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Resolving crises through automated bilateral negotiations ☆

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Abstract

We describe the development of an automated agent that can negotiate efficiently with people in crises. The environment is characterized by two negotiators, time constraints, deadlines, full information, and the possibility of opting out. The agent can play either role, with communications via a pre-defined language. The model used in constructing the agent is based on a formal analysis of the crises scenario using game-theoretic methods and heuristics for bargaining. The agent receives messages sent by its opponent, analyzes them and responds. It also initiates discussion on one or more parameters of an agreement. Experimental results of simulations of a fishing dispute between Canada and Spain indicate that the agent played at least as well as, and in the case of Spain, significantly better than a human player.

Keywords: Bilateral negotiation; Bounded rationality; Automated agent

1. Introduction

Negotiation is an important mechanism for resolving conflicts between agents [21]. Our goal is the development of automated agents that can negotiate efficiently with people in crises. Such agents may be used, for example, in electronic commerce and for training negotiators [15,18,32]. We focus on bilateral negotiations in simulated crises characterized by time constraints, deadlines, full information, and the possibility of opting out.

The automated agent can play the role of either side in such negotiations. The model used on which the automated agent is based is a formal analysis of a scenario using game-theoretic methods and heuristics for bargaining. The formal analysis applies a definition of a crisis that models various aspects of such situations. In particular, a crisis is a conflict between two agents that threatens core values, where time is short, and that requires urgent negotiation to reach an agreement. The crisis can end with the negotiators signing an agreement or with one of the sides opting out

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of the negotiations. Opting out is a stochastic action and thus the agents are uncertain about the result. If the crisis does not end within a pre-specified deadline then the status quo is implemented. In addition to the main issue of the negotiation or opting out, there are various other parameters of an agent's action. These parameters influence the utility of the negotiators from the crisis. Time plays an important role in the crisis. We focused on crises for which there is at least one agreement that both sides prefer over opting out or the status quo. If there is no such agreement, there is no reason to even begin negotiations. We also assume that agents have dominant actions both with respect to opting out and reaching agreements and that at least one of the sides prefers to opt out rather than allow its opponent to opt out.

Given the formal model of a crisis, a subgame-perfect equilibrium is identified and is used as a basis for the automated agent. In addition, various heuristics are presented, to make the agent more flexible when negotiating with people.

The specific scenario that we used to test our model is based on a historical crisis between Spain and Canada in 1995 over access to a turbot fishery in the North Atlantic. Simulation results based on the Canada–Spain fishing dispute indicate that utility outcomes for agents playing Spain are significantly higher than for humans playing Spain, while the agents playing Canada generate similar outcomes to humans playing Canada. The sum of the utilities of both players is significantly higher in simulations with agents participating than in simulations with two humans. These findings provide a test of the reliability of the agent, and open up important possibilities for the employment of these techniques for both training and in domains such as e-commerce. This agent can be generalized to situations with similar characteristics: time constraints, deadlines, full information, and opting out.

In Section 2 we present the formal model that is used as the basis for the construction of the automated agent. Section 3 presents the simulation environment that implements the formal model. Section 4 presents the design of the agent's model and in Section 5 we discuss our experimental results. In Section 6 we compare our results with related work. Our major conclusions are reviewed in Section 7.

2. A formal model of the negotiation environment

In this section we will present a formal model of the general type of situations that we consider.

2.1. A crisis

We begin with the presentation of the formal framework of a **crisis**. An example of a crisis can be found in Section 5.1. First, we formally define the elements of the crisis.

Definition 2.1 *(Crisis).* A crisis is a tuple $\mathcal{C} = \langle Ag, \mathcal{S}, k, A_1^1, \ldots, A_k^1, A_1^2, \ldots, A_k^2, Ac^1, Ac^2, Ac_o^1, Ac_o^2, \mathcal{T}, dl, \mathcal{O}, O_o, p, Res, U^1, U^2 \rangle$ where

Agents: $Ag = \{1, 2\}$ is a set of two agents.

Main negotiation issue: $\mathcal{S} \subset IN$ is the set of all possible agreements with respect to the main negotiation issue.
k is the number of parameters of an agent's action.

Domains of Actions' parameters: A_j^i, $i \in Ag$, $1 \leqslant j \leqslant k$, is the domain of parameter j of an action of agent i such that

- $\forall j,\ 1 \leqslant j \leqslant k$, $Null \in A_j^i$. Intuitively, *Null* indicates that this parameter is not relevant in a given action.
- A_1^i includes the following items:
  - For any $s \in \mathcal{S}$, $SA(s) \in A_1^i$, intuitively indicating signing an agreement s, and
  - OPT_i indicating opting out of the negotiation.

  Intuitively, A_1^i includes the part of i's actions that may lead to the termination of the crisis.

Actions: Ac^i, $i \in Ag$ is a set of actions such that for all $a^i \in Ac^i$, $a^i = \langle a_1^i, \ldots, a_k^i \rangle$ where $a_j^i \in A_j^i$.
$Ac_o^i \subset Ac^i$, $i \in Ag$, denotes the set of actions such that if $a^i \in Ac_o^i$ then $a_1^i = OPT_i$.

Time: Agents can take actions only at pre specified times in the set $\mathcal{T} = \{0, 1, 2, \ldots\}$. $dl \in \mathcal{T}$. Intuitively, dl is the deadline by which the crisis will end.

Outcomes: $\mathcal{O}$ is a set of possible outcomes of the performance of two actions by the agents. There are a few special outcomes in $\mathcal{O}$:

- $SQ \in \mathcal{O}$ intuitively indicating the status quo;
- $CC \in \mathcal{O}$ intuitively indicating that the crisis continues.

Results of actions: Res is a function, $Res: Ac^1 \times Ac^2 \times t \to \mathcal{O}$, such that

1. **Agreement:** If $a_1^1 = a_1^2 = SA(s)$, $s \in S$, then $Res(a^1, a^2, t) \neq CC$ and intuitively the crisis ends with the agreement s being implemented. The specific outcome depends also on the other values of a_j^i, $i \in Ag$, $j \neq 1$.
2. **Opting out:** If $a^i \in Ac_o^i$ then the result is in O_o (note that $CC \notin O_o$) and is chosen according to the probability function $p \to Ac^1 \times Ac^2 \times O_o \times \mathcal{T} \to [0,1]$ such that for any pair of actions $a^1 \in Ac^1$ and $a^2 \in Ac^2$ where there is $i \in Ag$ such that $a^i \in Ac_o^i$, and a time period t, $\sum_{o \in O_o} p(a^i, a^j, o, t) = 1$. Intuitively p associates with each possible action, $a^i \in AC_o^i$, an action $a^j \in Ac^j$, a time period $t \in \mathcal{T}$ and a possible outcome of O_o, the probability that the result of the performance of a^i and a^j at time t will be the specified outcome.
3. **Status quo:** For any $t \geqslant dl$, $Res(a^1, a^2, t) = SQ$, intuitively namely, if the crisis does not end by dl then the status quo (SQ) is implemented.[1]
4. **Negotiations continue:** If none of the conditions of 1–4 are satisfied then $Res(a^1, a^2, t) = CC$, i.e., the crisis does not terminate.

Utility functions: U^1, U^2 are functions, $U^i: \mathcal{O} \times \mathcal{T} \to R$.

We will refer to the action $\langle Null, Null, \ldots, Null \rangle$ as the *Null* action in which the agent does not do anything. We will denote the expected utility of agent $i \in Ag$, from taking a stochastic action a^i at time $t \in \mathcal{T}$ when the other agent is taking a^j by EU^i. For example, for $a^1 \in Ac_o^1$, $a^2 \in Ac^2$ and $t \in \mathcal{T}$, $EU^1(a^1, a^2, t) = \sum_{o \in O_o} U^1(o, t) p(a^1, a^2, o, t)$.

2.2. The negotiation language

We consider situations in which agents negotiate in order to resolve the crisis. Thus, in addition to an agent's ability to perform actions that change the world, it can send messages, using a predefined negotiation language, in an effort to influence its opponent's actions. The negotiation language $\mathcal{N}$ with respect to a crisis $\mathcal{C} = \langle Ag, \mathcal{S}, k, A_1^1, \ldots, A_k^1, A_1^2, \ldots, A_k^2, Ac^1, Ac^2, \mathcal{T}, \mathcal{O}, O_o, Ac_o^1, Ac_o^2, p, Res, U^1, U^2 \rangle$ consists of the following messages:

Offers: An offer is a triple $\langle O, a^1, a^2 \rangle$, where $a^i \in Ac^i$.

Conditional offers: A conditional offer is a triple $\langle C, a^1, a^2 \rangle$, where $a^i \in Ac^i$. Intuitively a conditional offer sent by agent i to agent j means that agent i will do a^i if j will do a^j.

Response to an offer: A response to an offer or to a conditional offer can be either *Yes* or *No*. We assume that accepting an offer by saying "Yes" does not commit the agent to actually signing the agreement. However, agreeing on the details of an agreement is necessary for signing an agreement (see additional explanations below).

Requests: A request is a pair, $\langle R, a^i \rangle$ where $a^i \in Ac^i$. Intuitively, a request sent by agent j to agent i means that agent j asks agent i to do a^i.

Threats: A threat is a triple $\langle T, a^1, a^2 \rangle$, where $a^i \in Ac^i$. Intuitively a threat sent by agent i to agent j means that if j does not do a^j, i will do a^i.

Comments on the negotiations: A comment is any sequence of characters.

2.3. The negotiation protocol

Consider a crisis

$$\mathcal{C} = \big\langle Ag, \mathcal{S}, k, A_1^1, \ldots, A_k^1, A_1^2, \ldots, A_k^2, Ac^1, Ac^2, \mathcal{T}, \mathcal{O}, Ac_o^1, Ac_o^2, O_o, p, Res, U^1, U^2 \big\rangle.$$

Each time period in $\mathcal{T}$ is divided into two steps, a negotiation step (Step 1) and an action step (Step 2). In a negotiation step of any time period $t < dl$ of the negotiation, if the negotiation has not terminated earlier, any agent in the set Ag can send a message. If the two agents send messages simultaneously, only one of these messages is considered. Each

[1] There may be other possibilities for ending the crisis, e.g., a third party might enforce an outcome. For simplicity, only the two most common options are included in the definition.

message has equal probability to be considered. If the considered message consists of an offer or a conditional offer, the other agent can accept the offer, i.e., send "Yes", or can reject the offer, i.e., send "No".

Accepting an offer or a counter offer by saying "Yes" does not commit the agent to actually signing an agreement. However, according to the protocol signing an agreement should be agreed upon during the negotiation period. If no agreement has been proposed and accepted, the agent can opt out or do nothing. In particular, let $s \in \mathcal{S}$, $a^1 \in Ac^1$ $a^2 \in Ac^2$, where $a^1_1 = a^2_1 = SA(s)$. If an offer $\langle O, a^1, a^2 \rangle$ or a conditional offer $\langle C, a^1, a^2 \rangle$ is accepted in the negotiation step of time period $t \in \mathcal{T}$, then agent $i \in Ag$ can take action $a^{i'} \in AC^i$ where $a^{i'}_1 = SA(s)$ at the action step of time period t. That is, only the details specified in s are enforceable. In addition each agent can always take an action $a^i \in Ac^i_o$ (i.e., opting out) or the *Null* action. If $Res(a^1, a^2, t) \neq CC$ then the negotiation will end and the result is as determined by *Res*. Otherwise, the negotiation proceeds to period $t + 1$. In contrast to other negotiation protocols (e.g., the model of alternating offers [12,19]) our protocol does not place any restrictions on the time periods in which an agent can make an offer or opt out.

2.4. Assumptions

We consider crises $\mathcal{C} = \langle Ag, \mathcal{S}, k, A^1_1, \ldots, A^1_k, A^2_1, \ldots, A^2_k, Ac^1, Ac^2, Ac^1_o, Ac^2_o, \mathcal{T}, dl, \mathcal{O}, O_o, p, Res, U^1, U^2 \rangle$ that satisfy the following constraints.

A1. Dominant agreement actions: For each possible agreement an agent has an action that includes reaching that specific agreement which dominates all the other actions that include that agreement.
For any $i \in Ag$, $s \in \mathcal{S}$ and $t \in \mathcal{T}$ there is $a^{s,t,i} \in Ac^i$ such that: (1) $a^{s,t,i}_1 = SA(s)$; (2) for any $a^1 \in Ac^1$ such that $a^1_1 = SA(s)$, and $a^2 \in Ac^2$ where $a^2_1 = SA(s)$, $U^1(Res(a^{s,t,1}, a^2), t) \geqslant U^1(Res(a^1, a^2), t)$ and $U^2(Res(a^1, a^{s,t,2}), t) \geqslant U^2(Res(a^1, a^2), t)$.

A2. Dominant opting out actions: Each agent has an opting out action that dominates all the other opting out actions.
For any $t \in \mathcal{T}$, there is $op^{t,1} \in Ac^1_o$ and $op^{t,2} \in Ac^2_o$ such that for any $a^2 \in Ac^2$, and $a^1 \in Ac^1_o$, $EU^1(op^{t,1}, a^2, t) \geqslant EU^1(a^1, a^2, t)$ and for any $a^1 \in Ac^1$ and $a^2 \in Ac^2$, $EU^2(a^1, op^{t,2}, t) \geqslant EU^2(a^1, a^2, t)$.

In the next assumption we will use the following notation. The best response of agent 1 to agent 2 opting out at time t is action $b^{t,1} \in Ac^1$ such that for every $a^1 \in Ac^1$, $EU^1(b^{1,t}, op^{t,1}) \geqslant EU^1(a^1, op^{t,2})$. Similarly, the best response of agent 2 to agent 1 opting out is $b^{t,2} \in Ac^2$ such that for every $a^2 \in Ac^2$, $EU^2(op^{t,1}, b^{2,t}) \geqslant EU^2(op^{t,2}, a^2)$.

A3. Preferences for opting out: In each time period there is at least one agent that prefers to opt out rather than allow its opponent to opt out.
For any $t \in \mathcal{T}$, either $b^{t,1} = op^{t,1}$ or $b^{t,2} = op^{t,2}$.

A4. Possible agreements: In time periods prior to *dl* there is at least one agreement that is preferred by both players over opting out. Furthermore, in $dl - 1$ one of these agreements is preferred by both players over the status quo at *dl*.
For any $t \in \mathcal{T}$, $t < dl$ there is $s \in \mathcal{S}$ and $a^{s,1,t} \in Ac^1$, $a^{s,2,t} \in Ac^2$, such that for any $a^2 \in Ac^2$, $U^1(Res(a^{s,1,t}, a^{s,2,t}, t), t) \geqslant EU^1(op^{t,1}, a^2, t)$ and for any $a^1 \in Ac^1$, $U^2(Res(a^{s,1,t}, a^{s,2,t}), t) \geqslant EU^2(a^{1'}, op^{t,2}, t)$; and for $t = dl - 1$, $U^1(Res(a^{s,1,t}, a^{s,2,t}, t), t) \geqslant U^1(SQ, dl)$ and $U^2(Res(a^{s,1,t}, a^{s,2,t}, t), t) \geqslant U^2(SQ, dl)$.

Crises where assumption A4 is true are ones where the agents have agreements that both prefer over opting out or over maintaining the status quo. If this assumption is not true, there is no place for negotiations. However, A4 is not true when opting out or the status quo yield a high utility for one of the sides. The assumptions that agents have dominant actions both with respect to opting out and reaching agreements (A2 and A3) is always true when the utility functions are additive functions and have a maximum with respect to each attribute. Additive utility functions are very common since they are easy to compute and make the elicitation of the utility from a person much easier to perform [39]. However, if the preferences are dependent this assumption may not be true. The assumption is that at least one of the sides prefers to opt out rather than its opponent opting out is true in crises where taking the initiative is beneficial. However, this may not be true, for example, in crises where being attacked first may gain public support.

There is literature on international relations concerning offense versus defense, which deals with situations, particularly where military technology is concerned, where some parties may do better in conflict situations if they launch the first attack (offense), while other parties may benefit if they are initially on the defensive. In part, this depends on their force structure at the time of the crisis [20].

2.5. Equilibrium

The negotiation protocol provides a framework for the negotiation process and specifies the termination condition. However, each agent needs to decide on its negotiation strategy. A strategy of an agent in an extensive game specifies the action to be chosen by the player for every history. A strategy profile is a collection of strategies, one for each agent.

In the following section we will present the definition of the concept of Nash equilibrium and a subgame-perfect equilibrium, which will be used in order to analyze the negotiation.

Nash equilibrium is the most commonly used solution concept in game theory. This notion defines a stable state of a game. It does not attempt to examine the process by which this state is reached.

Definition 2.2 *(Nash equilibrium).* A strategy profile (f_1, f_2) is a Nash equilibrium if each agent i does not have an alternative strategy yielding an outcome that it prefers to that generated when it chooses f_i, given that the other player j chooses f_j [17].

Thus, if both agents use the strategies specified in the strategy profile of the Nash equilibrium, then no agent is motivated to deviate and use another strategy. However, the use of the Nash equilibrium is not an effective way of analyzing the outcomes of our negotiation model since it evaluates the desirability of a strategy only from the viewpoint of the agents at the start of the game. In view of the fact that in our negotiation model agents know the history up until their move, there may be some point in the negotiation where one or more agents prefer to diverge from their Nash equilibrium strategies. That is, Nash equilibrium strategies may be in equilibrium only in the first step of the negotiation, but may be unstable in intermediate stages.

Motivated by these arguments we now present the concept of subgame-perfect equilibrium [19,23], which is a stronger concept, and will be used in order to analyze the negotiation.

Definition 2.3 *(Subgame perfect equilibrium).* A strategy profile is a subgame perfect equilibrium of our strategic model if the strategy profile induced in every subgame is Nash equilibrium of that subgame.

That is, at any step the negotiation process, no matter what the history is, no agent is motivated to deviate and use any another strategy other than that defined in the strategy profile.

2.6. Model analysis

We analyze the model to find the strategy that is in perfect equilibrium for a crisis $\mathcal{C} = \langle Ag, \mathcal{S}, k, A_1^1, \ldots, A_k^1, A_1^2, \ldots, A_k^2, Ac^1, Ac^2, Ac_o^1, Ac_o^2, \mathcal{T}, dl, \mathcal{O}, O_o, p, Res, U^1, U^2\rangle$, where the negotiation language $\mathcal{N}$ is as defined in Section 2.2, the protocol as defined in Section 2.3, and the crisis satisfies assumptions A1–A4 above. The identification of the perfect equilibrium is accomplished by backward induction. The following lemma is the basis of the induction. It claims that an agreement will be reached prior to the time period in which the status quo is implemented.

Lemma 2.1. *Assuming the agents use their perfect equilibrium strategies and the negotiation process has not ended by time period $dl - 1$. At time period $dl - 1$, agent i will offer $\langle O, a^{i_1}, a^{i_2}\rangle$, $a^{i_1} \in Ac^1$, $a^{i_2} \in Ac^2$ such that*

(1) ***Proposing a dominant agreement***: *$a^{i_1} = a^{s,dl-1,1}$, $a^{i_2} = a^{s,dl-1,2}$, $s \in \mathcal{S}$.*
(2) ***The agreement's utility is higher than the expected utility from opting out***: *For all $i \in Ag$, $U^1(Res(a^{i_1}, a^{i_2}, dl-1), dl-1) \geqslant EU^1(op^{dl-1,1}, b^{dl-1,2}, dl-1)$ and $U^2(Res(a^{i_1}, a^{i_2}, dl-1), dl-1) \geqslant EU^2(b^{dl-1,1}, op^{dl-1,2}, dl-1)$.*

(3) ***The agreement's utility is higher than the utility from the SQ in the next time period***: $U^i(Res(a^{i_1}, a^{i_2}, dl-1), dl-1) \geqslant U^i(SQ, dl)$.
(4) *For any* $a^1 \in Ac^1$, $a^2 \in Ac^2$ *that satisfy conditions* (1)–(3) $U^i(Res(a^{i_1}, a^{i_2}, dl-1), dl-1) \geqslant U^i(Res(a^1, a^2, dl-1), dl-1)$.

If $\langle O, a^{i_1}, a^{i_2}\rangle$ *will actually be considered then agent* $j \neq i$ *will accept the offer* (*sending "yes"*), *and in the action step, agent* 1 *will perform* a^{i_1} *and agent* 2 *will perform* a^{i_2}.

Proof. If the negotiations do not end at $dl-1$, then there will be a status quo at time period dl. According to assumption A4 there is at least one agreement that the players prefer over the status quo in time period dl. One of these agreements is also preferred by both players over opting out. The players should consider only dominant actions since other actions will not be performed. Such agreements exist according to assumption A1.

Among these possible agreements, i should prefer the one that is best for him, i.e., condition (3). □

Next we define a set of acceptable agreements for each time period by backward induction.

Definition 2.4 *(Acceptable agreements for agents* 1 *and* 2*).* The basis for the induction, A_1^{dl-1} and A_2^{dl-1} are the agreements defined in Lemma 2.1.

For $0 \leqslant t < dl-1$ we define the sets of possible acceptable agreements $\mathcal{P}^t$ and the proposed ones A_1^t and A_2^t. There may be a time period t such that $\mathcal{P}^t = \emptyset$ and A_1^t and A_2^t will not be defined.

• $\mathcal{P}^t$ is the set of offers of the form $\langle O, a^1, a^2\rangle$, $a^1 \in Ac^1$, $a^2 \in Ac^2$ satisfying the following conditions:

(1) Only dominant agreements should be considered: $a^1 = a^{s,t,1}$, $a^2 = a^{s,t,2}$, $s \in \mathcal{S}$.
(2) The utility of the agents from the acceptable agreements should be at least as high as the utility from future agreements:
Let $t' \in \mathcal{T}$, $t' > t$ the smallest t' such that $A_1^{t'} = \langle O, a^{t',1,1}, a^{t',1,2}\rangle$ and $A_2^{t'} = \langle O, a_2^{t',2,1}, a^{t',2,2}\rangle$ are defined. Denote by EA_i^t $0.5U^i(Res(a^{t',1,1}, a^{t',1,2}, t'), t') + 0.5U^i(Res(a^{t',2,1}, a^{t',2,2}, t'), t')$ and t' by $\hat{t}$. For any $i \in Ag$, $U^i(Res(a^1, a^2, t), t) \geqslant EA_i^t$.
(3) The utility for the agents from the acceptable agreements should be at least as high as the utility from opting out: for any $t < t' < \hat{t}$, $U^1(Res(a^1, a^2, t), t) \geqslant EU^1(op^{t',1}, b^{t',2}, t')$ and $U^2(Res(a^1, a^2, t), t) \geqslant EU^2(b^{t',1}, op^{t',2}, t')$.

• If $\mathcal{P}^t \neq \emptyset$ then for any $i \in Ag$, $A_i^t = \arg\max\{U^i(Res(a^1, a^2, t), t) \mid \langle O, a^1, a^2\rangle \in \mathcal{P}^t\}$.
• Otherwise, A_i^t is not defined.

Intuitively, the agent that makes an offer at time period t, say agent i, should consider the agreements in $\mathcal{P}^t$ and offer the one that is the best for him. $\mathcal{P}^t$ consists of agreements that are better for both agents than the expected utility from opting out and better than any possible future agreements. The choice of dominant actions is possible due to assumption A1.

Theorem 2.1. *The profile that consists of the following strategy for both agents is in perfect equilibrium if the crisis satisfies assumptions* A1–A4.

Agent 1*'s strategy* (*time* t):

• ***Step* 1:**

(1) ***Agent* 1 *makes an offer***: *If* A_1^t *is defined offer* A_1^t.
(2) ***Agent* 1 *needs to respond to a message*** m**:**
– *if* $m = \langle O, a^1, a^2\rangle$ *or* $m = \langle C, a^1, a^2\rangle$ *where* $a_1^1 = a_1^2 = SA(s)$, $s \in \mathcal{S}$ *then if*[2]

[2] Other strategies that are in equilibrium are those in which the agent says "Yes" to any agreement, but actually signs only those agreements that satisfy the condition specified here. We have presented a strategy in which an agent that has accepted an agreement during the negotiation phase will actually sign it.

(i) $U^1(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant EU^1(op^{t,1}, b^{t,2}, t)$ *and*
(ii) $U^2(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant EU^2(b^{t,1}, op^{t,2}, t)$ *and*
(iii) *if* $t \neq dl - 1$ *then*
for any $i \in Ag$, $U^i(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant EA_i^t$ *and*
for any $t < t' < \hat{t}$, $U^1(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant EU^1(op^{t',1}, b^{t',2}, t')$ *and*
$U^2(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant EU^2(b^{t',1}, op^{t',2}, t')$ *and*
(iv) *if* $t = dl - 1$ *then for any* $i \in Ag$, $U^i(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant U^i(SQ, dl)$ *then say "Yes".*

– *If m is of any other form (including threats) do not respond.*

• ***Step 2:*** *Agent* 1 *chooses what action to take*:

(1) *If an offer* $\langle O, a^1, a^2\rangle$ *or a conditional offer* $\langle C, a^1, a^2\rangle$ *where* $a_1^1 = a_1^2 = SA(s)$, $s \in \mathcal{S}$ *was made and accepted in the negotiation step and*
(i) $U^1(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant EU^1(op^{t,1}, b^{t,2}, t)$ *and*
(ii) $U^2(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant EU^2(b^{t,1}, op^{t,2}, t)$ *and*
(iii) *if* $t \neq dl - 1$ *then for any* $i \in Ag$, $U^i(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant EA_i^t$ *and for any* $t < t' < \hat{t}$, $U^1(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant EU^1(op^{t',1}, b^{t',2}, t')$ *and* $U^2(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant EU^2(b^{t',1}, op^{t',2}, t')$ *and*
(iv) *if* $t = dl - 1$ *then for any* $i \in Ag$, $U^i(Res(a^{s,t,1}, a^{s,t,2}, t), t) \geqslant U^i(SQ, dl)$ *then do* $a^{s,t,1}$.

(2) ***Else*** *if* $t = dl - 1$, ***then***
if $EU^1(op^{t,1}, b^{t,2}, t) \geqslant U^1(SQ, dl)$ *then do* $op^{dl-1,1}$.
Else *if* $EU^2(b^{t,1}, op^{t,2}, t) \geqslant U^2(SQ, dl)$ *then do* $b^{dl-1,1}$.

(3) ***Else*** *if* $EU^1(op^{t,1}, b^{t,2}, t) > EA_1^t$
and for any $t < t' < \hat{t}$, $EU^1(op^{t,1}, b^{t,2}, t) \geqslant EU^1(op^{t',1}, b^{t',2}, t')$
then *do* $op^{t,1}$.

(4) *Else, if* $EU^2(b^{t,1}, op^{t,2}, t) > EA_2^t$ *and for any* $t < t' < \hat{t}$, $EU^2(b^{t,1}, op^{t,2}, t) > EU^2(b^{t',1}, op^{t',2}, t')$ ***then*** *do* $b^{t,1}$

(5) ***else*** *do nothing.*

The strategy for agent 2 *is similar to that of agent* 1.

Proof. We will prove that the above strategy profile is a perfect equilibrium by backward induction on the time periods. We will consider agent 1. The proof for agent 2 is similar.

Base case (the last period before the deadline): According to Lemma 1, at $dl - 1$ agent 1 should offer A_1^{dl-1} when making an offer (1 of step 1) and accept any offer that yields it and its opponent a utility that is at least as good as the utility from opting out (conditions (i) and (ii) of 2 of Step 1) and at least as good as the utility from the status quo (condition (iv) of 2 of Step 1).

If the agents do not reach an agreement that is at least as good as opting out and the status quo to both agents and opting out is better than the status quo then it should opt out (2 of Step 2).

Inductive case ($0 \leqslant t < dl - 1$): We will examine the strategy backward starting from the action step (Step 2).

• **Step 2**: **Agent 1 chooses what action to take:**

(1) If an offer $\langle O, a^1, a^2\rangle$ or a conditional offer $\langle C, a^1, a^2\rangle$ where $a_1^1 = a_1^2 = SA(s)$, $s \in \mathcal{S}$ was made and accepted in the negotiation stage, then first, agent 1 should consider the associated dominant action. According to agent 2's strategy, it will do the same. Such an action exists according to assumption A1. The agent can deviate by opting out now or waiting and either opting out or signing an agreement in the future. Conditions (i) and (ii) of Step 2 of the strategy states that the agent will sign an agreement if it is not worse for both sides than opting out now and it is not worse for both than the best expected utility from signing an agreement in the future according to the induction hypothesis (e.g., EA_i^t). Furthermore, according to condition (iii) it is also not worse than opting out before it is possible to reach an agreement in the future, i.e., before $\hat{t}$. Thus, when conditions (i)–(iii) are true no deviation from signing the agreement will improve the agent's expected utility.

(2) If an agreement has not been reached, or if signing the accepted agreement is not profitable for one of the agents, agent 1 should decide whether opting out would be better for it than its expected utility from any possible future

agreements. Thus, if $EU^1(op^{t,1}, b^{t,2}, t) > EA_1^t$ it should consider opting out since it would be better than what it could gain in the future from signing agreements. Another requirement for opting out at time t is that it would better than opting out at any time before $\hat{t}$.

(3) If opting out is not beneficial for agent 1, it should check whether it would be beneficial for agent 2. If so, perform $b^{t,1}$ which is the best response to agent 2 opting out. Note that due to assumption A3 it is not possible that both players would prefer that their opponent opt out.

• **Step 1:**

(1) Agent 1 makes an offer: First, the offered agreement should be a dominant one since according to agent 2's strategy it will only perform dominant actions, regardless of what has been agreed upon. Similarly, agent 2 will know that agent 1 will deviate and perform only a dominant action with respect to the signed agreement.
Second, according to the inductive hypothesis, the agents will follow a strategy based on the theorems in the future and the best expected utility that agent 1 can expect in the future is E_1^t. Thus, it should offer only agreements that yield it a utility at least equivalent to E_1^t. Similarly, the proposed agreement should yield agent 2 a utility at least equivalent to E_2^t. In addition, it should prevent 2 from opting out, and thus 2's utility should be at least equivalent to the utility that it would gain from opting out now or until $\hat{t}$ where E_2^t is expected. Similarly, the utility of agent 1 should be at least equivalent to the utility that it would gain from opting out. From all these possible agreements agent 1 should choose the one that yields it the highest utility. This agreement is exactly A_1^t as defined in Definition 2.4.

(2) **Agent 1 needs to respond to a message:**
– Saying "Yes" to all offers will yield the highest utility possible since agreements are not enforceable and the agent can sign an agreement only if it was agreed upon. However, in the theorem we stated a strategy that if the agent says "Yes" it will really sign the agreement according to its strategy of Step 2.
– While there are several types of messages that are available to the agents, there is a need to respond only to offers and counter offers. This is due to the protocol which states that any other message exchange will not lead to a change in utility. □

The theorem provides the agent with a specific strategy for negotiations if all the agents are fully rational agents and follow the equilibrium strategies. It serves as the basis for the design of the automated negotiator presented in the next sections.

3. Simulation environment

We developed a simulation tool that enables simulating a crisis $\mathcal{C} = \langle Ag, \mathcal{S}, k, A_1^1, \ldots, A_k^1, A_1^2, \ldots, A_k^2, Ac^1, Ac^2, Ac_o^1, Ac_o^2, \mathcal{T}, dl, \mathcal{O}, O_o, p, Res, U^1, U^2\rangle$, defined in Definition 2.1. The negotiation language that is used for exchanging messages between the players is $\mathcal{N}$ as presented in Section 2.2. The simulation tool is able to support the negotiation of both people and automated agents.

The negotiation protocol of the simulation is more flexible than that defined in Section 2.3. This was done to make the simulations more realistic. First, time periods were not divided explicitly into 2 steps. Actions could be taken at any time during a time period. Second, we allowed the negotiators to send more than one message during each time period. Since only signed agreements can be implemented, and an agent prefers that its message will be considered, it will attempt to send a message as late as possible before the end of the time period. Modeling such strategies would have required information on the time it takes a message to reach its destination. For simplicity, this was modeled in Section 2.3 via the specification that if the two agents send messages simultaneously, only one of these messages is considered with equal probability.

In addition, the effects of actions that do not terminate the crisis are assumed to remain true unless they have been explicitly changed. In particular, suppose $a^i \in Ac^i$, $a^i = \langle a_1^i, \ldots, a_k^i\rangle$ where $a_1^i = Null$ and $a_j^i \neq Null$ $j \neq 1$ was performed during time period t and suppose no other non-terminated action in which j's parameter is not equal to $Null$ was performed later. Then, if at a later time the action that was performed, $a^{i'} = \langle a_1^{i'}, \ldots, a_k^{i'}\rangle$, terminates the negotiation for which $a_j^{i'} = Null$, it is considered as $a_j^{i'} = a_j^i$. This change does not modify the equilibrium strategies, since the agent can always cancel the effect of its earlier action by setting $a_j^{i'} \neq Null$. However, this possibility was used by people for signaling, as we will explain below.

Human players participating in the simulations were provided with a Generalized Decision Support System (GDSS) for the specific crisis in which they took part. Using the GDSS allowed them to evaluate different outcomes in terms of utility values. They also were introduced to a special menu based editor used to compose messages.

4. Agent design

The automated agent is a software agent that can participate in the bilateral negotiation simulations described above. During the simulations the agent receives messages sent by the opponent, analyzes them and responds. It also initiates a discussion on one or more parameters of the agreement. The strategy of the negotiations that was adapted is based on the equilibrium of the model with some modifications of the heuristics, which will be discussed later in this section.

4.1. Negotiation strategy

At the beginning of the crisis the agent can compute by backward induction the subgame-perfect equilibrium of Theorem 1. If the agent were to play against a rational opponent, with the ability to identify the subgame-perfect equilibrium, this would be sufficient. However, people do not necessarily follow equilibrium strategies, and in preliminary experiments when the automated agent followed its equilibrium strategy the human negotiators who negotiated with it became frustrated and the negotiation often ended with no agreement. Note that the complexity of finding the equilibrium is low, the players have full information, and the automated agent is able to find it quickly. Nevertheless, we observed that people do not follow equilibrium strategies. Such behavior has been observed by other researchers (e.g., [6,8,9,24,31,35–37]). In particular, this phenomenon has been observed in laboratory experiments on bargaining (e.g., [2,26,31].) Therefore, the formal theory is insufficient and we added heuristics and argumentation to complete the formal model and make the agent an effective negotiator with people.

The first heuristic that the agent uses is motivated by the assumption that many people keep their promises even when agreements are not enforceable [5,34,38]. Therefore, instead of considering only dominant agreement actions, the agent considers all possible agreement actions. At the beginning of the crisis the agent computes by backward induction the subgame-perfect equilibrium similar to that of Theorem 1, but under the assumption that once an agreement is accepted, it will be kept (non-dominant agreement actions are also considered, however the agreements must satisfy the conditions of the theorem's strategies, e.g., it is not worse than opting out or any future acceptable agreements). It stores the offers that it should make during each time period according to the "equilibrium" strategy in an array, referred to as the strategy array.

Another heuristic concerns opting out. Given our assumptions, while rational agents will not opt out, people may opt out. If the agent's expected utility from opting out is higher than its expected utility from its opponent opting out, it will try to predict whether its opponent is going to opt out. If so, it will opt out first. The heuristic for the prediction of whether an opponent will opt out is based on the messages sent by the opponent. For example, when a threatening message is received, or when a comment message indicating that the negotiations are heading in a dangerous direction is received, the estimation that the opponent may opt out increases.

There are two main activities that the agent performs during negotiations: sends messages and responds to incoming messages. The agent's heuristics for these activities were influenced by a set of parameters we present in the next section.

4.2. The agent's parameters

We allow the owner of the agent to determine the way the agent will deviate from the equilibrium strategies by determining parameters that influence the agent's behavior. They are instantiated before the beginning of negotiations.

In order to provide the agent with some flexibility when playing against people we allowed the agent to agree to agreements that have a lower utility than it would have obtained according to the relevant strategy array agreement. Therefore we added the margin parameter that determines the largest number of points lower than the desired utility value that the agent will agree to.

An additional parameter is the number of negotiation units by which the agent will increase or decrease its first offer from the agreement specified in its strategy array. Human negotiators usually begin negotiations with an offer higher (or lower, depending on the negotiator's role) than the value they would eventually like to reach at the end of negotiations. This leaves bargaining space and our agent uses this type of strategy.

Another parameter indicates whether the agent will send the first message in the negotiation or will wait for its opponent to make the first offer. We did not find any reference to this issue in the literature. The default value of this parameter is that the agent will send the first offer, since we wanted a trigger to initiate negotiations with the other agent.

The last parameter determines whether the agent will make a full offer, or will only make partial offers to negotiate each issue separately. That is, instead of sending a message with an action in which each action's parameter is specified, it will replace some of the action's parameters with *Null*. Note that the negotiation on other parameters, in addition to the main one, is possible because of the main heuristic of considering non-dominant agreement actions. The dilemma is between bargaining on a complete agreement that specifies the values of all the negotiation issues or bargaining in stages: first agree on one parameter and then move to the other. Since, again, we did not find an answer to this dilemma in the literature, we added a special parameter to the agent.

4.3. Responding to incoming messages and sending messages

The following describes the way agent i responds to incoming messages according to their categories. In each category we first consider messages that consist of fully specified actions and then ones that consider only some of the action parameters. We assume that the agent maintains two arrays of length k named $agreed^1$ and $agreed^2$ in which it stores the currently agreed partial actions. Originally $agreed^1[l]$ and $agreed^2[l]$, $1 \leqslant l \leqslant k$, are set to *Null*. In the following discussion, if the time period is t, we will refer to the agreement that is stored in t's object of the agent's strategy array as the array agreement. Agent i below is the role the agent plays and j is the other role.

Response to an offer or to a conditional offer: Suppose the agent receives a message of the form $\langle O, a^1, a^2\rangle$ or $\langle C, a^1, a^2\rangle$,where $a^i \in Ac^i$.
- If a^1 and a^2 are fully specified actions (i.e., without any *Null*) and the expected utility for i of the proposed agreement is higher than that of the array agreement or worse than the array agreement by only the margin parameter, then the offer is accepted, the relevant message is sent and the appropriate actions will be taken.
- If a^1 and a^2 are not fully specified actions and all the values of a^i and a^j that are not *Null* are the same as those of the actions of the array agreement then
  - If all the *Null* values are specified in the $agreed^j$ and $agreed^i$ arrays, then the agent accepts the offer, the relevant message is sent and the appropriate actions will be taken.
  - Otherwise, it chooses a parameter of j that is not specified in both a^j and in $agreed^j$ and sends a conditional offer $(C, a^i, a^{j'})$ where $a^{j'}$ consists of the non-null parameters of a^j and $agreed^j$ and the value of the chosen parameter according to the array agreement. If the opponent accepts the conditional offer, the agent will update $agreed^1$ and $agreed^2$ accordingly and will take the necessary actions if needed.
- Otherwise, the agent sends an offer specifying its array agreement.

Response to requests and threats: Suppose the agent receives a message of the form $\langle R, a^i\rangle$ where $a^i \in Ac^i$ or $\langle T, a^1, a^2\rangle$, where $a^i \in Ac^i$.
- If the requested action a^i matches the array agreement the agent will send a conditional offer saying it will do a^i if the opponent will do $a^{j'}$ where $a^{j'}$ is the opponent's action according to the array agreement.
- Otherwise, the agent will send a comment message saying: Your demands have not been made in the spirit of fairness. i would like j to be more considerate of i's interests during these negotiations.

For example, if the agent receives the following message: "These negotiations are taking too long. I am losing patience and considering other alternatives", the agent, playing the opponent's role will reply: "I urge that you be more patient during these negotiations as I need more time to consider your offer".

Whenever the other player promises to take an action that does not terminate the crisis (i.e., $a^i = \langle a^i_1, \ldots, a^i_k\rangle$ where $a^i_1 = Null$ and $a^i_j \neq Null$), the agent initiates a timer, and when the time has expired the agent checks if the other side has taken the action it said it would take. If the action has not been taken, a message regarding the issue is sent.

Another activity taken by the agent is sending a message regarding action parameters that have not yet been agreed upon. Every 3 minutes the agent randomly chooses one of the parameters that has a *Null* value according to $agreed^j$ and that does not appear in the last few messages. It sends an offer regarding that parameter proposing the array agreement value. The development of more complex heuristics for this activity is left for future work.

5. Experiments

On March 9, 1995, one of Canada's Department of Fisheries and Oceans (DFO) vessels, the Cape Roger, fired on and captured the Estai, a Spanish trawler, on the grounds that the Estai had been fishing turbot illegally. Spain responded by sending one of its naval vessels to the Grand Banks to protect other fishing vessels. During the ensuing weeks, Spain and Canada sparred with each other, each firmly believing that they were right and the other country was wrong. It was a period of accusation, rhetoric, name-calling, pacification, and ultimately negotiation. A settlement was reached on April 18, 1995, and the worst part of the Turbot War was over [29]. See also [30] and [20]. We applied our model to a specific scenario based on the fishing dispute between Canada and Spain and conducted simulations in which human players and our agent attempted to negotiate an agreement. A brief description of the scenario follows.

5.1. The scenario

A stock of flatfish straddles the Canadian exclusive economic zone (EEZ) and international waters. This stock has been severely over-fished in recent years, and Canada has taken measures to conserve this stock while allowing minimal fishing in order to maintain some level of employment for its fishing fleet. Spain has fished this same stock of flatfish for many years, and has respected Canada's EEZ by not attempting to fish within it. Spain is also dependent on fishing in the area outside the EEZ for both employment and trade.

The crisis is initiated by Canada's seizing one of Spain's ships in international waters adjacent to its EEZ, enforcing Canada's legislation regarding the conservation of the flatfish fishery. Canada claims to have found fishing gear aboard Spain's ship that is in violation of previous agreements (such as fine mesh nets). Canada maintains that continued over-fishing of the flatfish stock, even at the edges of the EEZ, will eliminate the stock completely within a short period of time. Spain claims, however, that her fishing is done in international waters, and therefore occurs outside of Canada's jurisdiction.

Canada and Spain have agreed to meet in an attempt to negotiate an agreement regarding the fishery dispute, according to procedures outlined in the United Nations Convention on the Law of the Sea (UNCLOS). Each party must consider four possible ways of ending the crisis:

(1) An agreement on Total Allowable Catch for the season. The Total Allowable Catch can be between 1 ton and 54 tons.
(2) Canada enforces conservation measures with military force against Spain (i.e., Canada opts out of the negotiation). This can result in either success, partial success or failure.
(3) Spain enforces its right to fish throughout the fishery with military force against Canada (i.e., Spain opts out of the negotiation). This can result in either success, partial success or failure.
(4) Status quo.

Other parameters associated with Canada's actions:

(1) Canada can subsidize the removal of Spain's ships. The possible values of this action parameter are: 0, 5, 10, 15, and 20 ships.
(2) Canada can impose trade sanctions on Spain. The possible values of this action parameter are yes and no.

Other parameters of the actions of Spain are:

(1) Spain can reduce the amount of pollution caused by the fishing fleet. The possible values of this action parameter are: 0%, 15%, 25% and 50%.
(2) Spain can impose trade sanctions on Canada. The possible values of this action parameter are yes and no.

The negotiation takes time and is divided into time periods. If the negotiation does not end by the beginning of the fishing season (i.e., the deadline), then the status quo will be implemented.

The utility points used in the simulations are presented in Appendix A. They satisfy the assumptions A1–A4 and therefore are an example of the environment that we are analyzing. In particular, there is always an agreement that is better for both sides than the expected utility associated with opting out. Canada prefers the Total Allowable Catch to be as low as possible, since it is determined to preserve the fishery. On the other hand Spain has no concern about the fish lasting in this specific area since it can move to another location. When an agreement is reached on the Total Allowable Catch, the quota is divided equally between the two countries.

Each country benefits from imposing trade sanctions, but each loses when trade sanctions are imposed against it. The pollution parameter is under Spain's control. Spain has old fishing vessels that cause a high percentage of pollution, polluting the area near Canada. Increasing the pollution reduction by improving the ships is costly to Spain but Canada will gain from it, as pollution will decrease. The ship subsidization parameter is under the control of Canada. Both Canada and Spain gain from increasing the number of ships subsidized by Canada. Spain will receive the subsidy and will compensate Canada by fishing less.

Formalizing the fishing dispute scenario as a crisis $\mathcal{C} = \langle Ag, \mathcal{S}, k, A_1^1, \ldots, A_k^1, A_1^2, \ldots, A_k^2, Ac^1, Ac^2, Ac_o^1, Ac_o^2, \mathcal{T}, dl, \mathcal{O}, O_o, p, Res, U^1, U^2 \rangle$ can be done as follows:

Agents: Without loss of generality we will refer to the player playing the role of Canada as agent 1 and the one playing the role of Spain as agent 2.

Main negotiation issue: The main negotiation issue between Canada and Spain is the Total Allowable Catch for the season. Thus, $\mathcal{S} = \{1, \ldots, 54\}$.
$k = 3$.

Domains of actions' parameters: For $i \in \{1, 2\}$, $A_1^i = \{Null, SA(1), \ldots, SA(54), OPT_i\}$.
For Canada, the second attribute of an action has to do with subsidizing the removal of Spain's ships. Thus, $A_2^1 = \{Null, 0, 5, 10, 15, 20\}$.
For Spain, the second attribute of an action has to do with Spain reducing the amount of pollution caused by the fishing fleet. Thus, $A_2^2 = \{Null, 0\%, 15\%, 25\%, 50\%\}$.
The third parameter of an action of both Canada and Spain is associated with imposing trade sanctions on the opponent. Thus, $A_3^1 = A_3^2 = \{Null, Yes, No\}$.
The *Null* value in all the actions indicates that no decision has been made with respect to this attribute. Thus, it is open for negotiation.

Actions: Ac^1 includes all possible combinations of the three attributes. For example, $(SA(34), 15, Yes)$ which means that Canada (agent 1) signs an agreement where the Total Allowable Catch is set to 34 while subsidizing the removal of 15 of Spain's ships and imposing trade sanctions on Spain.
Ac_o^1 includes all possible combinations of actions for which the first attribute is OPT_1. For example $(OPT_1, 0, No)$ which means that Canada enforces conservation measures with military force against Spain while not subsidizing the removal of any of Spain's ship and not imposing trade sanctions on Spain. Ac^2 and Ac_o^2 are defined similarly.

Outcomes:

- $SQ \in \mathcal{O}$ indicating the status quo; This can occur when one or both sides impose trade sanctions.
- $CC \in \mathcal{O}$ indicating that the crisis continues.
- Canada succeeds in enforcing conservation measures with military force against Spain, Canada fails to do it, or has partial success. This can occur when one or both sides impose trade sanctions.
- Spain succeeds in enforcing its right to fish throughout the fishery with military force against Canada, Spain fails to do so, or has partial success. This can occur when one or both sides impose trade sanctions.
- An agreement is signed with the value of $1 - 54$. This can occur when one or both sides impose trade sanctions, and when Spain possibly reduces fishing related pollution and Canada subsidizes the removal of some of Spain's ships.

Results of actions: We will demonstrate the probability function. For example, $p((OPT_1, 5, No), (Null, 15\%, Yes), Success, 1) = 0.1$.

Utility functions: We will demonstrate a few values of the utility functions calculated based on Appendix A: $U^1(Res((SA(34), 10, Yes), (SA(34), 25\%, No), 4), 4) = 565$.
$EU^1(Res((OPT_1, 5, No), (Null, 15\%, Yes), 1), 1) = 415$.

5.2. Experimental results

In order to evaluate the agent's performance in negotiation situations we conducted two sets of simulations. One set of simulations was performed with Computer Science students at Bar Ilan University in Israel. This set was performed in order to compare the agent's performance to the performance of people. The second set of simulations was conducted with Government and Politics students at the University of Maryland. While the Maryland simulations were designed to test hypotheses relating to foreign policy decision-making, they will be presented here as a reliability check of the main Bar Ilan results. Each student was told his/her role in the simulation and they had fifteen minutes to work out a strategy and check their options by means of the GDSS.

5.2.1. Comparison

In the Bar Ilan experiments, the negotiation was divided into ten seven-minute periods. Students were motivated to play seriously by the possibility of receiving one to five extra points on their final grade, depending upon their final utility point total. Our hypothesis was that the agent would do at least as well as the human players in the negotiations.

A total of 45 simulations were run at Bar Ilan: 15 simulations were humans against humans, and 30 simulations were humans against agents. In 14 simulations the agents played Spain and in 16 simulations the agents played Canada.

According to assumption A4 there is always an agreement that yields a higher utility for both sides than the expected utility associated with opting out. Therefore, opting out in this simulation is not a wise step to take. The expected utility from opting out was much lower than the agreements' values. Therefore, when presenting the simulation results we provide three types of results: the results of the simulations ending with an agreement, the results of simulations ending with opting out, and the results of all the simulations.

Table 1 presents the average utility outcomes of the experiments. It is divided into three columns. The first is a list of results for all simulations in which two humans played against each other ('C' stands for Canada and 'S' stands for Spain). The second and third columns report on the simulations where the agent played Canada's and Spain's roles. For the simulations that ended with one of the players opting out, there are separate lines for the cases where Canada or Spain opted out. There were five cases in which a human player opted out and one case where the agent opted out. In these cases the table specifies the average of the expected outcomes. If we compare the results of the humans to those of the agents for those simulations that ended with an agreement, we can see that the agent that played Spain's role did significantly better than the human ($t = -5.957$, $p < 0.01$) while the agent that played the role of Canada did just as well as the human. When looking at the results that include all the outcomes, again, the agent playing Spain played significantly better than the human playing Spain ($t = -2.51$, $p < 0.05$). The results for Canada did not show a significant difference between the agent and human players.

The average sum of the utility points in simulations where agreements were reached with only humans is 1336, the average sum of the simulations where an agent was involved is 1445 and 1434, and the average of both is 1440. We can conclude that when an agent participates in a negotiation the sum of the utilities is significantly higher than when two humans play ($t = -4.916$, $p < 0.01$). This can be explained by looking closely at the agreements that were reached in the simulations.

Table 2 presents all the details of the agreements that were reached. The average Total Allowable Catch in the all-human simulations is 23.6. Note that Canada would like the Total Allowable Catch to be as low as possible,

Table 1
The average utility of the players in the BIU simulations

	2 humans			Canada human and Spain agent			Spain human and Canada agent		
	C	S	SUM	C	Ag–S	SUM	S	Ag–C	SUM
Agreements	612	723	1336	599	845	1445	827	607	1434
Opt(C)	433	295	728	445	327	772	388	407	796
Opt(S)	530	335	865				502	385	887
Opt	481	315	796	445	327	772	445	396	841
Total:	595	669	1246	588	808	1397	731	554	1286

Opt(C) indicates Canada opting out and Opt(S) indicates Spain opting out.

Table 2
Details of the agreements of the BIU simulations

	TIME	TAC	SHIP	POLL
H–C H–S	4.7	23.6	13.5	30.8
Ag–S H–C	4.8	32.2	20	50
Ag–C H–S	3.8	31.2	20	45.8

TAC: the Total Allowable Catch. SHIP: the average number of ships that Canada subsidizes. POLL: the average of the percentage by which Spain reduces fishing related pollution.

while Spain would like it to be as high as possible. When the agent plays Spain, the Total Allowable Catch average increases to 32.2. This explains why the agent playing Spain achieves a better score than a human. When the agent plays Canada, the average Total Allowable Catch is 31.2, which is larger than 23.6. It is apparent that the agent can do better, since the human playing Spain agrees non-rationally even to agreements where the Total Allowable Catch is 23.6. This could explain why the agent does not do better than humans when playing Canada's role. Nonetheless the agent playing Canada does not do worse, because the other parameters are better from its point of view. The average POLL (i.e., the percentage by which Spain reduces fishing related pollution) and SHIP (i.e., the number of ships that Canada subsidizes) differs between simulations with and without the agent. These values are higher in the simulations in which the agent participates. The SHIP parameter increases the utility of both players; this compensates for the higher Total Allowable Catch value in the simulations where the agent plays the role of Canada. This also explains the result that the sum of the utility points of simulations where the agent participates in negotiations is significantly higher than when two humans negotiate with one another.

5.2.2. *Reliability check*

At the University of Maryland, a total of 48 experimental simulations were conducted using the automated negotiator in tests of hypotheses pertaining to belief change among negotiators during the course of negotiations (see [1]). Experimental subjects were tested to assess the extent to which they held hawkish versus dovish views pertaining to foreign policy issues. As noted above, we use some of the results of these simulations as a reliability check of the Bar Ilan simulation results. In the University of Maryland experiments, as in the Bar Ilan simulations, the negotiation was divided into ten seven-minute periods. Students were motivated to play seriously by the prospect of receiving extra credits for their final grade in the courses in which they were enrolled. Since we did not want prior knowledge of political relationships to affect the students that played in these simulations, we changed the names of the countries participating in the dispute: Canada was changed to Thule and Spain to Ultima.

In all 48 simulations the agent played Spain and the students played Canada. Our hypothesis is that the agent would do as well as it did in the Bar Ilan simulations.

The results presented in Table 3 support our hypothesis. The average utility obtained by the agent in the University of Maryland simulations when an agreement was reached is 848 (compared to an average of 845 in the Bar Ilan simulations reported in Table 1). The results were not significantly different than those obtained by the agent in the Bar Ilan simulations. The average utility of simulations that ended with an agreement for the UMD students was 568 (compared to an average of 599 for the Bar Ilan students in similar simulations reported in Table 1). We found that the Maryland students did significantly worse than the Bar Ilan University students ($t = -4.009$, $p < 0.01$) even though the UMD's students were trained in negotiations. One possible explanation for these results is that the two groups of students differed in both their nationality and their major. In addition, we believe that the Israelis majoring in Computer Science were motivated mainly to increase their utility, while the American Government and Politics students played according to their general understanding of how one should negotiate in such situations, and were less concerned with the utility they would gain.

Finally, we would like to note that from our non-systematic observation we found that in both experiments the human players who played against the agents were rarely able to reveal whether they were playing against a human counterpart or an agent.

Table 3
The average utility of the players in the UMD simulations

	Canada human and Spain agent		
	C	Ag–S	SUM
Agreements	568	848	1426
Opt(C)	444	325	769
Opt(S)	453	470	923
Opt	447	383	830
Total:	588	808	1397

Opt(C) indicates Canada opting out and Opt(S) indicates Spain opting out.

6. Related work

Several researchers have developed models for negotiations between rational automated agents, as surveyed in [12, 22]. However, only a few attempts have been made to develop automated agents that can negotiate with people.

Sycara [33] presented a model for labor negotiations that combines case-based reasoning and optimization of multi-parameter utilities, but she demonstrated its behavior only in simulations of automated agents which she designed all in a similar way.

Kraus and Lehmann [13] developed an automated diplomacy player that negotiates and plays well in actual games against human players (although the small number of runs precluded the type of statistical testing performed in the present study). While Diplomats' strategies were based only on heuristics, the automated negotiator model presented here is based on a formal analysis of the crisis coupled with heuristics.

Mudgal and Vassileva [16] present an automated agent that can negotiate on behalf of a student with other automated agents in the I-Help system. I-Help is an online system that provides a student in a university course with a matchmaking service to find a peer-student online for assistance. When a student needs help, his agent contacts a centralized matchmaker who provides a ranked list of potential helpers. The agent of the students requesting assistance begins negotiations about the price per unit of help time with the agent of the first potential helper from the list. If the agents fail to reach a deal, the agent of the student seeking help begins negotiations with the second agent on the list, etc. Mudgal and Vassileva's approach is based on decision theory and not on game theory as in our approach. Similar to our work, they model the opponent's behavior during one session, in order to better predict the opponent's reaction. They use influence diagrams, while we estimate the opponent's utility function. In addition, we consider multi-issue negotiations while they consider single-issue negotiations. Also, our agent has more information about the opponent than their agent. Finally, while we focus on scenarios where the agents need to negotiate with people who we have no control over, their agent negotiates with other agents that use strategies developed by the authors. Nevertheless, it will be interesting to try to adapt their approach to our domain. We leave this for future work.

Su et al. [32] present the design and implementation of a replicable Internet-based negotiation server for conducting bargaining-type negotiations in e-commerce. They make use of object-oriented, active database technology. They focus on enabling the companies to specify the goods and services in which they are interested or that they are willing to provide and to specify negotiation strategies. We focused on the development of autonomous agents that can negotiate with people in situations where the preferences of the agents are specified via a utility function. While they demonstrated their approach in various scenarios, we carried out carefully monitored experiments.

Sierra et al. [27] present a model of negotiation for autonomous agents to reach agreements about the provision of a service by one agent to another. Their model defines a range of strategies and tactics, distilled from intuition about good behavioral practice in human negotiations that agents can employ to generate offers and evaluate proposals. We apply a formal game-theory model with a dynamic analysis. In our model an agreement is complex. It contains different parameters that describe the state of the world. All parts of an agreement are negotiable.

Sierra et al. [28] describe a general framework for negotiation in which agents exchange proposals backed by arguments that summarize the reasons why the proposals should be accepted. The argumentation is persuasive because the exchanges are able to alter the mental state of the agents involved. We allow comments and requests to be passed between the agents in addition to the agreements offered. However, agents do not attempt to persuade each other or to explain why their proposal should be accepted. This is not necessary in domains of complete information.

Sandholm and Vulkan [25] analyze automated distributed negotiations where agents have firm deadlines that are private information. We analyzed a case with one deadline, which is common knowledge. If no agreement is reached prior to the deadline, a status quo is implemented.

Zhun and Tambe focus on the problem of negotiation in teamwork to resolve conflicts such as conflicting beliefs about different aspects of the agents' environment and resource availability. In our model, we do not deal with agents who are members of a team, but rather we consider conflicting sides that have to come to an agreement. However, both sides have complete information on the current world state and there are no conflicting beliefs. Thus, Zhun and Tambe's agents use argumentation to convince their teammates to adopt their beliefs and plans, while our agent bargains with its adversary. Similarly, Jung et al. [7] study the distributed constraints satisfaction problem (DCSP) as a computational model for investigating Negotiation via Argumentation in a cooperative multi-agent environment.

Faratin et al. [3] also consider situations where agents attempt to maximize the joint gains of the negotiating agents. They discuss trade-offs made by agents during automated negotiations in which the agents have uncertain information. They present an algorithm for performing trade-offs for multi-dimensional goods. Our agreements also consist of several parameters. In their settings, however, agents care about equity and social welfare, as well as their individual utility. This is not the case in our setting. In our settings both agents have competitive utilities. Trying to find similar offers for each counter-offer is not effective.

Fatima et al. [4] also consider negotiation when there is a deadline. They assert that because the negotiation has a deadline, they assume that the agents use time-dependent tactics for generating offers (they state, for example, linear, Boulware or Conceder tactics). They also assume that agents maximize their expected utility. Fatima et al. define six negotiation scenarios. They assume that they have incomplete information about the other agent's deadline. Thus, an agent negotiates in one of six scenarios. Since they assume that the agents use time-dependent tactics, each agent projects with some probability the deadline of the other agent. Using these facts they describe optimal strategies for the negotiation. We consider complete information about the deadline. However, since we deal with people, we cannot rely on the fact that the opponent maximizes her expected utility. Thus, we have to incorporate heuristics into our formal model.

Klein et al. [11] describe a simulated annealing based approach that is appropriate for negotiating complex interdependent issue contracts. It allows agents to find 'win–win' contracts in intractably large multi-optima search spaces in a reasonable amount of time. While they consider non-linear utility functions in a very large space, our utility function is linear and we consider a small space. However, since we consider negotiations between a human and an automated agent, even this small space causes difficulties for the human negotiator and our automated agent needs to reach beneficial agreements given its opponent's limitations.

There have been various attempts to develop an agent that negotiates using learning techniques (e.g., [10,14,18]). While these approaches seems very promising when either the agreements to be reached are relatively restricted (e.g., [10]) or when there is a lot of time for negotiation, they are not applicable to our situations that are characterized by time constraints, deadlines, and the possibility of opting out.

7. Conclusions

In this paper we presented an automated negotiator that interacts with humans. The agent is based on a game theory model, coupled with heuristics. The agent was tested in a simulation of a fishing dispute with humans. The results of the experiments revealed that the agent played at least as well as, and in the case of one of the two roles, significantly better than a human player. We believe that this is a good indication of the agent's possible behavior in other domains with similar characteristics: time constraints, deadlines, full information, and opting out. Modifying the agent to negotiate in other domains where the assumptions of the formal model hold is straightforward: there is a need to enter the new utility points via the agent's interface and to change the domain specific terms in the language. If the assumptions do not hold, then modifications based on the game theoretic analysis of the new scenario will need to be undertaken.

An important future research direction will involve the participation of an agent in negotiations involving incomplete information. In this case, greater attention will need to be paid to creating mechanisms for the agent to update its beliefs concerning the objectives and utilities of its opponent, as a result of information emerging during the course of the negotiations.

Appendix A. Utility points for the fishing dispute

Outcomes	Canada	Spain	
Agreement on Total			
Allowable Catch	705	410	
Point impact per ton of fish	-5	10	1–54
Canada uses military force			
Success	860	115	10%
Partial success	510	345	30%
Failure	310	305	60%
Spain uses military force			
Success	160	835	10%
Partial success	230	515	20%
Failure	700	155	70%
Status Quo	200	325	
Non-terminal action parameters			
Canada—ship subsidies			Agr*
0 Ships	0	0	
5 Ships	5	30	
10 Ships	20	50	
15 Ships	30	70	
20 Ships	45	100	
Canada—trade sanctions			All*
No trade sanctions	0	0	
Trade sanctions	10	−30	
Spain reduces fishing related pollution			Agr*
0%	0	0	
15%	10	−15	
25%	20	−20	
50%	30	−25	
Spain—trade sanctions			All*
No trade sanctions	0	0	
Trade sanctions	−10	15	
Time	−5	10	All*

Utility points. Agr*—affects only agreements. All*—affects all outcomes.
Impact of time on the probabilities of military action: Success: 2%. Partial success: −1%. Failure: −1%.

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