg}_e(\mathcal{L})$, then $\forall o \in \mathcal{O}_{t-1}^i$, $\mathcal{F}_t^i(o) = \mathcal{F}_{t-1}^i(o)$.

Remark: Without loss of generality, we assume that exchanged arguments are not self-defeating. Moreover, for the sake of simplicity, we assume that when a new argument is added to the original set $\mathcal{A}$ of arguments, other arguments cannot be built using the information underlying the new argument and that underlying arguments of $\mathcal{A}$.

As shown above, if an agent receives a new argument, then changes in the theory and consequently in its output may occur. Below, we describe the different situations that may be encountered.

Changing the set of options: By receiving a new argument, an agent may learn that there exists another option which is not considered in the set $\mathcal{O}$. This happens when the new argument is practical, and the agent has strong arguments in favor of this option (because for instance it satisfies more important goals). Let us illustrate this case by a simple example.

Example 3 *Paul prefers spacious, robust and safe cars, and he thinks that*

Peugeot cars are the ones that satisfy the three criteria at the same time. During his holidays in Germany, Paul tries to decide between two Volkswagen cars since he does not know that he may find Peugeot cars in Germany. If the seller proposes a car made by Peugeot, Paul will accept it.

The following property characterizes a situation where the new offer becomes a best possible choice for an agent.

Property 3 *Let* $\mathtt{AF}^i = (\mathcal{O}^i, \mathcal{A}^i, \mathcal{R}^i, \geq^i, \mathcal{F}^i)$ *be the theory of agent* i. *Let* $\delta \in \mathtt{Arg}_p(\mathcal{L})$ *be such that* $\mathtt{Conc}(\delta) \notin \mathcal{O}^i$. *If* $\forall \delta' \in \mathcal{A}^i \cap \mathtt{Arg}_p(\mathcal{L})$, $\delta >^i \delta'$ *and* $\mathcal{R}^i_m = \emptyset$, *then* $\mathtt{Conc}(\delta)$ *is credulous in the theory* $\mathtt{AF}^i \oplus \delta$.

A new offer can also be rejected in an extended theory if it is attacked by an epistemic argument which is skeptically accepted in the original theory.

Property 4 *Let* $\mathtt{AF}^i = (\mathcal{O}^i, \mathcal{A}^i, \mathcal{R}^i, \geq^i, \mathcal{F}^i)$ *be the theory of agent* i. *Let* $\delta \in \mathtt{Arg}_p(\mathcal{L})$ *be such that* $\mathtt{Conc}(\delta) \notin \mathcal{O}^i$. *If* $\exists \alpha \in \mathcal{A}^i \cap \mathtt{Arg}_e(\mathcal{L})$ *such that* α *is skeptically accepted in* $\mathtt{AF}^i$ *and* $(\alpha, \delta) \in \mathcal{R}'^i_m$ [3], *then* $\mathtt{Conc}(\delta)$ *is rejected in the theory* $\mathtt{AF}^i \oplus \delta$.

Note that this situation does not occur in our framework since we assumed that the two agents have the same set of offers.

Changing the set of epistemic arguments: Receiving a new epistemic argument allows an agent to *revise her beliefs*. Consequently, the output of the theory may change. Let us illustrate this phenomenon by a simple example.

Example 4 *Let* $\mathcal{O} = \{o_1, o_2\}$, $\mathcal{A}_e = \emptyset$, $\mathcal{F}(o_1) = \{\delta_1\}$, $\mathcal{F}(o_2) = \{\delta_2\}$ *and* $\delta_1 \geq_p \delta_2$. *This theory has one stable/preferred extension* $\mathcal{E} = \{\delta_1\}$. *Thus, option* o_1 *is credulous while* o_2 *is rejected. Consequently,* $o_1 \succ o_2$. *Assume now that this agent receives an epistemic argument* α *such that* $\alpha \mathcal{R}_m \delta_1$. *The new theory* $\mathtt{AF} \oplus \alpha$ *has one stable/preferred extension which is* $\mathcal{E}' = \{\alpha, \delta_2\}$. *Thus,* o_2 *is credulous while* o_1 *is rejected and* $o_2 \succ o_1$.

Changing the set of practical arguments: A new practical argument may also have a great impact on the outcome of a theory. If the new argument is not already in $\mathcal{A}^i \cap \mathtt{Arg}_p(\mathcal{L})$, this would mean that either a belief linking the option to goal(s) is missing or the agent may adopt the goal underlying the argument. In both cases, the new argument induces a *revision of either the beliefs or the goals* of the agent.

Example 5 *Let* $\mathcal{O} = \{o_1, o_2\}$, $\mathcal{A}_e = \emptyset$, $\mathcal{F}(o_1) = \{\delta_1\}$, $\mathcal{F}(o_2) = \emptyset$. *This theory has one stable/preferred extension* $\mathcal{E} = \{\delta_1\}$. *Thus, option* o_1 *is acceptable while* o_2 *is non-supported. Consequently,* $o_1 \succ o_2$. *Assume now that this agent*

[3] Note that $\mathcal{R}'^i_m$ is the mixed attack relation of the decision system $\mathtt{AF}^i \oplus \delta$.

receives a practical argument δ_2 in favor of o_2 and $\delta_2 \geq_p \delta_1$. The new theory $\texttt{AF} \oplus \delta_2$ *has one stable/preferred extension which is* $\mathcal{E}' = \{\delta_2\}$. *Thus, o_2 is acceptable while o_1 is rejected and $o_2 \succ o_1$.*

In [9], we performed an in-depth study of the changes that may occur in the status of arguments and the status of offers when a new practical argument is received. We have shown in particular under which conditions an offer may move from acceptance to rejection and vice versa. The first result shows that a new practical argument may improve the quality of its own conclusion but not that of other offers.

Property 5 ([9]) *Let* $\texttt{AF}^i = (\mathcal{O}^i, \mathcal{A}^i, \mathcal{R}^i, \geq^i, \mathcal{F}^i)$ *be the theory of agent i and* $\mathcal{O}^i_r$ *its rejected offers (under preferred semantics). Let $o \in \mathcal{O}^i_r$ and $\delta \in \texttt{Arg}_p(\mathcal{L})$. Then o is credulous in $\texttt{AF}^i \oplus \delta$ iff $\texttt{Conc}(\delta) = o$ and δ is not rejected in $\texttt{AF}^i \oplus \delta$.*

In [9], we have fully characterized when an argument is not rejected in $\texttt{AF}^i \oplus \delta$.

A second important result shows that a new practical argument may weaken the status of other offers than its own conclusion.

Property 6 ([9]) *Let* $\texttt{AF}^i = (\mathcal{O}^i, \mathcal{A}^i, \mathcal{R}^i, \geq^i, \mathcal{F}^i)$ *be the theory of agent i and* $\mathcal{O}^i_c$ *its credulous offers (under preferred semantics). Let $o \in \mathcal{O}^i_c$ and $\delta \in \texttt{Arg}_p(\mathcal{L})$. Then o is rejected in $\texttt{AF}^i \oplus \delta$ iff*

(1) $\delta \notin \mathcal{F}^i(o)$, *and*
(2) there does not exist a preferred extension $\mathcal{E}$ of $\texttt{AF}^i$ s.t. $\mathcal{E} \cap \mathcal{F}^i(o) \neq \emptyset$ and $\exists a \in \mathcal{E} \cap \mathcal{A}^i_e$ s.t. $(a, \delta) \in \texttt{Def}^i_m$, and
(3) there does not exist a preferred extension $\mathcal{E}$ of $\texttt{AF}^i$ s.t. there exists an admissible set $\mathcal{E}''$ of $\texttt{AF}^i$ with $\mathcal{E}'' \cap \mathcal{A}^i_p \subseteq \mathcal{E} \cap \mathcal{F}^i(o)$ and $\mathcal{E}'' \cap \mathcal{A}^i_e = \mathcal{E} \cap \mathcal{A}^i_e$ and $\forall a \in \mathcal{E}'' \cap \mathcal{F}^i(o), (a, \delta) \in \geq^i$ or $\exists a' \in \mathcal{E}'' \cap \mathcal{F}^i(o)$ s.t. $(\delta, a) \notin \geq^i$.

In the same paper [9], we have shown that a new practical argument has no impact on the status of epistemic arguments. Thus, each epistemic argument preserves its original status.

Changing the attack relation: When the set of argument changes, the attack relation may change as well since new attacks may appear between the new argument and the existing ones. Note that a new argument never leads to a new attack between two existing arguments since all the possible attacks should already be captured by the attack relation of the agent's theory.

Changing the preference relation between arguments: Recall that relation $\geq$ combines at least two preference relations: $\geq_e$ and $\geq_p$. In our model, these two relations are *static* and cannot change. Thus, it is not possible for an agent to prefer argument a over argument b, and when receiving a new argument its preference shifts. In order to allow the revision of preferences, we need a theory in which preferences are themselves subject to debate and are conclusions of arguments. Example of such model is the one proposed by Prakken and Sartor in [28] for reasoning about defeasible information.

In sum, the decision model presented in the previous section supports three situations:

- revising the set of options,
- revising the beliefs of the agent,
- revising the goals of the agent.

However, it does not support any change in the preference relation $\geq$. Consequently, the relation $\geq$ remains unchanged during a negotiation dialogue.

It is easy to show that in the particular case of non-argumentative dialogues, the output of a theory does not change.

Theorem 2 *Let* $\succeq_0^i$ *be the output of the theory of agent* i *before a dialogue. For all non-argumentative negotiation dialogue* $d = \langle m_1, \ldots, m_l \rangle$, $\succeq_t^i = \succeq_0^i$, *where* $t = 1, \ldots, l$.

This result confirms the intuition that game-theoretic and heuristic-based approaches for negotiation are not realistic since they do not allow any change of the preorder on the set of offers. While in Section 3.2, we have shown that new arguments may lead an agent to revise the preorder.

4 Negotiation outcomes

An important question is: what is a "good" solution/outcome in an ABN dialogue? In this section, we show that there are two categories of good solutions: time-dependent solutions and global ones. Time-dependent solutions are the good outcomes at a given step of a dialogue. They depend thus on the protocol that is used. Global solutions are the ideal outcomes that should be reached independently from protocol and dialogues. In what follows, we discuss each type of solution from an agent point of view and from a dialogue point of view.

4.1 Outcomes from Agents Perspective

From the point of view of a single agent, the best solution at a given step of a dialogue is that which suits best her preferences at that step.

Definition 10 (Accepted solution for an agent) *Let $d = \langle m_1, \ldots, m_l \rangle$ be a negotiation dialogue and $\mathtt{AF}_t^i$ the theory of agent i at step $t \leq l$. An offer $o \in \mathcal{O}$ is an* accepted solution *for agent i at step t iff $o \in \mathcal{O}_c(\mathtt{AF}_t^i)$.*

The status of accepted solutions may change during a negotiation. Indeed, it may be the case that at step t, an offer is accepted for an agent while it becomes rejected at step $t + 1$. Thus, such solutions are time-dependent. *Optimal solutions*, however, do not dependent on dialogue steps. They are offers that an agent would choose if she had access to all arguments owned by the other agent. New arguments allow agents to revise their mental states; thus, the best decision for an agent is the one she makes under 'complete' information.

Definition 11 (Optimal solution for an agent) *Let $\mathtt{AF}^i = (\mathcal{O}, \mathcal{A}^i, \mathcal{R}^i, \geq^i, \mathcal{F}^i)$ and $\mathtt{AF}^{-i} = (\mathcal{O}, \mathcal{A}^{-i}, \mathcal{R}^{-i}, \geq^{-i}, \mathcal{F}^{-i})$ be the initial theories of agents i and $-i$.*
An offer $o \in \mathcal{O}$ is an optimal solution *for agent i iff $o \in \mathcal{O}_c(\mathtt{AF})$ where $\mathtt{AF} = (\mathcal{O}, \mathcal{A}^i \cup \mathcal{A}^{-i}, \mathcal{R}^i \cup \mathcal{R}^{-i}, \geq^i, \mathcal{F})$ where $\mathcal{F} : \mathcal{O} \rightarrow 2^{(\mathcal{A}^i \cup \mathcal{A}^{-i}) \cap \mathtt{Arg}_p(\mathcal{L})}$.*

Note that an optimal solution may differ from one agent to another even if the arguments and the attacks used for computing such solution are the same. This is due to the fact that each agent i uses her own preference relation $\geq^i$ on arguments. This explains why in real life, from the same data, people do not necessarily draw the same conclusions.

Property 7 *If o is an optimal solution for an agent, then there exists a dialogue d such that o is accepted for that agent at a given step of d.*

4.2 Types of Negotiation Outcomes

Let us now analyze the different types of good solutions of negotiation dialogues. Three types of solutions are distinguished. The first one, called *local solution*, is an offer which is accepted for both agents at a given step of a negotiation.

Definition 12 (Local solution of a negotiation) *Let $d = \langle m_1, \ldots, m_t \rangle$ be a negotiation dialogue and $\mathcal{O}_c(\mathtt{AF}_t^i)$, $\mathcal{O}_c(\mathtt{AF}_t^{-i})$ be the sets of credulous offers at step t for the two agents. An offer o is a* local solution *for d iff $o \in \mathcal{O}_c(\mathtt{AF}_t^i) \cap \mathcal{O}_c(\mathtt{AF}_t^{-i})$.*

Local solutions do not always exist, and when they exist, the protocol should be efficient in order to reach them.

There are cases where non-argumentative dialogues have no local solutions. It is particularly the case when at the beginning of the dialogue the two agents have no common accepted offer.

Theorem 3 *Let* $\mathtt{AF}^i$ *and* $\mathtt{AF}^{-i}$ *be the initial theories of the two agents s.t.* $\mathcal{O}_c(\mathtt{AF}^i) \cap \mathcal{O}_c(\mathtt{AF}^{-i}) = \emptyset$*. There does not exist a non-argumentative dialogue d s.t. d has a local solution at a given step.*

Another situation in which non-argumentative dialogues may miss local solutions (if they exists) is when the two agents have opposite preferences, i.e. the credulous offers for one agent are the rejected ones for the other agent and vice versa, and agents do not exchange their rejected offers.

Theorem 4 *Let* $\mathtt{AF}^i$ *and* $\mathtt{AF}^{-i}$ *be the initial theories of the two agents s.t.* $\mathcal{O}_c(\mathtt{AF}^i) \cap \mathcal{O}_{ns}(\mathtt{AF}^i) = \mathcal{O}_r(\mathtt{AF}^{-i})$*. There does not exist a non-argumentative dialogue d s.t. d has a local solution at a given step and agents do not exchange their rejected offers.*

The following result characterizes the case where there exists a local solution. In order to reach it, the agents should exchange the appropriate sequence of arguments. In the next result, for a given set $\mathcal{A} = \{a_1, \ldots, a_n\}$ of arguments, we will use the notation $\mathtt{AF} \oplus \mathcal{A} = (\ldots(\mathtt{AF} \oplus a_1) \oplus a_2) \oplus \ldots \oplus a_n)$. It is clear that this operation is well-defined since the order of elements a_i has no impact on the result of this operation.

Property 8 *Let* $\mathtt{AF}^i = (\mathcal{O}, \mathcal{A}^i, \mathcal{R}^i, \geq^i, \mathcal{F}^i)$ *and* $\mathtt{AF}^i = (\mathcal{O}, \mathcal{A}^{-i}, \mathcal{R}^{-i}, \geq^{-i}, \mathcal{F}^{-i})$ *be the initial theories of the two agents. There exists a local solution iff* $\exists \mathcal{A}'^i \subseteq \mathcal{A}^i$ *and* $\exists \mathcal{A}'^{-i} \subseteq \mathcal{A}^{-i}$ *s.t.* $\mathcal{O}_c(\mathtt{AF}^i \oplus \mathcal{A}'^{-i}) \cap \mathcal{O}_c(\mathtt{AF}^{-i} \oplus \mathcal{A}'^i) \neq \emptyset$*.*

The next result studies the situation when agents do not have to agree on everything but they agree on the arguments related to a given part of the negotiation, which is separated from other problems. If the first agent owns more information than the second, then there exists a dialogue in which the second will agree with the first one.

Theorem 5 *Let* $\mathtt{AF}^i = (\mathcal{O}, \mathcal{A}^i, \mathcal{R}^i, \geq^i, \mathcal{F}^i)$ *and* $\mathtt{AF}^{-i} = (\mathcal{O}, \mathcal{A}^{-i}, \mathcal{R}^{-i}, \geq^{-i}, \mathcal{F}^{-i})$ *be the initial theories of the two agents. Let* $\mathcal{A} \subseteq \mathcal{A}^i \cup \mathcal{A}^{-i}$ *be s.t.* $\geq^i |_{\mathcal{A}} = \geq^{-i} |_{\mathcal{A}}$ *and let* $\mathcal{A}$ *be not attacked by arguments of* $(\mathcal{A}^i \cup \mathcal{A}^{-i}) \setminus \mathcal{A}$*. If* $\mathcal{A}^i \cap \mathcal{A} \supseteq \mathcal{A}^{-i} \cap \mathcal{A}$ *and* $\exists a \in \mathcal{F}^i(o) \cap \mathcal{A}^i \cap \mathcal{A}$ *s.t. a is skeptically accepted in* $\mathtt{AF}^i$*, then there exists a dialogue* $d = \langle m_1, \ldots, m_l \rangle$ *s.t. o is a local solution at step* $t \leq l$*.*

Another kind of time-dependent solution is the Pareto optimal solution. It takes into account the possible concessions that agents may make during a dialogue. In game-theoretic and heuristic-based approaches for negotiation, agents look for such solutions.

Definition 13 (Pareto optimal solution) *Let $d = \langle m_1, \ldots, m_l \rangle$ be a negotiation dialogue. An offer $o \in \mathcal{O}$ is a Pareto optimal solution at step t iff $\nexists o' \in \mathcal{O}$ s.t. ($o' \succ_t^i o$ and $o' \succeq_t^{-i} o$) or ($o' \succ_t^{-i} o$ and $o' \succeq_t^i o$).* [4]

It is worth mentioning that the protocols that have been developed in the literature for generating ABN dialogues lead to local solutions. Examples of such protocols are the one proposed in [2] and its extended version in [20]. Indeed, in those protocols, agents make concessions when they cannot defend their best offers.

It is easy to check that any local solution is also a Pareto optimal solution. However, the reverse is not true.

Property 9 *If an offer is a local solution in a given dialogue, then it is a Pareto optimal solution in that dialogue.*

The last kind of solution is the so-called *ideal solution*. It is an offer which is optimal for both agents.

Definition 14 (Ideal solution of a negotiation) *An offer $o \in \mathcal{O}$ is an* ideal solution *for a negotiation iff it is optimal for both agents i and $-i$.*

We can show that if an ideal solution exists, then there exists at least one dialogue in which this solution is local.

Property 10 *If an offer $o \in \mathcal{O}$ is an ideal solution, then there exists a dialogue d such that o is a local solution at a given step of d.*

It is natural to expect that two agents who share arguments and who agree on the preferences between those arguments can find a solution of good quality.

Theorem 6 *Let $\mathtt{AF}^i = (\mathcal{O}, \mathcal{A}^i, \mathcal{R}^i, \geq^i, \mathcal{F}^i)$ and $\mathtt{AF}^{-i} = (\mathcal{O}, \mathcal{A}^{-i}, \mathcal{R}^{-i}, \geq^{-i}, \mathcal{F}^{-i})$ be the theories of the two agents s.t. $\geq^i = \geq^{-i}$ and $\mathcal{A}^i \supseteq \mathcal{A}^{-i}$. If o is an accepted solution for agent i before the beginning of a dialogue, then o is an ideal solution.*

5 Added Value of Argumentation

The main goal of this paper is to shed light on the role argumentation may play in negotiation dialogues. The idea is to study whether argumentation may improve or decrease the *quality of the outcome* of a dialogue, and under

[4] $\succeq_t^i$ is the preference relation on $\mathcal{O}$ returned by theory $\mathtt{AF}_t^i$.

which conditions. It is clear that in real life, arguing does not necessarily lead to an agreement. In other words, it may be the case that two agents exchange arguments and at the end the negotiation fails. Does this mean that arguing was not necessary in this case or it was rather harmful for the dialogue? In order to answer these questions, we need to compare the best outcomes that may be reached by non-argumentative dialogues with those reached in argumentative ones. In this section, we show that argumentation may improve the quality of the outcome but never decreases it. Indeed, in the best case, arguing lead to better outcomes for both agents and in the worst case it improves the choices made by each agent.

Let $\mathtt{AF}^i$ and $\mathtt{AF}^{-i}$ be the initial theories of the two agents i and $-i$. We distinguish four situations which are the different combinations between local and ideal solutions.

Case 1. In the first case, there does not exist a local solution before a dialogue while there exists an ideal solution. In such a situation, argumentation will improve the outcome of a negotiation since it guarantees that such a solution will be reached. In the extreme case, it is sufficient for agents to exchange all their non-common arguments.

Theorem 7 *Let $\mathtt{AF}^i$ and $\mathtt{AF}^{-i}$ be the initial theories of the two agents. Let X be the set of ideal solutions and let $X \neq \emptyset$. For all $o \in X$, there exists an argumentative dialogue where o is a local solution at a given step.*

Since before a dialogue starts, there is no local solution (i.e. there is no offer which is accepted for both agents), the agents should exchange arguments in order to have chance to reach the ideal solution. This means that any non-argumentative dialogue will miss the ideal solution(s).

Theorem 8 *Let $\mathtt{AF}^i$ and $\mathtt{AF}^{-i}$ be the initial theories of the two agents s.t. $\mathcal{O}_c(\mathtt{AF}^i) \cap \mathcal{O}_c(\mathtt{AF}^{-i}) = \emptyset$ and let X be the set of ideal solutions such that $X \neq \emptyset$. There does not exist a non-argumentative dialogue where $o \in X$ is a local solution at a given step.*

A situation in which non-argumentative dialogues will miss the ideal solution is when the two agents have opposite preferences, i.e. the acceptable offers for one agent are the rejected ones for the other agent and vice versa.

Corollary 1 *Let $\mathtt{AF}^i$ and $\mathtt{AF}^{-i}$ be the initial theories of the two agents s.t. $\mathcal{O}_c(\mathtt{AF}^i) \cup \mathcal{O}_{ns}(\mathtt{AF}^i) = \mathcal{O}_r(\mathtt{AF}^{-i})$ and let X be the set of ideal solutions such that $X \neq \emptyset$. There does not exist a non-argumentative dialogue where $o \in X$ is a local solution at a given step.*

An important question is: what about Pareto optimal solutions? do they coincide with the ideal ones in case of non-argumentative dialogues? This may happen but by pure hazard. However, it may also happen that a non-argumentative dialogue finds a Pareto optimal solution which is not the idea one as illustrated by the following example.

Example 6 *Assume that $\mathcal{O} = \{o_1, o_2, o_3\}$, $o_1 \succeq^i o_3 \succeq^i o_2$ and $o_2 \succeq^{-i} o_3 \succeq^{-i} o_1$. It is clear that there is no local solution while o_3 is Pareto optimal one. If we assume that o_2 is the ideal solution, then it is clear that any non-argumentative dialogue will miss o_2.*

The above results show clearly that in case there is an ideal solution and no local solution, only argumentative dialogues guarantee that ideal solutions will be reached, of course provided that the protocols are defined in an efficient way. Non-argumentative dialogue miss for sure those solutions as local solutions. Finally, non-argumentative dialogues may find Pareto optimal solutions which are not ideal. In sum, arguing is certainly beneficial and improves greatly the quality of the outcome.

Case 2. Let us study the case where there exists at least one local solution before any dialogue and there exists an ideal solution. It is clear that if agents exchange appropriate offers, then a local solution may be reached even with non-argumentative dialogues. Let us assume that the outcome of a dialogue is the offer which is *uttered by both agents* during a dialogue.

Theorem 9 *Let $\mathtt{AF}^i$ and $\mathtt{AF}^{-i}$ be the initial theories of the two agents s.t. $\mathcal{O}_c(\mathtt{AF}^i) \cap \mathcal{O}_c(\mathtt{AF}^{-i}) \neq \emptyset$. There exists a non-argumentative dialogue whose outcome is a member of $\mathcal{O}_c(\mathtt{AF}^i) \cap \mathcal{O}_c(\mathtt{AF}^{-i})$.*

Note that the solution reached by non-argumentative dialogues may not be optimal for the two agents, i.e. is not ideal. Thus, an exchange of arguments helps to improve the quality of the output, i.e. to pass from a local solution to an ideal one. Moreover, according to Theorem 7, there exits an argumentative dialogue which leads for sure to an ideal solution. Thus, an argumentative dialogue will lead to an outcome which is at least as good as the outcome that may be reached by a non-argumentative dialogue. The following example illustrates this issue.

Example 7 *Assume that $\mathcal{O} = \{o_1, o_2, o_3\}$, $o_1 \succeq^i o_3 \succeq^i o_2$ and $o_1 \succeq^{-i} o_2 \succeq^{-i} o_3$. It is clear that o_1 is a local solution before any dialogue, and thus it can be reached with a simple exchange of offers (see Theorem 9). Assume now that o_2 is the ideal solution, i.e. if the two agents exchange all their arguments, then o_2 would be accepted for both agents. Thus, o_2 is clearly better than o_1 since o_2 is a choice that both agents make under 'complete' information.*

If a local solution exists before any dialogue, then that solution is also Pareto optimal (see Property 9). Thus, arguing improves the quality of the outcome by passing from Pareto optimal solutions to ideal ones.

Case 3. Let us now consider the case where there is no ideal solution (i.e. no optimal solution for both agents) while there is a local solution. Different situations may occur:

- The local solution coincides with the optimal solution of one of the agents. This solution may be reached by non-argumentative dialogues (provided an efficient protocol). With such outcome, both agents are satisfied since they get what they think is good for them. However, the agent whose optimal solution is different from the local one may be *misled* as illustrated next.
  Example 8 *Let us consider the case of an agent who wants to buy a house. She has to choose between two options:* o_1 *and* o_2*. Assume that, according to the agent, both options have the same characteristics except that* o_1 *has two bathrooms. Thus, this agent has the following preference:* $o_1 \succ^i o_2$*. But if this agent learns that* o_1 *has a high level of energy consumption which is undesirable for her, then her preference will shift to* $o_2 \succ^i o_1$*.*
  Arguing in this case may either lead to a Pareto optimal solution (if agents accept to make concessions) or to failure. The Pareto optimal solution here is either the same as the one reached by non-argumentative dialogues (i.e. the optimal solution of one of the two agents) or a solution which is not optimal for any agent. One may think that these results are worse than the one(s) reached by non-argumentative dialogues. We argue that this is not true since the aim of a negotiation is not to reach any solution but to reach a solution which is good for almost both agents. It is better for an agent to withdraw from a negotiation rather than to accept an offer which is not acceptable for her. Similarly, a Pareto optimal solution reached under complete information for both agents is better than a local solution where one of the agents is misled.
- The local solution does not coincide with the optimal solutions of the agents. As in the previous case, the local solution may be reached even by non-argumentative dialogues. However, both agents are misled in this case. Arguing allows them to make better decisions (in a more informed context). Thus, negotiation ends up with a failure or with a Pareto optimal solution.

Case 4. The last case corresponds to the situation where there is no ideal solution and no local solution. Non-argumentative dialogues may only find Pareto optimal solutions if agents accept to make concessions. However, those solutions may be bad for both agents as illustrated by the following example.

Example 9 *Assume that* $\mathcal{O} = \{o_1, o_2, o_3\}$*. The initial theory of agent* i *returns* $o_1 \succ^i o_3 \succ^i o_2$ *while the theory of agent* $-i$ *returns* $o_2 \succ^{-i} o_1 \succ^{-i} o_3$*. It* *is clear that there is no local solution. If agents accept to make concessions, then o_1 is a Pareto optimal solution. Assume now that if agents exchange* all *their arguments, then the new theories of the two agents return respectively $o_2 \succ^i o_3 \succ^i o_1$ and $o_3 \succ^{-i} o_2 \succ^{-i} o_1$. This means that o_2 is the optimal solution of agent i while o_3 is the optimal solution of agent $-i$. We can also see that o_1 is the worse solution for both agents. Thus, if the two agents have sufficient information, they will never opt for o_1. Arguing allow them to reach in the extreme case the Pareto optimal solution o_2 or o_3.*

In sum, in this case arguing allows agents to make better decisions and to reach outcomes in a rich context.

6 Related Work

Several proposals have been made in the literature for modeling argumentation-based negotiation. However, the work is still preliminary. Some researchers have mainly focused on relating argumentation with protocols. They have shown how and when arguments in favor of offers can be computed and exchanged. Others have focused on the decision making problem. In [7,23], the authors argued that selecting an offer to propose at a given step of the dialogue is a decision making problem. They have thus proposed an argumentation-based decision model, and have shown how such a model can be related to the dialogue protocol.

Argumentation has been integrated into negotiation dialogues in the early nineties by Sycara [34]. In that work, the author emphasized the advantages of using argumentation in negotiation dialogues, and a specific framework was introduced. In [24], the different types of arguments that are used in a negotiation dialogue, such as threats and rewards, were discussed. Moreover, a particular framework for negotiation was proposed. In [25,35], additional frameworks were proposed. Even if all these frameworks are based on different logics, and use different definitions of arguments, they all have at their heart an exchange of offers and arguments. However, none of those proposals explain when arguments can be used within a negotiation, and how they should be dealt with by the agent that receives them. Thus the protocol for handling arguments was missing. Another limitation of the above frameworks is the fact that the argumentation frameworks they use are quite poor, since they use a very simple acceptability semantics. In [6] a negotiation framework that fills the gap was suggested. A protocol that handles the arguments was proposed. However, the notion of concession is not modeled in that framework, and it is not clear what is the status of the outcome of the dialogue. Moreover, it is not clear how an agent chooses the offer to propose at a given step of the dialogue. In [1,23], the authors have focused mainly on this decision problem. They have proposed an argumentation-based decision framework that is used by agents in order to choose the offer to propose or to accept during the dialogue. In that work, agents are supposed to have a belief base and a goal base. In [2], a more general setting was proposed. Indeed, the authors proposed an abstract argument-based decision model, and have shown how it is updated when an agent receives a new argument. Finally, they proposed a simple protocol allowing agents to exchange offers and arguments. In [20], a slightly different version of that protocol was proposed. However, in both papers nothing is said about the quality of the outcome that may be returned under those protocols.

To the best of our knowledge the only work that attempted to show that argumentation is beneficial in negotiation is [30]. In that paper, agents need resources in order to reach their goals. Thus, they negotiate with each other by exchanging resources and their goals following an extended version of the bargaining protocol. The paper shows that an exchange of goals may increase the utility of the outcome. Our work is more general in the sense that we do not focus on a particular negotiation object (like resources). Our notion of argument is much more general, and our analysis is made independently from any protocol. Finally, in our paper we have identified the different types of outputs and we have shown that arguing is always beneficial whatever the negotiation object is.

To summarize, despite the huge number of works on argument-based approach for negotiation, there is no work which formally studies the impact of arguments on a negotiation dialogue as well as the role that is played by argumentation. we believe that our work is the first attempt in formalizing and identifying these issues.

7 Conclusions and Future Work

In this paper we have presented a general framework for argumentation-based negotiation. Like any other argumentation-based negotiation framework, as it is evoked in (e.g. [31]), our framework has all the advantages that argumentation-based negotiation approaches present when related to the negotiation approaches based either on game theoretic models (see e.g. [33]) or heuristics ([22]). This work is a first attempt to formally show the role of argumentation in negotiation dialogues. More precisely, for the first time, it formally establishes the link that exists between the status of the arguments and the offers they support, it defines the notion of concession and shows how it influences the evolution of the negotiation, it determines how the theories of agents evolve during the dialogue, it defined the different kinds of outcomes, and performs an analysis of the impact of argumentation on negotiation outcomes. We have shown for the first time that argumentation can improve the quality of an outcome but never decreases it.

Our future work concerns several points. A first point is to relax the assumption that the set of possible offers is the same to both agents. Indeed, it is more natural to assume that agents may have different sets of offers. During a negotiation dialogue, these sets will evolve. Arguments in favor of the new offers may be built from the agent theory. Thus, the set of offers will be part of the agent theory. Another urgent work would be to study the case where the preference relations between arguments may evolve. This means that the decision model should be able to reason about preferences. Another possible extension of this work would be to allow agents to handle both arguments PRO and CON offers. This is more akin to the way human take decisions. Considering both types of arguments will refine the evaluation of the offers status. In the proposed model, a preference relation between offers is defined on the basis of the partition of the set of offers. This preference relation can be refined. For instance, among the acceptable offers, one may prefer the offer that is supported by the strongest argument. In [8], different criteria have been proposed for comparing decisions. Our framework can thus be extended by integrating those criteria. Another interesting point to investigate is that of considering negotiation dialogues between two agents with different profiles. By profile, we mean the criterion used by an agent to compare its offers.

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Appendix

Proof of Property 2 *This follows from the fact that the sets $\mathcal{A}^1, \mathcal{A}^2, \mathcal{O}^1$ and $\mathcal{O}^2$ are all finite.* ■

Proof of Property 3 *This result is a consequence of Theorem 1.* ■

Proof of Property 4 *Let $\mathtt{AF}^i = (\mathcal{O}^i, \mathcal{A}^i, \mathcal{R}^i, \geq^i, \mathcal{F}^i)$ be the decision system of agent i, and $\delta \in \mathtt{Arg}_p(\mathcal{L})$ such that $\mathtt{Conc}(\delta) \notin \mathcal{O}^i$. Assume that $\exists \alpha \in \mathcal{A}^i \cap \mathtt{Arg}_e(\mathcal{L})$ such that α is skeptically accepted in $\mathtt{AF}^i$ and $(\alpha, \delta) \in \mathcal{R}'^i_m$. From Proposition 7 in [9], α is also skeptically accepted in $\mathtt{AF}^i \oplus \delta$ (under preferred semantics). Since α attacks β, thus β is rejected in $\mathtt{AF}^i \oplus \delta$. Consequently, $\mathtt{Conc}(\delta)$ is rejected in the decision system.* ■

Proof of Theorem 2 *This follows directly from the fact that* $\mathcal{A}_0^i = \mathcal{A}_j^i$, $\forall j = 1, \ldots, t$. *Consequently,* $\mathcal{R}_0^i = \mathcal{R}_j^i$. *Moreover,* $\geq_0^i = \geq_j^i$. ■

Proof of Property 7 *From Definition 11, o is acceptable in* $(\mathcal{O}, \mathcal{A}^i \cup \mathcal{A}^{-i}, \mathcal{R}^i \cup \mathcal{R}^{-i}, \geq^i)$. *This means that in a dialogue in which all arguments are exchanged, o is acceptable at the end of that dialogue.* ■

Proof of Theorem 3 *Let* $d = \langle m_1, \ldots, m_l \rangle$ *be a non-argumentative dialogue. From Theorem 2,* $\succeq_0^i = \succeq_j^i$ *and* $\succeq_0^{-i} = \succeq_j^{-i}$ *for each* $j = 1, \ldots, l$. *Since both agents do not accept to make concessions, thus* $\forall j = 1, \ldots, l$, $\texttt{Offer}(m_j) \in \mathcal{O}_c(\texttt{AF}^i) \cup \mathcal{O}_c(\texttt{AF}^{-i})$. *Since* $\mathcal{O}_c(\texttt{AF}^i) \cap \mathcal{O}_c(\texttt{AF}^{-i}) = \emptyset$, *then there is no local solution for d.* ■

Proof of Theorem 4 *Assume that* $\mathcal{O}_c(\texttt{AF}^i) \cup \mathcal{O}_{ns}(\texttt{AF}^i) = \mathcal{O}_r(\texttt{AF}^{-i})$. *From Property 2, it follows that* $\mathcal{O}_c(\texttt{AF}^{-i}) \cup \mathcal{O}_{ns}(\texttt{AF}^{-i}) = \mathcal{O}_r(\texttt{AF}^i)$. *Thus,* $(\mathcal{O}_c(\texttt{AF}^i) \cup \mathcal{O}_{ns}(\texttt{AF}^i)) \cap (\mathcal{O}_c(\texttt{AF}^{-i}) \cup \mathcal{O}_{ns}(\texttt{AF}^{-i})) = \emptyset$.

Let $d = \langle m_1, \ldots, m_l \rangle$ *be a non-argumentative dialogue. Since agents are not allowed to exchange rejected offers, thus* $\forall j = 1, \ldots, l$, $\texttt{Offer}(m_j) \in (\mathcal{O}_c(\texttt{AF}^i) \cup \mathcal{O}_{ns}(\texttt{AF}^i)) \cup (\mathcal{O}_c(\texttt{AF}^{-i}) \cup \mathcal{O}_{ns}(\texttt{AF}^{-i}))$. *Since* $(\mathcal{O}_c(\texttt{AF}^i) \cup \mathcal{O}_{ns}(\texttt{AF}^i)) \cap (\mathcal{O}_c(\texttt{AF}^{-i}) \cup \mathcal{O}_{ns}(\texttt{AF}^{-i})) = \emptyset$, *then there is no local solution for d at any step.* ■

Proof of **of Property 8** $\Rightarrow$ *If there are* $\mathcal{A}'_1$ *and* $\mathcal{A}'_2$ *which satisfy the conditions of the property, then from Definition 12, after a dialogue in which exactly* $\mathcal{A}'_1$ *and* $\mathcal{A}'_2$ *are sent by two agents respectively, o is acceptable by both agents which means that it is a local solution.*
$\Leftarrow$ *If a local solution exists, then* $\exists d = (m_1, \ldots, m_l)$ *s.t.* $\exists o \in \mathcal{O}$ *s.t. o is accepted by both agents after step l of dialogue d. This means that the condition of this property is verified.* ■

Proof of Theorem 5 *Let* $d = (m_1, \ldots, m_l)$ *be a dialogue in which agent i sends exactly all arguments from* $\mathcal{A}^i \cap \mathcal{A}'$ *to agent* $-i$. *Status of the argument a did not change for agent i from the beginning until the step l, and the status of this argument will be the same for agent i and for agent* $-i$ *after this step. Since a is skeptically accepted for agent i, than it is skeptically accepted for agent* $-i$. *Thus, offer o is now acceptable by both agents, than it is a local solution at step l.* ■

Proof of Property 10 *From Definition 14, o is acceptable in* $(\mathcal{O}, \mathcal{A}^i \cup \mathcal{A}^{-i}, \mathcal{R}^i \cup \mathcal{R}^{-i}, \geq^i)$ *and in* $(\mathcal{O}, \mathcal{A}^i \cup \mathcal{A}^{-i}, \mathcal{R}^i \cup \mathcal{R}^{-i}, \geq^{-i})$. *This means that in a dialogue in which all arguments are exchanged, o is acceptable at the end of that dialogue for both agents.* ■

Proof of Theorem 6 *Let o be accepted for agent i before the negotiation starts. Since* $\mathcal{A}^{-i} \subseteq \mathcal{A}^i$, *then o is an accepted offer in* $(\mathcal{O}, \mathcal{A}^i \cup \mathcal{A}^{-i}, \mathcal{R}^i \cup \mathcal{R}^{-i}, \geq^i)$ *and in* $(\mathcal{O}, \mathcal{A}^i \cup \mathcal{A}^{-i}, \mathcal{R}^i \cup \mathcal{R}^{-i}, \geq^{-i})$, *thus it is an ideal solution.* ■

Proof of Theorem 7 *Let X be the set of ideal solutions such that $X \neq \emptyset$. For each $o \in X$, there exists at least one dialogue d in which agents exchange the two sets of arguments $\mathcal{A}^i \setminus \mathcal{A}^{-i}$ and $\mathcal{A}^{-i} \setminus \mathcal{A}^i$.* ■

Proof of Theorem 8 *According to Theorem 3, there is no local solution for any non-argumentative dialogue. Thus, ideal solutions may never be local.* ■

Proof of Corollary 1 *According to Theorem 4, there is no local solution for any non-argumentative dialogue. Thus, ideal solutions may never be local.* ■

Proof of Theorem 9 *Let $\mathtt{AF}^i$ and $\mathtt{AF}^{-i}$ be the decision systems of the two agents i and $-i$ before a dialogue such that $\mathcal{O}_c(\mathtt{AF}^i) \cap \mathcal{O}_c(\mathtt{AF}^{-i}) \neq \emptyset$. Let $o \in \mathcal{O}_c(\mathtt{AF}^i) \cap \mathcal{O}_c(\mathtt{AF}^{-i})$. The sequence $\langle m_1, m_2 \rangle$ such that $\mathtt{Player}(m_1) = i$, $\mathtt{Offer}(m_1) = o$ and $\mathtt{Player}(m_2) = -i$, $\mathtt{Offer}(m_2) = o$ is a dialogue whose output is o.* ■

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