A Collaboration Mechanism on Positive Interactions in Multi-agent Environments

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Abstract

In multi-agent environments where agents independently generate and execute plans to satisfy their goals, the resulting plans may sometimes overlap. In this paper, we propose a collaboration mechanism using social law, through which rational agents can smoothly delegate and receive the execution of the overlapping parts of plans in order to reduce the cost of plan execution. Also, we consider collaboration with agents that do not abide by social law, that is, self-centered agents. Simulation results show that our mechanism also has the property of balancing the cost of plan execution and shows flexibility towards self-centered agents.

1 Introduction

In multi-agent environments where agents generate and execute plans which satisfy their own goals, plans are generated independently, thus two relationships [Martial, 1992] exist among plans. The first is called a *negative* relationship and exists between plans which attempt to use the same resource at the same time. This relationship will cause conflicts. Such conflicts must be avoided or resolved because they prevent actions from being properly executed. The other relation is called a *positive* relationship and exists between plans which include overlapping subplans, subplans consisting of both common actions and individual actions. When there is a positive relationship and one agent delegates the execution of the overlapping subplan to the other agent, it can reduce the cost of execution.

A lot of research has been done on negative relationships, such as conflict avoidance, by using a social law [Shoham and Tennenholtz, 1992] and conflict resolution based on game theory [Zlotkin and Rosenschein, 1990]. However, despite the importance of a positive relationship for the agents' effective execution of plans, not much has been made [Foulser *et* al., 1991] to utilize this, except to reduce costs by deleting the overlapping actions in a domain consisting of only one agent [Hayes, 1989] and for multi-agent systems where irrational agents delegate and receive plans [Martial, 1992] and for multi-agent systems where agents mutually construct a collaborative plan [Osawa and Tokoro, 199l] .

In this paper we propose a collaboration mechanism by which rational agents can delegate and receive subplans in a positive relationship so that the cost of execution is reduced. If an agent delegates its actions to the other agent, it can reduce the execution cost greatly and benefit from it. On the other hand, when an agent receives actions, the cost increases a little even though the reduction in the cost of the sender is larger than the gain in its own cost. As rational agents can delegate actions but may not be willing to receive, it is very hard to collaborate in a positive relationship. However, if an agent which receives actions is guaranteed to be able to delegate some actions in the future, then even a rational agent can collaborate in a positive relationship. We propose a mechanism based on a social law (the guarantee) in which agents must balance the costs of received actions. With this mechanism, rational agents can collaborate through the expected cost based on game theory.

Moreover, there are two other benefits arising from this law: (1) just as agents can expect another agent's proposition (strategy) at negotiation on delegation, they can avoid conflicts of strategies and can collaborate smoothly; and (2) the macroscopic problem that arises when the load of the whole multi-agent system is concentrated on an irrational agent can be solved with this microscopic cost-balancing law.

Although the image related to the benefit of such a law is implicit in many AI works, the social law was only recently formalized and discussed [Shoham and Tennenholtz, 1992]. However, this work does not consider agents which do not abide by the law. When treating a multi-agent environment as an open distributed environment, it is quite natural to think that such agents exist. Therefore, our mechanism considers collaboration with *self-centered* agents. It is a very simple solution for agents to not collaborate with self-centered agents. Nevertheless, it is problematic that an agent which exceptionally did not abide by the law for some reason, cannot collaborate any more, and that agents could benefit by collaborating with the self-centered agents. Therefore, agents should collaborate in a more rational and fiexi-

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ble way: they collaborate if they can benefit and do not collaborate when they cannot. Our mechanism allows agents to collaborate in this way.

Simulation results show that with our mechanism, rational agents can reduce their cost by delegating/receiving actions. The results also show that the mechanism has the important properties of flexibility and guarantee cost-balancing.

The outline of the rest of the paper is as follows. In the next section, some of the assumptions are presented before discussion. Our mechanism is proposed in Sections 3 and 4. In Section 3, two evaluation functions are defined using the game theory. Also, the social law and the model of agents are described. In Section 4, the other part of our mechanism is described. In Section 5, some examples are presented. Experimental results are shown and discussed in sections 6 and 7, respectively.

2 Assumptions

Assumptions on the agents' plans and actions are as follows:

1. Each agent has a plan to achieve its own goal, and doesn't know the plans of other agents'.
2. Subplans (plans which achieve sub goals) consist of sequences of actions.
3. The meanings of actions and associated costs are predefined and common to all agents.

In order to concentrate on the algorithm of delegation/reception decision, we assume the following:

4. Agents can find which parts (subplans) of their plan can be delegated.
5. Agents can discover other agents with which to negotiate delegation.
6. Negotiation is carried out between two agents only.

Positive relationship that is implicitly contained between plans is divided into two relationships[1] [Martial, 1992]: a subsumption relationship and a favor relationship.

If the actions of an agent's plan are the same or subsume another agent's actions, the plans are in a subsumption relationship and one agent does not need to execute its plan if the other agent executes its own plan. If an agent's plan partially overlaps with another agent's plan and is not in a subsumption relationship, the plans are in a favor relationship. In this case, an agent does not need to execute its plan if another agent is willing to receive the plan and to execute its own plan together with the non-overlapping part of the received plan.

Now, we assume the following [2]:

7. Agents collaborate when their plans are in a favor relationship.

[1] Martial divided the relationships in more detail.

[2] It is not necessary for agents to collaborate in a subsumption relationship because it is enough for an agent to check whether its actions were already done after execution of the other agent's plan.

3 Definitions

3.1 Change of cost by delegation

The change in agent A's subplan, which has a favor relationship to B's subplan and the associated cost through delegation/reception, is shown in Figure 1 where some actions are indicated as circles.

For instance, if a subplan of agent A (a) consists of three actions: "go to store" then "buy food" and finally "come back," and that of agent B consists of: "go to store" then "buy juice" and finally "come back," then the subplans are in a favor relationship (partly overlapping). If A receives the execution of B's subplan, the replanned subplan (b) that A must execute is: "go to store" then "buy food" and "buy juice" (B's action) and finally "come back" and "hand B juice" (action to adjust A's initial plan).

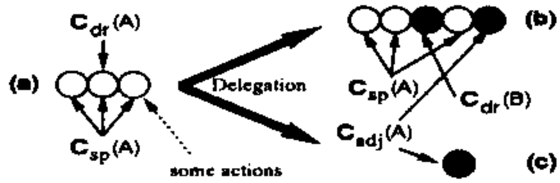

Figure 1: Change of subplan and its cost.

In order to express costs, we use the following notation:

- $C_{sp}(A)$: A's cost for executing a subplan which has a favor relationship to B's subplan.
- $C_{dr}(A)$: The cost of A's actions when executed by B when delegated *(e.g.,* "buy food").
- $C_{adj}(A)$: The cost of A's additional actions in the case of delegation/reception *(e.g.,* "hand B juice").

If A receives the execution of B's actions, A's overall cost is the cost of its own actions $(C_{sp}(A))$ plus the cost of the delegated actions from B $(C_{sp}(B))$ and the cost of adjusting a plan to a new plan $(C_{adj}(A))$

On the other hand, if A delegates the execution of its subplan, the subplan will become (c). In this case, A's overall cost is only the cost of adjusting a plan $(C_{adj}(A))$

3.2 Social law for delegation

Social law is formalized in [Shoham and Tennenholtz, 1992] and is treated as the pair of actions and conditions about states that prohibit taking action. Intuitively, social law *l* is the law by which *agents must balance the costs of the individual received actions.*

Definition 1 (Social law for delegation) *Social law l is defined to obey the next constraints.*

(a) If an agent receives more actions than the other agent, it cannot receive actions at the next negotiation.

(b) If an agent delegates more actions than the other agent, it cannot delegate actions at the next negotiation.

When agents abide by this law, each agent can delegate actions and benefits in the future according to (a), even if it receives actions and loses by that. Therefore, even a rational agent can propose the strategy "receive."

Though this law may not be the only one that makes agents collaborate on positive relationships, the search for such a law is beyond the scope of this paper. However, this law has the following two advantages: (1) as (a) and (b) are exclusive, agents can avoid the conflicts of strategies proposed in the negotiation, or collaborate smoothly, and (2) the microscopic law defined between two agents can balance the agents' costs of executing received actions in a whole system.

3.3 Expected payoff

We use payoff in game theory as the increase in cost arising when an agent proposes its strategy at negotiation and defines the expected payoff. The strategy consists of two propositions: "delegate" and "receive" [3] Therefore, agent A's strategy p is a mixed strategy (p_1, P_2) where p_1 is A's probability of proposing strategy "delegate" and $p_2 = 1-p_1$ is that of the reception. Also, the other agent B proposes a mixed strategy $q = (q_1, q_2)$ expressing the same idea. Please note that the expected payoff is not the expected cost but the expected increase in cost.

Because of the existence of social law l, the strategy that is selected by A not only influences the strategy of B in the future, but also influences the cost of A in the future. Hence, the expected payoff is the sum of the expected payoff of current negotiation, *present expected payoff* ($E_P(p, l)$) and the negotiation in the future, *future expected payoff* ($E_F(P, l)$).

However, other agents (say, agent B) may not abide by the law. With the reliability of B ($P_l(B)$), *i.e.*, the probability of B abiding by the law, the expected payoff, is defined as follows:

Definition 2 (Expected payoff of agent A)

$$\begin{aligned} E(p, l, P_l(B)) &= P_l(B)(E_P(p,l) + E_F(p,l)) \\ &\quad +(1 - P_l(B))(E_P(p,\phi) + E_F(p,\phi)) \end{aligned}$$

where $E_P(p,\phi), E_F(p,\phi)$ is the value of E_P, E_F when B does not abide by the law.

3.3.1 When the other agent abides by the law

If the other agent, B, abides by the law, A's payoff of current negotiation is expressed in the next payoff matrix. Entries '—' (undefined) represent cases that cannot happen because both agents abide by the law.

		B	
		delegate	receive
A	delegate	—	$C_{adj}(A) - C_{sp}(A)$
	receive	$C_{adj}(A) + C_{dr}(B)$	—

Table 1: A's payoff (increase in cost)

		B	
		delegate	receive
A	delegate	—	$C_{adj}(A) + C_{dr}(A)$
	receive	$C_{adj}(A) - C_{sp}(B)$	—

Table 2: A's payoff in the future

[3]There is also one other strategy: "do nothing," in which agents must execute the subplan for themselves. This strategy is taken when the expected payoff is not less than 0.

Also, A's payoff in the future is expressed in the same way. For example, if A proposes "receive" and B proposes "delegate," A loses by receiving the actions of B. Nevertheless, in the future (or at the next negotiation), A's cost will be decreased $-(-C_{sp}(B) + C_{adj}(A))$ as A can delegate its actions.

Therefore, $E_P(p,l)$ and $E_F(p,l)$ are calculated by the following formulas:

$$\begin{aligned} E_P(p,l) &= p_2q_1(C_{adj}(A) + C_{dr}(B)) \\ &\quad +p_1q_2(C_{adj}(A) - C_{sp}(A)) \\ E_F(p,l) &= p_2q_1(C_{adj}(A) - C_{sp}(B)) \\ &\quad +p_1q_2(C_{adj}(A) + C_{dr}(A)) \end{aligned}$$

3.3.2 When the other agent does not abide by the law

If the other agent does not abide by the law, both agents have the same strategies and conflict occurs. In such a case, we flip a coin to resolve conflict as will be mentioned in Section 4. Therefore, A's payoff will be $C_{adj}(A) + (C_{dr}(B) - C_{sp}(A))/2$ regardless of whether A proposes "delegate" or "receive." That is because the payoff is dependent only on the flipping of a coin. However, a greater negotiation cost is needed to resolve conflicts because such resolution will need more communications for information. Agent must consider the cost C_{neg}.

The payoff in the future is C_{penal}, a cost that is defined individually for each agent. Although $C_{penal} = 0$ in general, if other laws exist that constrain the organization and the priority of agents, a collision of strategies will lead to high priority agents delegating more tasks to low. In such a case, we have $C_{penal} > 0$.

Therefore, $E_P(p,\phi)$ and $E_F(p,\phi)$ are calculated as follows:

$$\begin{aligned} E_P(p,\phi) &= C_{neg} + C_{adj}(A) + (C_{dr}(B) - C_{sp}(A))/2 \\ E_F(p,\phi) &= C_{penal} \end{aligned}$$

3.4 The other agent's model

The behavior of the other agent, B, is modeled upon the following two points.

1. Strategy $q = (q_1, q_2)$

   Before we define the other agent's strategy ($q = (q_1, q_2)$), we define $\Delta(B)$, a relative amount of cost for executing received actions.

   $$\Delta(B) = \sum_{k=1}^{j} C_{rec}(k),$$

   where $C_{rec}(j)$ is agent A's j-th cost of receiving a plan expressed as follows:

   $$C_{rec}(j) = \begin{cases} +C_{dr}(B), & \text{if A received the actions} \\ -C_{dr}(A), & \text{if A delegated the actions} \\ 0, & \text{otherwise} \end{cases}$$

   Then, the other agent's strategy is modeled as a function of $\Delta(B)$ and the law l.

   $$q_1 = s(\Delta(B), l) = \begin{cases} 1 & \Delta(B) > 0 \\ 0.5 & \Delta(B) = 0 \\ 0 & \Delta(B) < 0 \end{cases}$$

2. Reliability $P_l(B)$

   This reliability means the probability of B abiding by the law. The reliability P_l at the n-th negotiation of the delegation is defined as a function of h_n, which is calculated by the last model of strategy q_m and the actual, previous strategy of B, $q' = (q'_1, q'_2)$.

$$P_l(B) = 1 - \exp(-\beta h_n(B))$$

$$h_n = \begin{cases} h_{n-1} + 1 & q' = q_m \vee q' = (1/2, 1/2) \\ h_{n-1} - 1 & q' \neq q_m, \end{cases}$$

where $h_1(B) = \alpha$ and the values of α, β are defined for each agent[4].

4 Negotiation Process

Based on the functions defined in Section 3, the negotiation process is described below. As mentioned in Section 2, we assume that steps 1 and 2 are available.

1. **Search for a subplan to delegate.**
   The agent searches for a subplan which can be delegated to another agent.
2. **Search for an agent to which the subplan can be delegated.**
   The agent proposes a subplan to delegate and searches for an agent which can participate in the negotiation of delegation.
3. **Decision on strategy**
   After receiving the subplan, the agent decides on the strategy which *minimizes* the expected payoff $E(p, q, P_l(B))$ based on reliability $P_l(B)$ and B's strategy model q (which is obtained by $q = s(\Delta(B), l)$ according to the relative amount of costs for B ($\Delta(B)$) and social law l). If, for all p, $E(p, q, P_l(B)) \geq 0$, the agent executes the subplans by itself (and doesn't delegate them) and proposes "do nothing".
4. **Proposition of strategy**
   Both agents propose their strategies to each other, including "do nothing."
5. **Decision of behavior**
   The agent decides its behavior according to the other agent's strategy.
   (a) **If strategies do not conflict**
   They modify their plans according to the strategy.
   (b) **If strategies conflict**
   They decide which agents delegate and receive the actions by flipping a coin. However, if one of the strategies is "do nothing," the agreement is to "do nothing".

5 Example

As an example, we consider a negotiation where agent A and B have subplans consisting of three actions. The cost of agent A's subplan is 8,3,8, the cost of B's subplan is 7,4,7, and $\alpha = 5$ and $\beta = 0.14$ for both agents.

We explain our mechanism based on this example.

[4]These parameters can express the characteristics of the agent.

1 and 2.

As agent A can find a subplan to delegate and agent B with which to negotiate the delegation/reception, A knows the change in its subplan (Figure 2). Numbers in circles express costs. Therefore, $C_{sp}(A) = 8+3+8 = 19$, $C_{dr}(A) = 3$, $C_{sp}(B) = 7+4+7 = 18$, $C_{dr}(B) = 4$. For simplicity, $C_{adj} = C_{neg} = C_{penal} = 0$

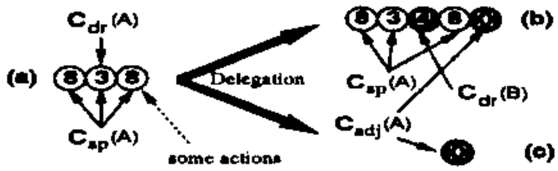

Figure 2: Change in subplan and its costs.

3. According to the costs, the following present and future expected payoffs are obtained. Also, $P_l(B)$ is obtained by $h_1(B) = \alpha = 5, \beta = 0.14$.

$$\begin{aligned} E_P(p, l) &= 4p_2q_1 - 19p_1q_2 \\ E_F(p, l) &= -18p_2q_1 + 3p_1q_2 \\ E_P(p, \phi) &= (4 - 19)/2 \\ E_F(p, \phi) &= 0 \\ P_l(B) &= 1 - exp(-5 \cdot 0.14) = 0.5 \end{aligned}$$

As $q = (q_1, q_2) = (1/2, 1/2)$ according to $\Delta(B) = 0$, the expected payoff, $E(p, l, P_l)$, is the following:

$$E(p, l, P_l(B)) = (-3.5p_2 - 4p_1) - 3.75$$

. The strategy which minimizes this is $p = (1, 0)$.

4. Also, as agent B gets $E(q, l, P_l(A)) = (-4q_2 - 3.5q_1) - 3.75$, B proposes minimizing strategy $q = (0, 1)$.
5. As the strategies do not conflict, there is no need for more negotiation. The agents just modify their own plans according to the proposed strategy.

In this way, the first decision about delegation/reception has finished. We will explain the second decision. For simplicity, the conditions are the same as before and we focus on the decision part of our mechanism.

We get $q = (1, 0)$ according to $\Delta(B) = -3$, the present and future expected costs are obtained as the following. Also, $P_l(B) = 1 - exp(-6 \cdot 0.14) = 0.57$ is obtained by $h_2(B) = 6$.

$$\begin{aligned} E_P(p, l) &= 4p_2 & E_F(p, l) &= -18p_2 \\ E_P(p, \phi) &= (4 - 19)/2 & E_F(p, \phi) &= 0 \end{aligned}$$

The expected payoff $E(p, l, P_l(B))$ is the following:

$$E(p, l, P_l(B)) = -7.98p_2 - 3.2$$

The strategy which minimizes this is $p = (0, 1)$.

As B gets $E(q, l, P_l(A)) = -7.98q_1 - 3.2$, B proposes strategy $q = (1, 0)$. Then, the strategies do not conflict and no more negotiation is required.

6 Simulation

We simulated the execution of an agent using our mechanism as proposed in Sections 3 and 4 in the cases where it negotiates with various agents. We used parameters $\alpha = 15$ and $\beta = 0.07$ for both agents, and used completely overlapping plans. The cost of the execution of each part of the plan was simulated according to table 3.

The costs for agent B are taken for the same table with B replacing A. However, the cost of the subplan (25-30) and the cost of the delegated part of the plan (5-12) was randomly selected and was not necessarily common to both agents. The results are the average of 5000 simulations.

$C_{sp}(A)$	25-30	$C_{adj}(A)$	3
$C_{dr}(A)$	1-10	C_{neg}	2 (and 4)

Table 3: Cost of actions for agent A

6.1 Reduction of cost

Figure 3 shows the relation between the cost for executing a subplan and the frequency of negotiation for delegation.

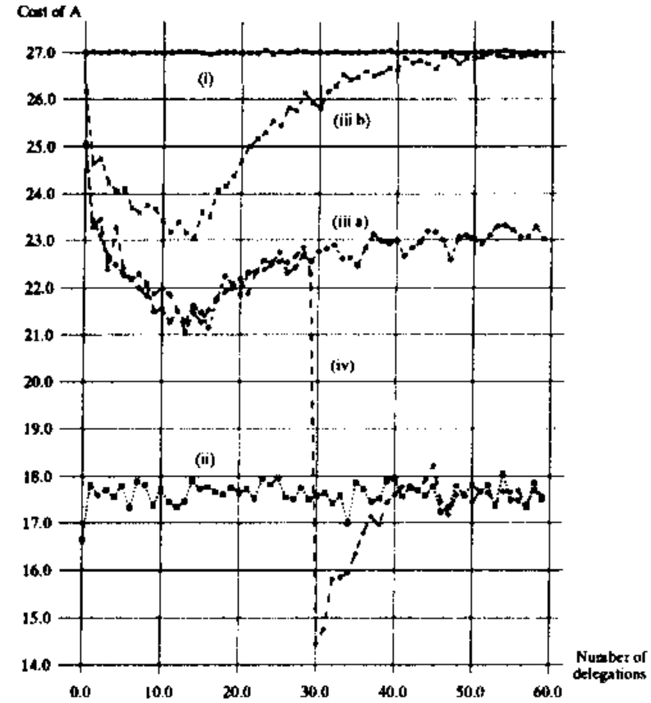

Figure 3: Agent's cost (average)

Curves in the figures are the result of the next conditions ($C_{neg} = 2$ except for (iii b)).

(i) B does not exist (agent A has to execute the actions alone),

(ii) B uses our mechanism,

(iii a) B is self-centered (B's strategy is only "dele-

(iii b) B is self-centered ($C_{neg} = 4$)

(iv) B is the same as (iii a) till the 30-th negotiation, after then, it is the same as (ii).

Although the cost doesn't decrease when agent A executes the actions alone (i), A can reduce the cost when the other agent uses our mechanism (ii). When the other agent is self-centered (iii), the cost is at first a little bit more than when the other agent uses our mechanism from the start. This is caused by a decision made by both flipping a coin when strategies collide and usage of the "do nothing" strategy when A cannot benefit from it. However, when the delegation precedes with $C_{neg} = 4$ (a cost-consuming negotiation), as the agent using our mechanism does not come to collaborate with the self-centered agent, the cost approaches the cost of (i). When negotiation is not cost-consuming (C_{neg} = 2), the agent continues to collaborate with the self-centered agent, because it can reduce its cost more than when doing it alone (i) but less than when in situation (ii).

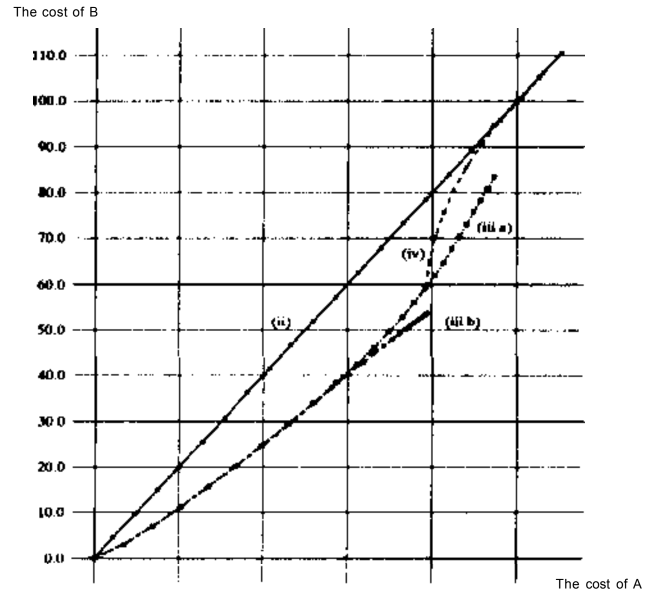

Figure 4: Sum of the cost of the plan received

In the case where the other agent changes its mind and decides to use our mechanism rather than being self-centered (iv), the same result obtained for the self-centered agent is obtained at first. If the other agent has decided to use our mechanism, it returns the benefit obtained up till then in order to balance the individual received cost. Therefore, the cost is extremely reduced at that time, and approaches the cost of (ii).

Furthermore, we simulated the case when α and β are different from 15 and 0.07. With α less than 15, result (iii) presents the largest change among all simulations. The agent decides not to collaborate with the self-centered agent earlier. If β is greater than 0.07, result (iv) represents the largest change. The cost when the other agent has come to use our mechanism is smaller. The reason for this is that as β larger, $P_l(B)$ larger so that the agent comes to collaborate earlier on the social law. But if $P_l(B)$ is smaller, the agent will propose the "do nothing" strategy so that the "delegate" strategy would be less used and the cost is not reduced.

6.2 Cost balancing of received actions

Figure 4 shows the received cost of both agents. Curves (ii)-(iv) in the figure are the same conditions as before.

When both agents use our mechanism (ii), the costs received are balanced. When the other agent is self-centered (iii), the agent receives too many actions because of the flexibility of the mechanism. However, this loss cannot continue to increase because A does not get to participate in the negotiation on delegation if A thinks that it cannot benefit from it. Also, in the case of the self-centered agent which changes its mind and decides to use our mechanism in the course of negotiation, the received costs are finally balanced (iv).

7 Discussion

We discuss some issues related to our mechanism.

The social law which guarantees that an agent can delegate its actions in the future even if it receives the actions of another agent, not only enables rational agents to reduce their cost by collaborating, but also enables our mechanism to have two important properties: a guarantee of balanced costs for individually received actions and an avoidance of conflicts in strategies.

As our microscopic law, defined between two agents, enables the agents to balance the received costs between them so that the costs are macroscopically balanced in a whole multi-agent system. With this law, an irrational agent that may receive too many actions would not be a bottleneck of the whole system if other agents that-delegated tasks to it waited until they finished.

With agents A and B abiding to this law, if A receives more than B $(\Delta(B) < 0, \Delta(A) > 0)$, A proposes "delegate" and B proposes "receive." Therefore, the strategies do not conflict, so that agents can easily reach an agreement. In [Shoham and Tennenholtz, 1992], social law is used to constrain actions to avoid conflicts. It became unnecessary for agents to negotiate for conflict resolution. However, agents must negotiate to exchange information about plans when they collaborate in a positive relationship. Our mechanism used the law to con strain the strategy of negotiation so as to avoid conflict.

Moreover, we considered self-centered agents, or agents that do not abide by the law. This is a case which is not considered in [Shoharn and Tennenholtz, 1992]. It is very simple for agents not to collaborate with self centered agents after they realize what kind of agents they are dealing with. However, it is problematical that an agent which exceptionally does not abide by the law for some reason, cannot collaborate any more. Also, problematical is the fact that agents do not col laborate with self-centered agents even when benefit can be obtained. Our mechanism is flexible: reliability P_1 is gradually decreased every time the strategies conflict, so that the chance to collaborate with a real self-centered agent is decreased and agents collaborate only if they can benefit from it. However, agents with our mechanism may receive a little more action than a self-centered agent because of this flexibility.

Here, we consider the situation where the bank and post office are in the same direction and both agents plan to go to both places. Because their plans are "go to bank" and "go to post office" and "return," the resulting plan of our mechanism is that one agent goes to both places. Nevertheless, if the places are in different directions, the resulting plans are that each agent goes to a different place. The latter result is obtained through two negotiations because their plans are "go to bank" and "return" and "go to post office" and "return." Our mechanism also provides such an optimal solution.

In [Zlotkin and Rosenschein, 1990], flipping a coin is used to resolve conflicts, but the purpose for our work is to avoid conflict. Since the mentioned work is designed for collaboration in negative relationships, the conflict in goals must be resolved. On the other hand, as our work is directed to positive relationships, the conflicts are not necessarily resolved (in this case, agents cannot reduce costs).

In a related piece of research [Martial, 1992], the proposed algorithm focuses on the optimization of plans of agents. Therefore, agents are willing to receive the actions even if they cannot benefit from them, and the received costs would not be balanced. Our mechanism does not require such irrational agents; each agent can rationally and flexibly select its own strategies.

8 Conclusion

The utilization of positive relationships has not received much attention in DAI. We proposed a mechanism using a social law by which rational agents can reduce the cost of their execution by delegating and receiving actions. With this law, agents can avoid conflicts of strategies in a negotiation and reach an agreement easily. Furthermore, we considered the case in which agents do not abide by the law (self-centered agents) and the case in which agents that are self-centered at first come to abide by the law eventually. Simulation results show that by using our mechanism, rational and flexible collaboration is possible with these kinds of agents.

We intend to use a more complex model of agents, and consider communication costs and collaboration with multiple agents by introducing market mechanisms. Also, we will introduce a mechanism based on incomplete information for more detail, as stated in [Kakehi and Tokoro, 1993].

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