

Multi-issue negotiation processes by evolutionary simulation: validation and social extensions

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Multi-Issue Negotiation Processes by Evolutionary Simulation, Validation and Social Extensions *

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Abstract. We describe a system for bilateral negotiations in which artificial agents are generated by an evolutionary algorithm (EA). The negotiations are governed by a finite-horizon version of the alternating-offers protocol. Several issues are negotiated simultaneously. We first analyse and validate the outcomes of the evolutionary system, using the game-theoretic subgame-perfect equilibrium as a benchmark. We then present two extensions of the negotiation model. In the first extension agents take into account the fairness of the obtained payoff. We find that when the fairness norm is consistently applied during the negotiation, agents reach symmetric outcomes which are robust and rather insensitive to the actual fairness settings. In the second extension we model a competitive market situation where agents have multiple bargaining opportunities before reaching the final agreement. Symmetric outcomes are now also obtained, even when the number of bargaining opportunities is small. We furthermore study the influence of search or negotiation costs in this game.

Key words: multi-issue bargaining, evolutionary algorithms, fairness, multiple bargaining opportunities, game theory

1. Introduction

Automated negotiations have received increasing attention in the last years, especially from the field of electronic trading [4, 15, 16, 18]. In the near future, an increasing use of bargaining agents in electronic market places is expected. Ideally, these agents should not only bargain over the price of a product, but also take into account aspects like the delivery time, quality, payment methods, return policies, or specific product properties. In such *multi-issue* negotiations, the agents should be able to negotiate outcomes that are mutually beneficial for both parties. The complexity of the bargaining problem increases rapidly, however, if the number of issues becomes larger than one. This explains the need for ‘intelligent’ agents, which should be capable of negotiating successfully over multiple issues at the same time.

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In this paper, we consider negotiations that are governed by a finite-stage version of the Rubinstein–Ståhl multi-round bargaining game with alternating offers [24, 25]. We investigate the computation of strategies of the agents by evolutionary algorithms (EAs). EAs are powerful search algorithms (based on Darwin’s evolution theory) which can be used to model social learning in societies of boundedly-rational agents [8, 20]. It is important to note that EAs make no explicit assumptions or use of rationality. Basically, the fitness (i.e., quality) of the individual agents is used to determine whether a strategy will be used in future situations.

A small, but growing, body of literature already exists in this field [5, 16, 18, 26]. These papers demonstrate that, using an EA, artificial agents can learn effective negotiation strategies. In [26], a systematic comparison between game-theoretic and evolutionary bargaining models is also made, in case negotiations concern a single issue.

The focus of this paper lies on negotiations where multiple issues are involved. We first analyse the results and compare these with game theory. We study both models in which time plays no role and models in which there is a time pressure to reach agreements early (because a risk of breakdown in negotiations exists after each round).

We subsequently present two important extensions of this negotiation model. The first extension introduces a fairness norm and is based on the following observation. When no time pressure is present, extreme divisions of the payoff occur in the computational experiments, due to a powerful ‘take-it-or-leave-it’ position for one of the negotiating agents in the last round of the negotiation. Although such extreme outcomes are in agreement with game-theoretic results, they are usually not observed in real-life situations, where social norms such as fairness play an important role [9, 14, 21, 28]. We therefore introduce a fairness norm and incorporate this in the agents’ behaviour. We perform computational experiments with various fairness settings, and show that, depending on the actual settings, ‘fair’ deals indeed evolve.

In the second extension, we endow agents with additional bargaining opportunities in case of a disagreement. Agents can now choose to refuse unacceptable take-it-or-leave-it deals and negotiate with another opponent. This extension introduces competition among the agents and is probably a better model of real-life bargaining situations, where often several negotiation partners are available (e.g., within a market place). Because agents now no longer have to accept extreme deals, the situations for agents in a bad bargaining position improves. We perform various experiments with this setup, and we observe efficient and ‘fair’ agreements. We also study the effect of search costs for finding a new negotiation partner.

These evolutionary models are a first attempt to study complex bargaining situations which are more likely to occur in practical settings. A rigorous game-theoretic analysis is typically much more involved or may even be intractable under these conditions.

The remainder of this paper is organised as follows. Section 2 gives an outline of the setup of the computer experiments. A comparison of the computational results with game-theoretic results is presented in Section 3. The extensions with fairness and with multiple bargaining opportunities are the topic of Sections 4 and 5 respectively. Section 6 summarises the main results and concludes.

2. Experimental Setup

This section describes the setup of the computational system and experiments. The alternating-offers negotiation protocol is described in Section 2.1. Section 2.2 then describes the EA.

2.1. NEGOTIATION PROTOCOL AND AGENT MODEL

2.1.1. *Negotiation Protocol*

During the negotiation process, the agents exchange offers and counter offers in an alternating fashion at discrete time steps (rounds). In the following, the agent starting the negotiations is called ‘agent 1’, whereas his opponent is called ‘agent 2’.

Bargaining takes place over m issues simultaneously, where m is the total number of issues. We assume (without loss of generality) that the total bargaining surplus available per issue is equal to unity. We express an offer as a vector \vec{o} , where the i th component o^i specifies the share that agent 1 receives for issue i if the offer is accepted. Agent 2 then receives $1 - o^i$ for issue i . The index i ranges from 1 to m . Note that an offer always specifies the share obtained by agent 1.

As stated above, agent 1 makes the initial offer. If agent 2 accepts this offer, an agreement is reached and the negotiations stop. Otherwise, play continues to the next round with a certain continuation probability p ($0 \leq p \leq 1$). When a negotiation is broken off prematurely, both agents receive nothing.

If negotiations proceed to the next round, agent 2 needs to propose a counter offer, which agent 1 can then either accept or refuse. This process of alternating bidding continues for a limited number of n rounds. When this deadline is reached without an agreement, the negotiations end in a disagreement, and both players receive nothing.

2.1.2. *Agent Model*

The agent model contains the negotiation strategy used by the agent and a utility function to evaluate an opponent’s offer. In a game-theoretic context, a strategy is a plan which specifies an action for each history [2]. In our model, the agent’s strategy specifies the offers $\vec{o}_j(r)$ and thresholds $t_j(r)$ for each round r in the negotiation process for agents $j \in \{1, 2\}$. The threshold determines whether an offer of the other party is accepted or rejected: If the value of the offer (see below)

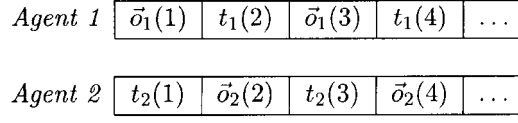


Figure 1. The strategies for agent $j \in \{1, 2\}$ specify a sequence of offers $\vec{o}_j(r)$ and thresholds $t_j(r)$ for rounds $r \in \{1, 2, \dots, n\}$ of the negotiation.

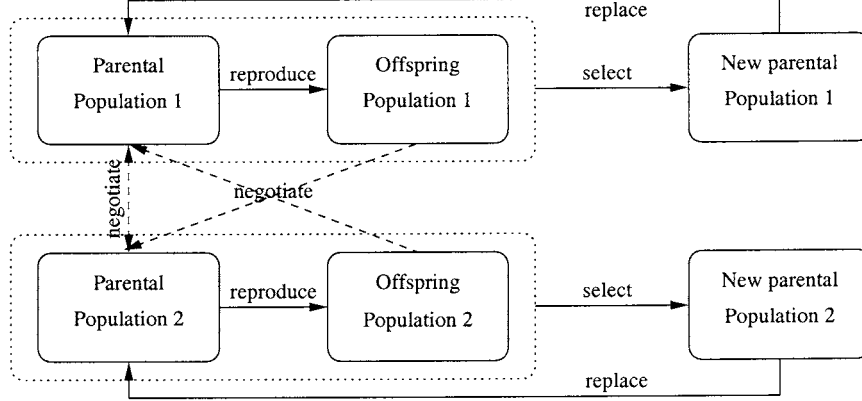


Figure 2. Iteration loop of the evolutionary algorithm.

falls below the threshold the offer is refused; otherwise an agreement is reached.¹ This strategy representation is depicted in Figure 1. Notice that in each round, the strategy of an agent specifies either an offer or a threshold, depending on whether the agent proposes or receives an offer in that round.

The agents evaluate the offers of their opponents using an additive multi-attribute utility function [16, 18]. Agent 1's utility function is $\vec{w}_1 \cdot \vec{o}_j(r) = \sum_{i=1}^m w_1^i \cdot o_j^i(r)$, where $j = 1$ if the offer is proposed by agent 1 and $j = 2$ otherwise. Agent 2's utility function is $\vec{w}_2 \cdot [\vec{1} - \vec{o}_j(r)]$. Here, \vec{w}_j is a vector containing agent j 's weights w_j^i for each issue i . The weights are normalised and larger than zero, i.e., $\sum_{i=1}^m w_j^i = 1$ and $w_j^i \geq 0$. Because we assume that $0 \leq o_j^i(r) \leq 1$ for all i , the utilities are real numbers in $[0, 1]$.

2.2. THE EVOLUTIONARY SYSTEM

We use an EA to evolve the negotiation strategies of the agents. The implementation is based on 'evolution strategies' (ES), using a real-encoding of the offers and thresholds [1].² A technical description of our implementation is given in Appendix A. An outline of the EA is given in Figure 2.

The system initially starts with two separate (and randomly initialised) 'parental' populations of bargaining agents. Each agent within a population contains a bargaining strategy, which is encoded on his 'chromosome' as a set of real values.

Table I. Default settings of the evolutionary system.

EA parameters	Parental population size (μ)	25
	Offspring population size (λ)	25
	Selection scheme	$(\mu + \lambda)$ -ES
	Mutation model	Self-adaptive
	Initial standard deviations ($\sigma_i(0)$)	0.1
	Minimum standard deviation (ϵ_σ)	0.025
Negotiation parameters	Number of issues (m)	2
	Number of rounds (n)	10
	Weights of agents in population 1 (\vec{w}_1)	$(0.7, 0.3)^T$
	Weights of agents in population 2 (\vec{w}_2)	$(0.3, 0.7)^T$

These values specify the offers for each round and for each issue separately, and also the thresholds for each round (see Appendix A.1).

Agents in population 1 start the bargaining process (i.e., they are of the ‘agent 1’ type). The fitness of the parental agents is determined by negotiation between the agents in the two parental populations. Each agent negotiates with all agents in the other population. The utility functions are the same for agents within the same population (i.e., the weight settings are equal). The average utility obtained in all negotiations is an agent’s fitness value.

Subsequently, ‘offspring’ agents are created (Figure 2). An offspring agent is generated by first (randomly, with replacement) selecting an agent in the parental population, and then mutating his chromosome to create a new offspring (see Appendix A.2). The fitness of the new offspring is evaluated by negotiation with the parental agents.³ A social or economic interpretation of this parent-offspring interaction is that new agents can only be evaluated by competing against existing or ‘proven’ strategies.

In the final stage (Figure 2), the fittest agents from the parental and offspring populations are selected as the new ‘parents’ for the next iteration (see Appendix A.3). This final step completes one iteration (or ‘generation’) of the EA. All relevant settings of the evolutionary system are listed in Table I (further explanation is provided in Appendix A).

3. Validation and Interpretation of the Evolutionary Experiments

Experimental results obtained with the evolutionary system are presented in this section. A comparison with game-theoretic results is made to validate the evolutionary approach. Section 3.1 addresses the evolution of efficient negotiation results. Section 3.2 further analyses the results and compares the experimental

results with predictions from game theory. In the following, we refer to the agents in the evolutionary system as ‘evolutionary agents’.

3.1. EFFICIENCY

First, we investigate the experimental results w.r.t. disagreements. Without breakdown ($p = 1$), disagreements can only occur when the deadline is reached. The experiments show that the percentage of disagreements is then very small (around 0.1% after 1,000 generations if $n = 10$). With a risk of breakdown of 30% ($p = 0.7$), this percentage is between 1% and 10%. Timing is now important for efficiency. The evolutionary agents avoid disagreements by reaching agreements early: after 1,000 generations, approximately 75% is reached in the first round.

Next, we study the efficiency of the agreements reached in the experiments. The agreements are depicted in Figure 3. This figure shows the utilities for both agents of the deals reached. Also depicted in Figure 3 is the so-called ‘Pareto-efficient frontier’. An agreement is located on the Pareto-efficient frontier when an increase of utility for one agent necessarily results in a decrease of utility for the other agent. Agreements can therefore never be located above the Pareto-efficient frontier. A special point is the symmetric point S [at $(0.7, 0.7)$], where both agents obtain the maximum share of the issue they value the most, and receive nothing of the less important issue.

Figure 3 shows that initially, many agreements are located far from the Pareto-efficient frontier. After 100 generations, however, the agreements are chiefly Pareto-efficient. We note that, even in the long run, the agents keep exploring the search space, resulting in a continuing moving ‘cloud’ of agreements along the frontier.

Conclusion. Results in this section thus show that the evolutionary agents reach efficient agreements, viz. on the Pareto-efficient frontier, and that disagreements are avoided. The next section studies the actual outcomes more closely, using results from game theory as a benchmark.

3.2. FURTHER ANALYSIS

The computational results are analysed in more detail in this section and compared with game-theoretic results, and in particular the subgame perfect equilibrium (SPE) predictions. Two strategies are in SPE if they constitute a Nash equilibrium in *any* subgame that remains after an arbitrary sequence of offers and replies. Rubinstein and (much earlier) Ståhl applied this notion to the alternating-offers bargaining game [24, 25]. Our experimental setup differs in two respects from their model, however. First, the agents bargain over multiple issues instead of a single issue. Second, the evolutionary agents are ‘myopic’: they do not apply any explicit rationality principles in the negotiation process, nor do they maintain any history. Actually, they only experience the profit of their interactions with other agents.

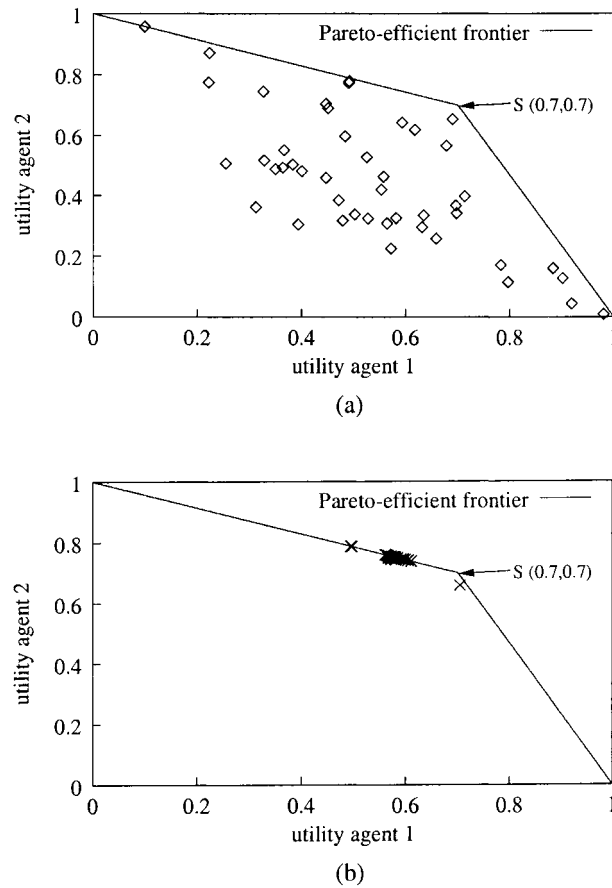


Figure 3. Agreements reached by the evolutionary agents at (a) the start of a typical EA run and (b) after 100 generations. The negotiation settings are $p = 0.7$ and $n = 10$.

The SPE behaviour of rational agents with complete information will nevertheless serve as a useful theoretical benchmark.

We distinguish between three classes of experiments w.r.t. the breakdown probability: (1) no risk of breakdown ($p = 1$), (2) a low breakdown probability ($0.8 \leq p < 1.0$) and (3) a high breakdown probability ($p < 0.8$). For each of these classes we consider the role of n on the outcomes.

We found that in our experiments, when $p = 1$, in the long run almost all agreements are delayed until the last round (about 80% after 1,000 generations). Furthermore, the last offering agent makes a take-it-or-leave-it deal and demands almost the entire surplus (on each issue), which is accepted by the opponent. This extreme division of the surplus agrees with game theory [9]; it is rational for the responder to accept any positive amount in the last round. Note, however, that rational agents are indifferent about the actual round in which the agreement

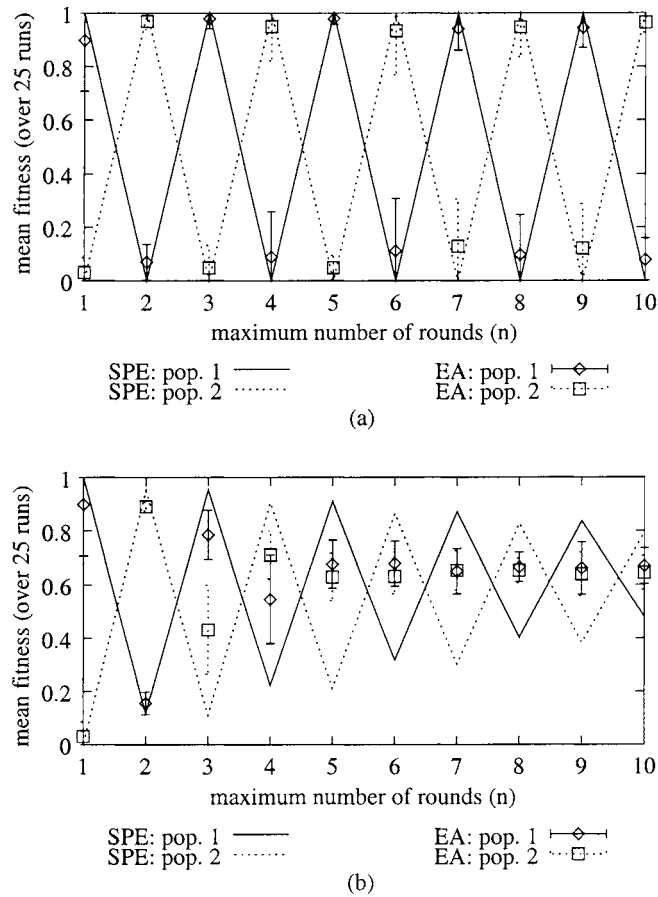


Figure 4. Comparison of the long-term evolutionary results with SPE results for (a) $p = 1$ (time indifference) and (b) $p = 0.95$. The error bars indicate the standard deviations across 25 runs.

is reached. The deadline-approaching behaviour in our experiments corresponds better to ‘real-world’ behaviour [22], however.

The EA results and SPE outcomes for different values of n (game length) are compared in Figure 4a. To guide the eye, the SPE outcomes for successive values of n are connected. Notice that fitness of agents in population 1 converges to unity if n is odd, and to zero if n is even (the opposite holds for the agents in population 2).

Figure 4b shows the results for $p = 0.95$. Note that the partitioning outcomes becomes less extreme with a low breakdown probability compared to no breakdown. This holds for both SPE outcomes and EA results, although the effect is much stronger in the evolutionary system (Figure 4b). These differences with SPE are due to the myopic properties of the agents in the EA. The evolutionary agents do not reason backwards from the deadline (as in SPE), since most agreements are reached in the first few rounds (if $p < 1$). As a result, the deadline is not

perceived accurately by the evolving agents. In fact, the game length is strongly overestimated. Furthermore, in SPE *all* agreements are reached without delay (see [26]). The EA, on the other hand, also continues to explore other strategies, which results in a remaining small number of disagreements (see Section 3.1).

As p becomes smaller, the influence of the game length on the SPE outcome also decreases (see [26]). Therefore, if p becomes sufficiently small (e.g., $p < 0.8$), the computational results automatically show a much better match with SPE outcomes than if p is large: the match is almost perfect, although a small number of disagreements occur due to a continuing exploration of new strategies.

Interestingly, in the limit of $n \rightarrow \infty$, game theory predicts that the agents in population 1 have a fitness of ≈ 0.71 when $p = 0.95$, whereas the agents in population 2 have a fitness of ≈ 0.68 . This corresponds to a point in the vicinity of the symmetric point S , indicated in Figure 3. The results reported in Figure 4b show that the behaviour of the agents corresponds much better to an infinite-horizon model than the finite-horizon model for $n \geq 5$ (Figure 4b). The same behaviour was observed for other EA settings (e.g., larger population size) and other negotiation situations (e.g., other weight settings).

We also studied the performance of the EA in case the number of issues m is increased to 8.⁴ We observe that, for $p = 1$, the long-term outcomes of the EA are unstable and do not converge to the extreme partitioning. When we increase the population size for the EA from 25 to 100 agents,⁵ the extreme partitioning reappears. Thus, for more complicated bargaining problems, the EA parameters must be adjusted. For $m = 8$ and $p < 1$, similar observations are found as reported in Section 3.2 (like Figure 4) when using the adjusted population size.

Conclusion. Game-theoretic (SPE) results appear to be a very useful benchmark to investigate the results of the evolutionary simulations. In computational simulations without a risk of breakdown (case 1), agreements are predominantly reached in the final round. This deadline effect is consistent with human behaviour [22]. Furthermore, the last agent in turn successfully exploits his advantage and claims a take-it-or-leave-it deal (as in SPE). In case of a small risk of breakdown (case 2), the deadline is not accurately perceived by the evolving agents, and the last-mover advantage is smaller than predicted by game theory. In fact, if the finite game becomes long enough, results match the SPE outcomes for the infinite-horizon game. With a high risk of breakdown (case 3), however, this deviation from SPE becomes negligible. Finally, it appears to be important to adjust the EA parameter settings (e.g., by increasing population sizes) for more complex bargaining problems.

4. Social Extensions: Fairness

We extend the agent model within our evolutionary system in this section to study the influence of ‘fairness’, an important aspect of real-life bargaining situations. The motivation and description of this fairness model is given in Section 4.1. In the fairness model studied in Section 4.2 the evolving agents only take the fairness

of a proposed deal into account when the deadline is reached. Section 4.3 presents results obtained when agents perform a ‘fairness check’ in each round. Section 4.4 further analyses the model in Section 4.3 for a simple case. Game-theoretic models for rational agents often predict the occurrence of very asymmetric outcomes for the two parties. We showed in Section 3.2 (Figure 4a) that such ‘unfair’ behaviour can also emerge in a system of evolving agents, in particular when $p = 1$ or n is small (Figure 4). Large discrepancies between human behaviour in laboratory experiments and game-theoretic outcomes are found, however, both for ultimatum (1 round) and multi-stage (several rounds) games [3, 7, 14, 21, 23, 28]. A possible explanation for the occurrence of these discrepancies between theory and practice is the strong influence of social or cultural norms on the individual decision-making process. In [21, p. 264] and [11], for example, it is argued that responders tend to reject unfair or ‘insultingly low’ proposals. Therefore, an anticipating agent should lower his demand in order to avoid a disagreement, this way taking into account the expectations about his opponent’s behaviour.

In [14] a model is proposed in line with this hypothesis. In their model, the probability of acceptance of an offer increases with the amount offered to the responder. Such a model, making more realistic assumptions about the agents’ behaviour, appears to organise the data from experiments with humans better than the SPE model [14].

Following [14], we introduce a fairness model in our evolutionary system. The agent model (see Section 2.1.2) is extended as follows. If the value of an offer exceeds the responder’s threshold, the agent has the opportunity to re-evaluate his decision. The probability that he finally accepts the agreement is then a function of the acquired utility. This so-called ‘fairness function’ is assumed to be piece-wise linear (with up to three segments).⁶ The instances that we use are shown in Figure 5.⁷ We now further distinguish between two different extended agent models. In the first model, the fairness function is used at the deadline only. This situation is studied in Section 4.2. In the second model, the fairness function is effective at any moment. This case is studied in Section 4.3. The first case is motivated by the deadline-effect observed in the experiments without a risk of breakdown (see Section 3.2), where most agreements are reached in the last round. The second case, however, is more likely to be an appropriate model of human behaviour.

4.1. FAIRNESS CHECK AT THE DEADLINE

In this section, fairness is applied in the last round. We study the case in which $p = 1$ and $n = 3$. Figure 6 shows that if the evolving agents in population 2 use fairness function 1 (i.e., a ‘weak’ fairness model), the partitioning is much less extreme than in case of no fairness check (function 0). However, the agents in population 1 still reach a relatively high fitness (utility) level. Fair agreements evolve, on the other hand, when the agents in population 2 use function 2 (a case with average fairness). In this case the mean long-term fitness is approximately

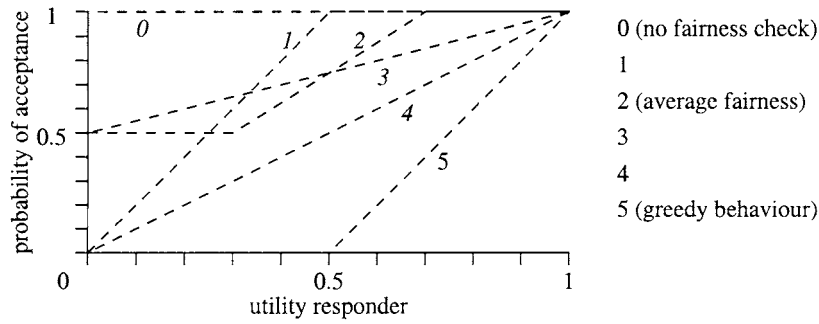


Figure 5. Fairness functions used by the agents in the EA.

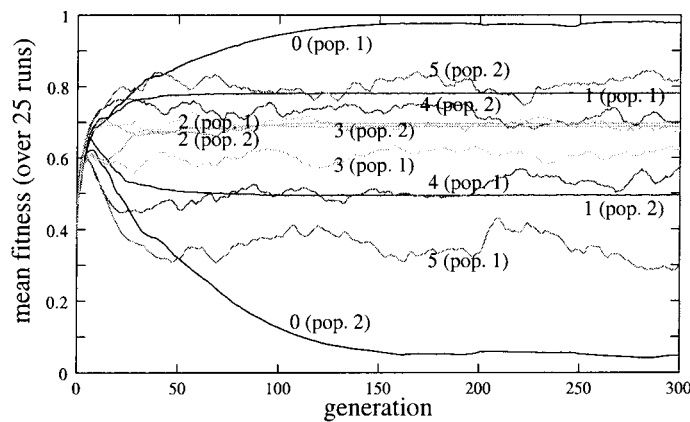


Figure 6. Mean fitness when fairness functions 0–5 are applied at the deadline.

equal to 0.7 for all agents (most agreements are thus located close to the symmetric point S in Figure 3).

When stronger fairness functions (e.g., functions 3 through 5) are used by the agents the roles reverse, and the agents in population 2 reach a *higher* fitness level than their opponents in population 1 (Figure 6). Because of the strong fairness check, many last-round agreements are rejected in this case and agents in population 2 can demand a larger share of the surplus in the round before last. As a result, the deadline is effectively reached one round earlier. This effect indeed occurs in our experiments.

Conclusion. Our results show that fair outcomes can evolve in an evolutionary system with a fairness model in the last round. However, there is a rather large sensitivity to the actual fairness function that is used by the evolved agents; an ‘average’ fairness function yields symmetric results, whereas more extreme fairness functions yield more asymmetric outcomes.

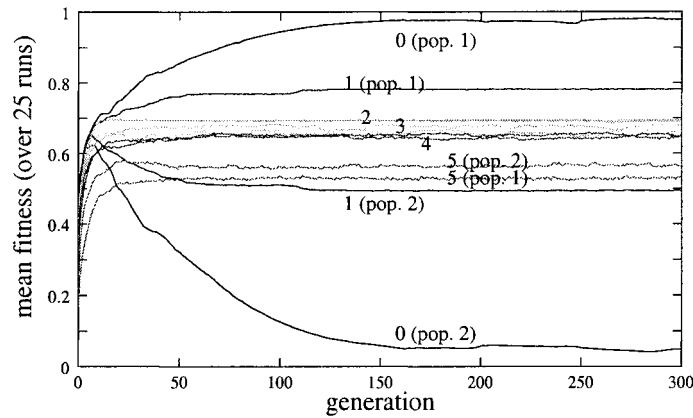


Figure 7. Mean fitness when fairness functions 0–5 are applied each round.

4.2. FAIRNESS CHECK IN EACH ROUND

This section studies the second fairness model, in which the responding agent re-evaluates all potential agreements. The EA settings are the same as in the previous section.

The results in Figure 7 for fairness functions 1 are similar to the previous case (Figure 6). However, when fairness functions 2 through 5 are used, the agents in both populations reach almost identical fitness levels. Most agreements now occur in the vicinity of point *S* in Figure 3. Note that the agents have no explicit knowledge about the location of this point, and that this knowledge is also not incorporated within the fairness functions. We also observe that agreements are now reached in different rounds, whereas in earlier experiments without fairness most agreements occur at the very end of the game.

Figure 7 thus shows that the agents' long-term behaviour is much less sensitive to the shape of the fairness function: the various 'stronger' fairness functions all yield similar results. Figure 7 however indicates that when the agents use fairness function 5, the mean fitness of both agents decreases. This is due to the increasing number of disagreements which are a result of the strong fairness check.

We furthermore studied a 2-issue negotiation problem with an asymmetric Pareto-efficient frontier, as shown in Figure 8. In this case, agent 1 values both issues equally important, whereas agent 2 has different valuations for each issue (his weights are 0.2 and 0.8 for issues 1 and 2 respectively). If each agent obtains the whole surplus on his most important issue, agent 1 obtains 0.5, whereas agent 2 gets 0.8. This outcome corresponds to the Nash bargaining solution (NBS) [2, Ch. 5]. The symmetric point (*S*), on the other hand, is located at $(\frac{8}{13}, \frac{8}{13})$.⁸

Both solutions can be considered to be fair outcomes in different ways: the first solution maximises the product of the agents' utilities and also splits the surplus equally, whereas in the second case equal utility levels are obtained for both agents (see [19, Ch. 16] for a related discussion). In the computational results, we observe

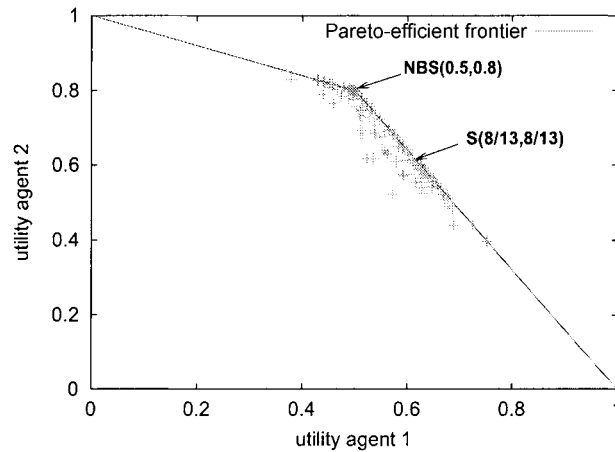


Figure 8. Resulting agreements in a single generation when the Pareto-efficient frontier is asymmetric and fairness function 4 is used.

that, when fairness functions 2–5 are applied, the agreements are divided and are usually concentrated in two separate clusters (‘clouds’), see Figure 8. The issue of the choice of and distribution over multiple ‘fair’ agreement points seems an important issue for further research, both in a computational setting as well as in experimental economics.

We also experimented with different weight vectors and with $m > 2$. A general finding is that extreme outcomes do not occur in the evolutionary process if the agents apply a fairness check.

Conclusion. We have shown that fair agreements can evolve if fairness is evaluated each round, even with strong fairness norms: the fairness of the deals is much more stable w.r.t. the actual choice of the fairness function. Of course, the number of actual agreements drops if a very strong fairness function is used, resulting in a lower fitness for both parties. In case of two-issue negotiations with a symmetric Pareto-efficient frontier, most agreements are reached in the vicinity of the symmetric point. In the asymmetric case, fair solutions can also be obtained. The solutions are then distributed over various possible outcomes, which can all be considered fair in different ways.

In the next section, we investigate the evolving strategies of the agents in more detail, but for single-issue negotiations.

4.3. VALIDATION AND STRATEGY ANALYSIS FOR A SIMPLE CASE

Although our incorporation of fairness aspects makes a game-theoretic analysis much more complicated, SPE strategies can again be derived for a very simple version: the game with only a single issue ($m = 1$) and fairness function 4. These settings were chosen because of mathematical feasibility. The general equations are presented in Appendix B.

Table II. Comparison of the agent's payoffs in the EA with SPE results.

	Payoff agent 1	Payoff agent 2
SPE	0.419	0.391
EA	0.391 (± 0.022)	0.412 (± 0.014)

Table III. Comparison of the evolved strategies with game-theoretic (SPE) results for each round.

Round	Offer (SPE)	Offer (EA)	Threshold (SPE)	Threshold (EA)
1	0.609	0.58 \pm 0.06	0.391	0.23 \pm 0.21
2	0.375	0.39 \pm 0.07	0.250	0.14 \pm 0.13
3	0.500	0.48 \pm 0.09	0.000	0.13 \pm 0.13

Table II shows both the SPE results and the payoffs obtained by the evolving agents (in the long run) in the a with $m = 1$, $n = 3$, $p = 1$, and with the (rather strong) fairness function 4. Note that since $m = 1$, an agent's payoff equals the share obtained for issue 1. Results for the EA are obtained after 300 generations (averaged over 25 runs). Notice that the SPE payoffs are in good agreement with the outcome of the evolutionary experiments. However, in SPE agent 1's payoff is slightly larger than agent 2's payoff. In the EA this is reversed, although Table II shows that differences between theory and experiment are very small. We will further analyse the evolving strategies below.

Table III compares the offers of the evolving agents (for each round) with SPE results, showing a good match. From Table III, it can be derived that agreements are reached in *all* rounds, with some emphasis on the first round.⁹

Table III also shows the acceptance thresholds (the thresholds are calculated based on the payoff which an agent expects to receive if he rejects the current offer, see Appendix B). Because the thresholds in rounds 2 and 3 are much lower than the obtained utility, the thresholds in these rounds are not really relevant in SPE. This explains the large variance of the thresholds in the EA and why these thresholds can deviate from SPE predictions in these rounds. In round 1, the threshold is important in SPE and influences the offer made. The experiments show a much lower average threshold value than the SPE (Table III). Nevertheless, the thresholds influences the offers made in the EA due to a high variance of the threshold values. We analyse this more closely.

Figure 9 shows the evolution of the threshold value for the first round for a single experiment. The indicate the variance in the population. Notice that this variance

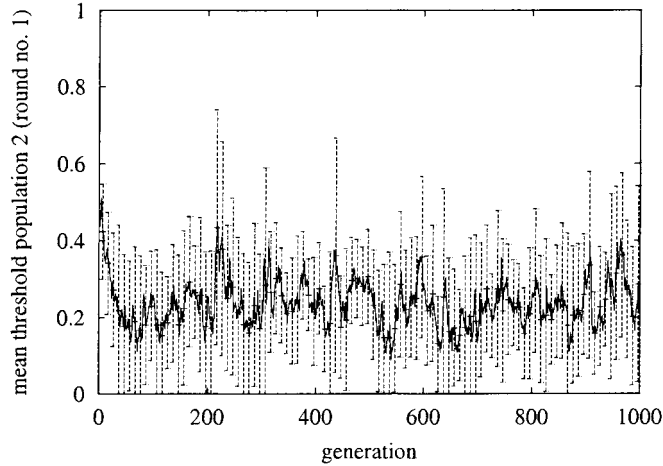


Figure 9. Average threshold values of the agent strategies in the EA in the first round.

Table IV. Comparison of the evolutionary agents' payoffs after 1,000 generations (using exponentially decreasing mutation step-sizes) with SPE results.

	Payoff agent 1	Payoff agent 2
SPE	0.419	0.391
EA with decreasing σ_i	0.416 ± 0.012	0.395 ± 0.009

and the volatility of the mean threshold is rather high. This forces the offers in population 1 to be similar as in SPE.

In order to obtain an even better match with SPE results, we reduced the occurrence of frequent peaks by using a decreasing mutation step-size in the EA (instead of self-adaptive mutation step-sizes, see Appendix A.2). At the beginning of each EA run, σ_i is set to 0.1 for all i (as before, see Table I) and then exponentially decrease until $\sigma_i = 0.01$ after 1,000 generations. This procedure indeed reduces the fluctuations in the threshold values and the offers in the long run. Results for experiments with this EA setting appear to be in excellent agreement with SPE results, see Table IV. We found no significant effect of the new mutation scheme on the evolutionary outcomes for $m = 2$, however. We suspect that this is due to the integrative nature of the negotiation problem, where the results obtained are already beneficial for both parties.

Conclusion. This relatively simple bargaining situation shows a good match between theoretical (SPE) and experimental results. Furthermore, when fairness norms are applied, the outcome of the negotiation process comes to depend on the actual round in which an agreement is finally reached, while thresholds play an important role in some of the rounds. We also showed that EA parameters can be

fine-tuned for a more stable situation if needed. This rendered an excellent match with the SPE for $m = 1$.

5. Social Extensions: Multiple Bargaining Opportunities

In the negotiation game discussed so far, both parties receive nothing in case of a disagreement. This section, on the other hand, considers a model of an agent society in which agents have a number of additional bargaining opportunities if negotiations should fail. This game is a step further towards reality, where (for instance) consumers can go to various brokers until a satisfactory deal is reached (e.g. when buying a house, car, etc.). This model introduces the important concept of *competition* among agents. The payoff received by an agent now results from the bargaining behaviour of all competitors. This makes an analytical treatment extremely difficult compared to the easier case of one-on-one negotiations. Below, we describe the game in more detail and discuss the results of the simulations.

5.1. DESCRIPTION OF THE GAME

As before, we model a society with two groups of agents (e.g. buyers and sellers), which correspond to the two populations in our EA. In the extended game, every agent within either population can subsequently bargain with up to k opponents to reach a deal. A simple bargaining game is denoted as an ‘encounter’ in the following and we use ‘m-game’ to denote a game with multiple bargaining opportunities. If an encounter does not result in an agreement, an agent is again matched with a randomly selected opponent for his next encounter (provided that the agent still has another bargaining opportunity). Thus, an agent can now refuse offers which are unsatisfactory and wait for a better deal in another encounter, which is usually played against a different opponent.

We also introduce search costs in our model. The search costs represent the amount of money, time, or effort that an agent may incur in finding another negotiation partner [6, Ch. 7]. These costs, however, can also represent the costs involved in the negotiation process itself. Search costs are fixed and associated with each new encounter (only the first encounter is ‘free’).

5.2. IMPLEMENTATION

The m-game is implemented as follows. First, a pair of agents is randomly selected from the populations and negotiate using the alternating-offers protocol as before, where agent 1 makes the first offer and agent 2 either rejects or accepts. We take $n = 1$, i.e., just one round of bargaining. This is justified based on the results in Section 3.2, where it was observed that each agreement was completely determined by the last round only. If agent 2 refuses the deal, the bargaining ends, and the agents can participate in another encounter, provided that they have not exceeded

their maximum number of bargaining opportunities. An agent incurs some fixed costs (which could be zero) for locating another negotiation partner. If an agent has no more bargaining opportunities or if an agreement is reached, this concludes an agent's m -game and he is deactivated.

Next, another encounter is arranged by selecting once again a (random) pair of active agents. The process is then repeated, until one of the populations has no more active agents. Note that because the agents are randomly matched, two encountering agents may differ in their remaining number of bargaining opportunities. Therefore, the bargaining position of the opponent is not known.

To reduce stochastic effects and to remove initiatory and end effects (explained below), each agent actually plays a number of consecutive m -games in the simulation: If an m -game is concluded, the agent starts with a new m -game. A distinct payoff results from each m -game. The maximum number of m -games that an agent can play is fixed to 10.

The fitness of an agent is the average payoff obtained in his m -games. However, since initially all agents of both populations start with their first encounters, in the first rounds of the encounters the opponent's bargaining position is not completely random (i.e., there is an initiatory effect). Furthermore, we note that when one of the populations has no more active agents, the other population may still be active (i.e., there is also an end effect). To suppress these undesired effects, we do not include an agent's payoff received in the first m -game and the last four m -games when calculating his fitness value. This way, we model an ongoing bargaining society.

5.3. AGENT MODEL

The strategy representation and the utility function of Section 2.1.2 are somewhat altered in the m -game. Agent 1's negotiation strategy now consists of k offers, one for each encounter, and agent 2 has k thresholds (where k is the maximum number of encounters). The utility functions are changed to $\vec{w}_1 \cdot \vec{o}_j(e) - \sigma_1 \cdot (e - 1)$ and $\vec{w}_2 \cdot [\vec{1} - \vec{o}_j(r)] - \sigma_2 \cdot (e - 1)$ for agent 1 and 2 respectively, where σ_j is agent j 's search cost and $e \in \{1, 2, \dots, k\}$ counts the opponents. Notice that an agent's payoff can also become negative.

5.4. RESULTS WITHOUT SEARCH COSTS

The settings used for the experiments without search costs are shown in Table V. The evolutionary settings remain as before (Table I). The fitness obtained for negotiations over two issues ($m = 2$) are shown in Figure 10. The agents reach agreements near the symmetric point (Figure 3) when $k = 5$, in contrast to the take-it-or-leave-it deals observed when $k = 1$. The last-mover advantage appears to diminish rapidly if agents are allowed additional bargaining opportunities, even for $k = 2$ (Figure 10). In fact, three encounters are already sufficient to obtain

Table V. Settings for the experiments with multiple bargaining opportunities.

Maximum number of encounters per m-game (k)	1–20
Maximum number of m-games	10
M-games used for fitness evaluation	2–6

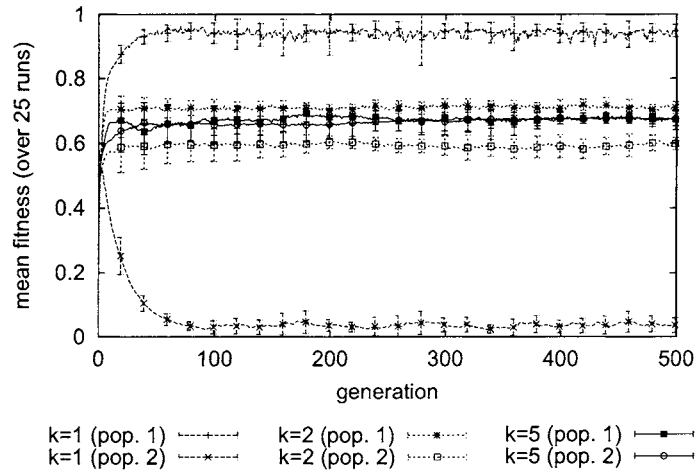


Figure 10. Evolving fitness value for $k = 1$, $k = 2$ and $k = 5$.

almost symmetric fitness values. Furthermore, this symmetry remains for larger values of k (experiments have been performed with k up to 20). These outcomes are also robust for various other EA settings.

We also performed experiments using the asymmetric Pareto-efficient frontier shown in Figure 8. Results in generation 500 of a typical run are shown in Figure 11. Recall from Section 4.3 that the bargaining game has two fitness outcomes which are specific candidates for a ‘fair’ outcome: the symmetric point and the Nash bargaining solution. Figure 11 shows that most agreements in the simulation with multiple bargaining opportunities are located in between both bargaining solutions, and that thus fair deals emerge.

Conclusion. We show that competition among agents induced by multiple bargaining opportunities results in ‘fair’ agreements. These results are obtained without any additional constraints on the agent model.

5.5. INFLUENCE OF SEARCH COSTS

We now consider the case where both agents have symmetric (i.e., equal) positive search costs. Clearly, if search costs are excessive, most agreements should be reached at the first encounter, and, effectively only a single bargaining opportunity

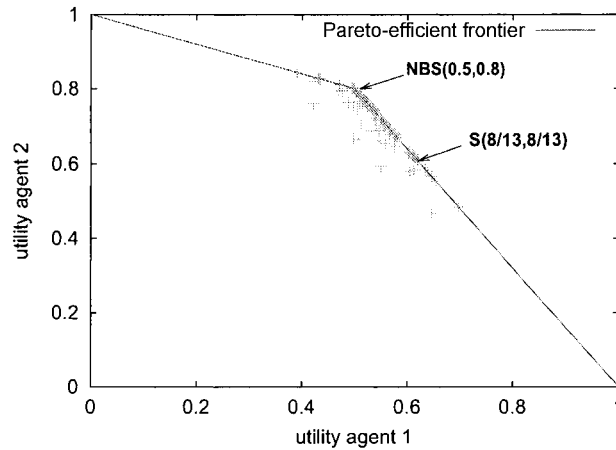


Figure 11. Resulting agreements (after 500 generations) when the Pareto-efficient frontier is asymmetric and the agents have 5 bargaining opportunities.

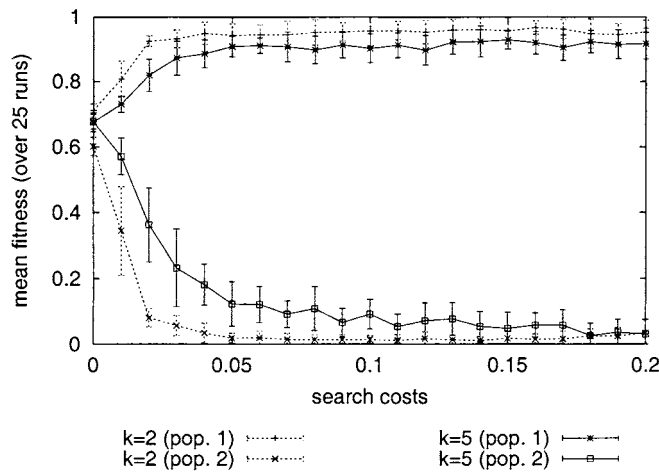


Figure 12. Long-term EA results for varying (symmetric) search costs for $k = 2$ and $k = 5$.

remains. We then expect the proposing agent to be able to make an extreme take-it-or-leave-it deal as before. These results are indeed found in the simulation: if the search costs are greater than unity, agent 1 will receive almost the whole surplus.

Similar results, however, are also obtained for much smaller search costs, see Figure 12. This figure shows the fitnesses after 1,000 generations of both agent populations for experiments with $k = 2, 5$ and different (but symmetric) search costs. Even when search costs are relatively small, the agents are stimulated to reach agreements early. Notice that, even if search costs are as low as 0.05, the utility of agent 2 decreases from ≈ 0.68 (without search costs) to ≈ 0.15 when $k = 5$. This decrease in fitness of ≈ 0.53 is much larger than the possible total search costs (0.2 in case of 5 encounters). Thus, the search costs have a ‘leverage’ effect on the outcome of the bargaining process.

This leverage effect can be explained as follows. As the costs increase, agents in population 2 concede a part of their bargaining surplus in the first encounter to reach an earlier agreement. As a result, the search costs relative to the obtained bargaining surplus increase for the agents in population 2 (and decrease for the agents in population 1). This stimulates the agents in population 2 to reach agreements even earlier on average and concede even more. The opposite holds for agents in population 1. Thus, the leverage effect occurs because the costs are fixed and independent of the obtained bargaining surplus. In fact, the leverage effect disappears if a discount factor (instead of a fixed cost per encounter) is used.

Conclusion. Without search costs or with very small search costs, fair deals occur. If agents incur more substantial search costs, however, a leverage effect may result in extreme deals as before.

6. Conclusions

We have investigated a system for negotiations, in which agents learn effective negotiation strategies using evolutionary algorithms (EAs). Negotiations are governed by a finite-horizon version of the alternating-offers game. Several issues are negotiated simultaneously. Both negotiations with and without a risk of breakdown have been studied. Our approach facilitates the study of cases for which a rigorous mathematical approach is unwieldy or even intractable. We presented computational results for several difficult bargaining problems in this paper.

We first validated the long-term evolutionary behaviour using the game-theoretic concept of subgame-perfect equilibrium (SPE). When no risk of breakdown exists, the last agent in turn proposes a take-it-or-leave-it deal in the last round and demands most of the surplus for each issue. This extreme division is consistent with SPE predictions. When a risk of breakdown exists, most agreements in the EA are reached in the first round. If the finite game becomes long enough, the deadline is therefore no longer perceived by the evolutionary agents and results actually match SPE predictions for the infinite-horizon game.

We also modelled and studied two important aspects of real-life negotiations: (1) the concept of ‘fairness’ and (2) competition by allowing for multiple bargaining opportunities. In the first extension, a responding agent carries out a fairness check before an agreement is definitely accepted. This fairness check was modelled in two ways: a responding agent considers fairness only at the deadline or all the time, for any potential agreement. In both cases, fair outcomes can be obtained but the outcomes in the second case are much less sensitive to the actual choice of the fairness function. In case of an asymmetric bargaining situation (where the players have asymmetric preferences), multiple outcomes then exist which can be considered ‘fair’ in different ways. We also found a good match between the EA results and game-theoretic SPE predictions for a simple bargaining game (concerning a single issue).

In the second extension, each agent is allowed to subsequently negotiation with a number of opponents and therefore has several opportunities to reach an agreement. It appears that agents now no longer propose a take-it-or-leave-it deal and fair agreements spontaneously emerge in the evolutionary system. This effect is reduced when agents incur some more substantial search costs, and results then again show an unequal partitioning of the bargaining surplus.

We are currently researching a more complex negotiation strategy representation using finite state machines [27]. A finite state machine is more general and enables agents to react to the opponent's behaviour.

Appendix A. Technical Description of the Evolutionary Algorithm

A.1. GENETIC REPRESENTATION OF THE STRATEGIES

The chromosome specifies the strategy which an agent uses in the bargaining game. A chromosome consists of a sequence of real values in the unit interval for the offers and thresholds (one offer or threshold for each negotiation round). We use x_i to denote the (real) value at location i of the chromosome. The agents' strategies are initialised at the beginning of each EA run by drawing random numbers in the unit interval (from a flat distribution).

A.2. MUTATION AND RECOMBINATION

Mutation and recombination are the most commonly used EA operators for reproduction. Recombination exchanges parts of the parental chromosomes, whereas mutation produces random changes in a chromosome. Earlier experiments [26] showed little effect on the results when a recombination operator was applied. We therefore focus on mutation-based models.

The mutation operator changes the chromosome of an agent as follows. Each real value x_i is mutated by adding a zero-mean Gaussian variable with a standard deviation σ_i [1, 26]:

$$x'_i := x_i + \sigma'_i N_i(0, 1). \quad (1)$$

All resulting values larger than unity (or smaller than zero) are set to unity (respectively zero). In our simulations, we use an elegant mutation model with self-adaptive control of the standard deviations σ_i [1, pp. 71–73; 26]. This model allows the evolution of both the strategy and the corresponding standard deviations at the same time. More formally, an agent consists of strategy variables $[x_0, \dots, x_{l-1}]$ and ES-parameters $[\sigma_0, \dots, \sigma_{l-1}]$ in our model, where l is the length of the chromosome.

The mutation operator first updates an agent's ES-parameters σ_i in the following way:

$$\sigma_i := \sigma_i \exp[\tau' N(0, 1) + \tau N_i(0, 1)], \quad (2)$$

where τ' and τ are the so-called learning rates (1, p. 72], and $N(0, 1)$ denotes a normally distributed random variable having expectation zero and standard deviation one. The index i in N_i indicates that the variable is sampled anew for each value of i . We use commonly recommended settings for these parameters.¹⁰ After the strategy parameters have been modified, the strategy variables are mutated as indicated in Equation (1). The initial standard deviations σ_i in the EA are set to a value of 0.1. The particular initial value chosen for σ_i is typically not crucial, because the self-adaptation process rapidly scales σ_i into the proper range. To prevent complete convergence of the population, we force all standard deviations to remain larger than a small value $\varepsilon_\sigma = 0.025$ [1, pp. 72–73].

A.3. SELECTION MODEL

Selection is performed using the $(\mu + \lambda)$ -ES selection scheme [1], where μ is the number of parents and λ is the number of generated offspring ($\mu = \lambda = 25$, see Table I). The μ survivors with the highest fitness are selected (deterministically) from the union of parental and offspring agents.

Appendix B. Game-Theoretic Analysis of Multi-Issue Negotiations

Subgame perfect equilibrium (SPE) strategies for multiple-stage games with complete information can be derived using a backward induction approach. The fairness models evaluated in Section 4.2 (i.e., with a fairness check at the deadline only) and in Section 4.3 (i.e., with a fairness check in each round) are analysed in this appendix. As in [9, 26], we apply backward induction to deduce the SPE partitioning. The fairness function is now formally denoted as $g_r(u)$. This (real-valued) function returns the probability of acceptance of a proposal in round r in case the responding agent's utility is equal to u . If a fairness check is performed only in the last round, $g_r(u) = 1$ for all $r < n$ (where n is the number of rounds). In case the same fairness check is performed each round, $g_r(u)$ is independent of r . We assume that the fairness function is a monotonic non-decreasing function of u and that $g_r(u = 1) = 1$. Let agent j be the agent proposing a deal at round r and agent $-j$ the responder. We then abbreviate $g_r[u_{-j}(\vec{o}_j(r))]$ (the probability of acceptance of agent j 's offer \vec{o} in round r) as $p_r^{acc}(\vec{o})$.

If n is even, agent 2 will propose an offer in the last round (at $r = n$). Agent 2 will then propose an offer $\vec{o}_2(r = n)$ which, in SPE, maximises his payoff, i.e., his expected utility. The payoff π_2 received by Agent 2 if his offer is accepted equals $p^n u_2[\vec{o}_2(r = n)]$, where u_2 is agent 2's utility function (see Section 2.1.2). The acceptance probability is equal to $p_n^{acc}[\vec{o}_2(r = n)]$. Agent 2's payoff in round $r = n$ is therefore:

$$\pi_2(r = n) = \max_{\vec{o}_2(r=n) \in \mathcal{P}} p^n u_2[\vec{o}_2(r = n)] p_n^{acc}[\vec{o}_2(r = n)], \quad (3)$$

where $\mathcal{P} \subset [0, 1]^m$ is the set containing all Pareto-efficient offers. Analogously, the payoff π_1 for agent 1 in round $r = n$ is equal to:

$$\pi_1(r = n) = p^n u_1[\vec{o}_2(r = n)] p_n^{acc}[\vec{o}_2(r = n)], \quad (4)$$

where u_1 is agent 1's utility function.

It is again straightforward to show that it is optimal to propose a Pareto-efficient deal. Assume for instance, that a Pareto-inefficient offer is made. The proposer of this offer can then improve his payoff by selecting an offer on the Pareto-frontier which yields his opponent the same payoff. Because the probability of acceptance only depends on the responder's utility of this offer, this will not affect the fairness evaluation.

We now analyse the previous round ($r = n - 1$). In SPE, at $r = n - 1$ agent 2 only accepts a deal which is at least equal to the payoff $\pi_2(r = n)$ that he receives in the next round (in SPE). Therefore, $\pi_2(r = n - 1) \geq \pi_2(r = n)$ in SPE. Effectively, $\pi_2(r = n)$ acts as a threshold used by agent 2 to determine the minimal acceptable offer at $r = n - 1$. Some elementary manipulations then show that in SPE agent 1 should make an offer $\vec{o}_1(r = n - 1)$ such that

$$p^{n-1} u_2[\vec{o}_1(r = n - 1)] \geq \pi_2(r = n), \quad (5)$$

otherwise, agent 2 rejects the proposal at $r = n - 1$ to earn $\pi_2(r = n)$ in the last round. We now define $\mathcal{R} \subset [0, 1]^m$ to be the set of offers for which Equation (5) is not violated. In SPE, agent 1's payoff in round $r = n - 1$ then equals

$$\begin{aligned} \pi_1(r = n - 1) = & \max_{\vec{o}_1(r = n - 1) \in \mathcal{P} \cap \mathcal{R}} p^{n-1} u_1[\vec{o}_1(r = n - 1)] p_{n-1}^{acc}[\vec{o}_1(r = n - 1)] \\ & + \{1 - p_{n-1}^{acc}[\vec{o}_1(r = n - 1)]\} \pi_1(r = n). \end{aligned} \quad (6)$$

In a similar fashion, we can calculate agent 2's payoff at $r = n - 1$ in SPE:

$$\begin{aligned} \pi_2(r = n - 1) = & p^{n-1} u_2[\vec{o}_1(r = n - 1)] p_{n-1}^{acc}[\vec{o}_1(r = n - 1)] \\ & + \{1 - p_{n-1}^{acc}[\vec{o}_1(r = n - 1)]\} \pi_2(r = n). \end{aligned} \quad (7)$$

For $r = n - 2$ expressions very similar to Equations (6) and (7) can be derived (but the roles of the two agents switch). This procedure is then repeated until the beginning of the game is reached (at $r = 1$). The same line of reasoning holds if the number of rounds is odd (simply switch the roles of agent 1 and agent 2).

In the basic model without fairness all agreements occur in the first round in SPE (for $p < 1$). When the agents apply a fairness check in each round, however, even in SPE a significant number of agreements occurs after the first round. In this case, the strategy followed in all rounds comes to play a role in determining the outcome of the game.

We also remark that, although a responder's fairness considerations determines for a large part the offers made by a proposing agent, this does not make the responder's thresholds superfluous in SPE. Recall that the role of the threshold is reflected in Equation (5).

Notes

- ¹ The same approach was used in [18, 26].
- ² The widely-used genetic algorithms (GAs) are more tailored toward binary-coded search spaces [12, 17, 10].
- ³ In an alternative model, not only the parental agents are used as opponents, but also the newly-formed offspring. Similar dynamics have been observed in this alternative model.
- ⁴ The 8-dimensional weight vector for agents in population 1 is set to $\frac{1}{39}(0.7, 0.3, 0.5, 0.2, 0.3, 0.4, 0.5, 1.0)^T$ and equal to $\frac{1}{39}(0.3, 0.7, 0.5, 1.0, 0.5, 0.5, 0.2, 0.2)^T$ for agents in population 2. These settings are such that they contain both ‘competitive’ issues (e.g., issue 3) and issues where compromises can be made (e.g., issue 8).
- ⁵ To avoid a (quadratic) increase in the number of fitness evaluations, each agent negotiates with 25 (random) opponents.
- ⁶ Piece-wise linear functions nicely fit the experimental data reported in [14, 23].
- ⁷ We want to remark here that, although the fairness function is the same for all agents, the actual fairness function can depend on cultural norms in the real world [14].
- ⁸ This outcome corresponds to the Kalai–Smorodinsky solution [13].
- ⁹ Acceptance rates are approximately 39%, 22%, 20% in SPE in rounds 1–3, and $36 \pm 4\%$, $25 \pm 3\%$, $20 \pm 2\%$ for the EA in rounds 1–3.
- ¹⁰ Namely, $\tau' = (\sqrt{2l})^{-1}$ and $\tau = (\sqrt{2\sqrt{l}})^{-1}$ [1, p. 72], where l is the length of the chromosome.

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