A Two-level Framework for Coalition Formation via Optimization and Agent Negotiation

Hoong Chuin LAU Lei Zhang
The Logistics Institute - Asia Pacific,
National University of Singapore, Singapore 119260
lauhc@comp.nus.edu.sg tlizl@.nus.edu.sg

Abstract

We present a two-level coalition formation approach based on a centralized optimization model on the upper level, and a distributed agent-negotiation model on the lower level. This approach allows us to balance agent self-interests against a high joint utility. Experimental results show that the two-level coalition formation mechanism will increase not only the overall utility of the coalition, but also the individual utility of most participating agents. The results also suggest it is better for the agents to be partially cooperative rather than either fully cooperative or self-interested in our setting.

1. Introduction

Coalition formation in Multi-Agent systems (MAS) has been well studied in recent years. Until now almost all related work on coalition formation can be categorized into two general classes: computation-oriented approach and negotiation-oriented approach. In computation-oriented approach, agents are group-rational with little or no self-interests and they work to find a solution that increase their joint utility – the sum of the utilities of all involved agents. A central authority will take charge of the whole coalition formation process and it is able to achieve a high-quality coalition configuration by extensive calculation. On the contrary, for a negotiation-oriented approach, the agents are self-interested and their goals are to maximize their own utilities. Agents will form coalition by themselves by negotiating with each other. Both of these two approaches have their own strength and weakness. Computation-oriented approach tries to maximize the joint utility of the group by neglecting each agent' individual interest; Negotiation-oriented approach tries to satisfy agents' self interests but the joint utility of the group is somehow sacrificed.

Little work has been done to achieve a balance between these two extreme approaches that gives agents certain level of freedom and is still able to achieve a high joint utility of the group. We believe that as the sophistication of multi-agent system increases, agents will not be purely self-interested, seeking to maximize their own utility, nor fully cooperative working to maximize the joint utility. It is more realistic to expect agents being something in the middle, i.e. partially cooperative in the coalition formation process. Motivated by this, we propose a framework in which coalition formation is performed at two levels. The upper-level deals with high-level goals (increase group utility) and the lower-level works to refine the coalition formed in the upper-level. In the upper-level, agents are cooperative and a central host will adopt the computation-oriented approach to form coalitions. In the lower-level, agents are concerned with their own interests and they can negotiate with each other on prices in order to maximize their own utilities. These two levels are tightly integrated with each other and together they manage to achieve a balance between agents' self interests and joint utility of the group. The upper-level coalition formation process will encourage agents to be partially cooperative during the lower-level negotiation process. In turn, agents' attitude in the lower-level negotiation process will affect how the coalitions are formed in the upper-level. Agents in the system can dynamically change their attitudes towards negotiation. Jobs arrive at the coalition formation system in batches and agents will revise their attitudes after fulfilling each batch of the jobs. An agent's attitude will be affected by its long-term goal, current situation, other agents' attitudes towards negotiation, etc.

2. Related works

[1] developed a measure of social consciousness called "brownie points" (BP) which encourage self-interested agents to be partially cooperative during negotiation. [2] proposed a classification of coalition formation problem based on three driving factors (job demands, resource availability and profit objective). The agents in that paper are fully cooperative and there exists a central authority that performs coalition formation. [3] proposed a protocol for price negotiation to increase the chances of coalition formation. [4] presented a stable buyer coalition formation scheme for e-markets by considering volume discounts. In [5], the idea of a round in continuous double auctions was introduced. . A history of past transaction prices was maintained to guide agents

in their subsequent bidding behavior. Each agent is associated with a utility function that describes its attitude towards risk. Our work makes use of their ideas of a history list and negotiation round. In [6], the authors provided two algorithms for self-interested agents to form coalition in a non-super-additive environment. [7] proposed an iterative distributed greedy algorithm for coalition formation for fully cooperative agents. This is a computation-oriented approach and by extensive calculation, it can achieve a high-quality coalition configuration. [8] believed that reciprocity is the foundational principle for promoting cooperative behavior among self-interested agents. The principle of reciprocity means that agents help others who have helped them in the past or can help them in the future. This paper is motivated by the idea in [9], where the authors presented a negotiation framework in which the negotiation process is performed at two levels. The upper level deals with the formation of high-level goals and objective for the agent and the lower-level deals with feasibility and implementation operations. [10] introduced an integrative negotiation mechanism which enables agents to choose any attitude in the spectrum between self-interested and fully cooperative. It suggested that agents should be partially cooperative in their negotiation with other agents.

3. Preliminaries

In this section, we present definitions, notations and assumptions used throughout this paper.

3.1. Jobs

There are m jobs in the system that arrive in batches. Each job i consists of a fixed k number of sub-jobs. Each sub-job j requires a unique resource of its type. Let a_{ij} denote the quantity of resources required for performing job i sub-job j. Each job i is associated with a revenue value R_i and the profit for performing this job P_i can be derived from subtracting from R_i the sum of the final bid prices of the agents in the coalition.

3.2. Agents

There are n agents denoted as $\{A_1, A_2, \ldots, A_n\}$. Each agent A_i has a vector of non-negative resource capacities $C_i = [c_{i1}, c_{i2}, \ldots, c_{ik}]$, where c_{ij} is agent A_i's quantity of resource capable of performing sub-job j. A sub-job may be performed by one or more agents. Each agent has a price vector $P_i = [\rho_{i1}, \rho_{i2}, \ldots \rho_{ik}]$, where ρ_{ij} is the unit bid price for A_i to perform sub-job j, which is a negotiable variable within the range $[\rho_{ij}^{\min}, \rho_{ij}^{\max}]$, where $\rho_{ij}^{\min}$ and $\rho_{ij}^{\max}$ are A_i's minimum and maximum unit bid price for performing sub-job j respectively. Each agent has a set of attitudes toward negotiation denoted as cooperative factors (*CF*). The *CF* value ranges from 0 to 1.0 where a higher *CF* value means a more cooperative attitude. For each batch of jobs that arrives, the value of ρ_{ij} is a negotiable variable between $\rho_{ij}^{\min}$ and $\rho_{ij}^{\max}$ depending on its attitude toward negotiation at that juncture. Its profit for performing sub-job j is hence the difference between its revenue (i.e. ρ_{ij} times resource usage) and cost (conveniently defined as $\rho_{ij}^{\min}$ times resource usage).

3.3. Coalition

A coalition is defined as a group of agents to achieve a common job. Each coalition is associated with a *coalition value*, which is intuitively defined as the joint utility that the members of a coalition derive by cooperating to satisfy a specific job. In this paper, we allow overlapping coalitions, i.e. each agent can belong to more than one coalitions. A coalition is termed *feasible* if the utility gained from forming this coalition is above certain threshold value and defined as infeasible otherwise. In this paper, we simply define a coalition as feasible if the total bid price for all agents does not exceed the revenue of the job. Coalitions which violate the pricing constraint are termed *infeasible* and there is a need to get agents in an infeasible coalition to reduce their individual bid prices.

3.4. Coalition host and negotiation host

There are two hosts in the system: a coalition formation host (denoted CH) and a negotiation host (denoted NH). CH takes charge of upper-level coalition formation process in which it will form a set of coalitions for the current batch of jobs. NH is responsible for coordinating the lower-level negotiation process. It calculates and sends the proposed drop price to each agent in the infeasible coalition. Upon receiving the responses from the agents, NH will either re-propose drop prices for agents or announce the failure of negotiation. NH will pass each agent's behavior to CH after fulfilling each batch of jobs. This information will be used to measure the cooperativeness of each agent and will affect the coalition formation process for the next batch of jobs.

3.5. Agent behavior

Each agent i is associated with a probability function $\Pr_i$ that captures its past bidding behavior, where $\Pr_i(z)$, $0 \le z \le \alpha_i$, gives the probability (or willingness) that agent i has offered z percent discount off its initial bid price in the past. The expected value of $\Pr_i$ is denoted by $E\Pr_i$. In this paper, $\Pr_i$ is represented as a monotonically decreasing step function with t_i number of intervals. Each agent's past behavior is known to other agents in the system. Other agents will use the agent's past behavior to estimate its future behavior and this estimation will be used by agents to make decisions during the negotiation.

3.6. Coalition factor (*CF*) vs. coalition level (*CL*)

As mentioned above, each agent has a set of attitudes toward negotiation denoted as coalition factor (*CF*). *CF* value represents how cooperative the agent is willing to be toward negotiation and is determined by the agent itself. Note that the *CF* value is unknown to NH as it is the agent's own strategy and should not be revealed to others. Instead, NH derives the cooperative level (*CL*) of the agent by observing its *bidding behavior* in response to the previous batch of jobs. In short, *CF* and *CL* are two different measures of agent's attitude toward negotiation. *CF* is determined by the agent itself while *CL* is determined by NH.

4. Upper level coalition formation

We will now present the two-level coalition formation framework in detail. In our model, we assume that jobs arrive in batches. The objective is to form coalitions for each batch of jobs in the upper-level coalition formation process and invoke the lower-level negotiation process only when some formed coalitions in the upper-level are infeasible. Task (i.e. job) allocation via coalition formation problem is NP-hard as it can be reduced from multi-dimensional knapsack problem which is a well-known NP-hard problem [2]. Here we propose a polynomial time heuristic algorithm to form coalitions by maximizing the profit of the most valuable coalition, and continue recursively until all the jobs have been fulfilled or no more coalition can be formed (see [2] for more details). In this way, we expect the overall profit of the system to be maximized as well.

4.1. Coalition formation algorithm

There are 3 stages in our coalition formation algorithm:

Stage 1: *Preprocessing*. For each sub-job *j*, we sort all agents that have capabilities for the sub-job in the increasing order of their *unit decision prices*. We call the sorted list the agent list for sub-job *j*.

Stage 2: *Coalition value computation*. For each remaining job *i* in the job list and for each sub-task *j* of job *i*, pick agents in order from the agent list of sub-job *j* until job *i*'s resource requirement for sub-job *j* is met. Compute its coalition value according to following:

$$\frac{P_i}{\sqrt{a_{i1} * f_{i1} + a_{i2} * f_{i2} + \ldots + a_{ik} * f_{ik}}}$$

where $f_{it} = \sum_{j \neq i} \frac{a_{jt}}{R_t - a_{it}}$ and R_t is the total remaining capacities (of all agents) for resource *t* before allocating job *i*.

Stage 3: *Coalition formation*. Form the coalition for the job with highest coalition value among all jobs.

1. Choose the highest among all coalition values computed in Stage 2. That coalition will be formed and the corresponding job for it would be assigned to the coalition.
2. For each agent that becomes a member of the coalition formed, the resource capabilities are updated.
3. The job assigned to the coalition at this iteration is removed from the job list.
4. Go to Stage 2. Stop when no more jobs are left or no more coalitions can be formed.

4.2. Computing agent's unit decision price

The agent's unit decision price is determined by the agent's current unit bid price as well as its *CL* presented during serving last batch of jobs. Here is how we measure agent's *CL* and its unit decision price: let d_{ij}^{ave} be agent *i*'s average drop price for sub-job *j*, p_{ij} and p'_{ij} be its unit bid price for the last and current batch of jobs, and u_{ij} be agent *i*'s unit decision price for sub-job *j*, agent *i*'s *CL* for sub-job *j* is determined by $\frac{d_{ij}^{ave}}{p_{ij}}$ which represents the percentage of unit bid price that the agent has agreed to drop for last batch of jobs. Thus we have $u_{ij} = p'_{ij}\,(1 - \frac{d_{ij}^{ave}}{p_{ij}})$.

5. Lower level agent negotiation

5.1. Lower-level negotiation protocol

The set of infeasible coalitions that have been formed in the upper-level are then passed to the lower-level negotiation system. Here, NH tries to persuade agents to drop their respective bid prices by a proposed drop price. Each agent performs its own computation and either accepts or rejects this amount. In the latter case, it either re-proposes another bid price or simply rejects the host. When NH receives rejections or re-proposals, it re-computes the drop price based on the current state and the history of the negotiation process. Subsequently, the agent is informed of this new drop price and does its computation to decide the next step. These exchanges will iterate until the coalition either becomes feasible or when a predetermined number of rounds has elapsed.

In the following, we consider an infeasible coalition *C* as an example and present how the negotiation proceeds among the agents in the coalition. Let $|C|$ denote the size of coalition, i.e. the number of agents in coalition *C*, *R* be the revenue of the job that is associated with the coalition. For simplicity, since we are dealing with only one job at a time, the index *j* is dropped and all notations henceforth will refer to the current job being negotiated.

The current state information $D^r = \left\langle d_1^r, d_2^r, ..., d_{|C|}^r \right\rangle$ is computed at the start of each negotiation round *r* and d_i^r denotes agent *i*'s confirmed drop price after round *r*. Let ρ_i^r be agent *i*'s unit bid price at round *r* then we have $\rho_i^r = \rho_i^0 - d_i^{r-1}$ .Let $\delta^r = \sum_{\forall d_i^r \in D^r} d_i^r$ and $\varepsilon^r = \sum_{\forall A_i \in C} \rho_i^0 - R - \delta^r$ denote the amount in which the sum of all agents' bid prices is in excess of the job revenue during round *r*. Let π^r denote the sum of all agents' bid prices at during round *r*. The proposed drop price of each agent *i* at round *r* is given by $\Delta_i^r = \left\lceil \varepsilon^{r-1} \cdot \frac{\rho_i^{r-1}}{\pi^{r-1}} \right\rceil$.

Upon receiving the proposed drop price from NH, agents will decide whether they should accept or reject the proposal. The key measure used in its decision making is its expected revenue. Let X_i^r be the random variable that denotes the revenue of agent *i* during *r*; C_i^r be the ordered set of agents except agent *i* during round *r*; $k = |C_i^r| - 1$; $C_i^r[t]$ be the t^{th} agent in C_i^r respectively; $\sigma^\infty = \left(\rho_1^\infty, ..., \rho_k^\infty\right)$ and $\sigma^r = \left(\rho_1^r, ..., \rho_k^r\right)$ be the tuples of minimum and current round bid prices of all agents in C_i^r ; θ^r denote the sum of initial bid prices of agents during round *r*; $\xi^r = R - \delta^r - \theta^r$; $Q_i^r = \xi^r - \rho_i^\infty$; G_i^r be the set of $\left(\sigma^\infty, \sigma^{r-1}, \xi^{r-1}, \rho_i^\infty, \rho_i^0\right)$ -constrained-*k*-integer partitions of Q_i^r (see [3] for technical details); *g* be an arbitrary tuple in G_i^r and g_t be the t^{th} element of *g*. The expected revenue of agent *i* at round *r* is:

$$\mathrm{E}[X_i^r] = \sum_{\forall g \in G_i^r} \left[\xi^r - \sum_{1 \le t \le k} g_t \right] \cdot \left[\frac{\prod_{1 \le t \le k} \Pr_a\left(\frac{g_t}{v_a}\right)}{\sum_{\forall g \in G_i^r} \prod_{1 \le t \le k} \Pr_a\left(\frac{g_t}{v_a}\right)} \right],$$

where $a = C_i^r[t]$. If $\mathrm{E}[X_i^r] = \infty$ because no partitions can be formed ($G_i^r = \varnothing$), the agent will reject the proposed drop price and set $\rho_i^r = \rho_i^{r-1}$ (see [3] for more details).

5.2. Agent decision making strategy

In our problem, as the agent's attitude toward negotiation will be used by CH to form coalition, the agent has to be partially cooperative in order to have a high chance to join the coalition in the future. For this purpose, we introduce a new term $CF * d_i^r$ which denotes the percentage of the proposed drop price agent *i* is willing to accept. This new term is directly affected by the agent's current *CF* and represents how much an agent is willing to sacrifice its own profit to make the coalition feasible. Hence, agent *i*'s decision making strategy becomes as follows:

If $\rho_i^r - d_i^r + CF * d_i^r \ge \mathrm{E}[X_i^r]$ and $\rho_i^r - d_i^r \ge \rho_i^{\min}$, then agent *i* will accept the proposed drop price. Otherwise, it will reject the proposal and re-propose $\rho_i^{r+1} = \mathrm{E}[X_i^r]$.

5.3. Dynamic adjustment of agent's attitude

In our model, each agent can dynamically adjust its attitude toward negotiation. This is necessary to support the agent's negotiation in a complex organizational context. It also strengthens our system's capability of modeling human decision makers.

We define the *resource utilization rate* of the agent for the previous batch of jobs as the ratio of its revenue gained from serving last batch of jobs over the estimated value of the agent's total resource before serving the last batch of jobs. After serving each batch of jobs, an agent will compare its own resource utilization rate with other agents' in the system. Let u_i be agent *i*'s resource utilization rate, u_{ave} be the average of other agents' resource utilization rates, CF_i be agent *i*'s CF for the last batch of jobs and $CF_i^{'}$ be the new CF after adjustment. The following shows how the agent adjusts its attitude periodically.

(i) If $\frac{u_i - u_{ave}}{u_i} > \alpha$, agent *i* decreases its CF by 0.1 if it is greater or equal than 0.1; otherwise remains the same.

(ii) If $\frac{u_i - u_{ave}}{u_i} < \beta$, agent *i* increases its CF by 0.1 if it is less or equal than 0.9; otherwise it remains the same.

(iii) If $\alpha \ge \frac{u_i - u_{ave}}{u_i} \ge \beta$, agent *i*'s CF remains unchanged.

The value of α and β need to be carefully chosen and in this paper we set $\alpha = 0.3$ and $\beta = -0.3$.

5.4. Agent's new bid price

After fulfilling a batch of jobs, the agent will adjust its unit bid price for the next batch of jobs. Let ρ'_{ij} and $CF_i^{'}$ be agent *i*'s unit bid price for sub-job *j* and CF for the next batch jobs respectively, then we have $\rho'_{ij} = \rho_{ij}^{\max} - CF_i^{'} * (\rho_{ij}^{\max} - \rho_{ij}^{\min})$. Clearly, when the agent is completely cooperative, it will use $\rho_{ij}^{\min}$ as the unit bid price for the next batch of jobs. When the agent is fully selfish, it will use $\rho_{ij}^{\max}$ as the unit bid price.

6. Experimental results

We compare our proposed two-level coalition formation mechanism with the standard one-level coalition formation algorithm, which has shown to obtain very promising results in our previous research [2]. The experimental results show that with the two-level coalition formation structure, it will not only increase the overall profit of the system, but also increase the individual profit of most participating agents. The results also show that it is better for an agent to be partially cooperative rather than being fully cooperative or self-interested in order to maximize its profit.

Table 1 shows the experimental result of comparing the two-level coalition formation mechanism with one-level approach. The first column is the number of jobs in the system. The second column is the number of feasible coalitions that have been successfully formed under one-level and two-level approaches. The third column is the ratio of total profit of two-level approach over that of one-level approach. The last column shows the percentage of agents who obtain higher profits in two-level approach than in one-level approach. This table shows that the two-level coalition formation framework increases the total profit of the system as more feasible coalitions have been formed. At the same time, the majority of agents are also more profitable from this two-level approach.

We also study how an agent's attitude toward negotiation affects its own profit. Here we choose the test instance of 30 jobs and arbitrarily select some agents whose *CF* values are changed from 0 to 1. Figure 1 shows the relationship between an agent's Profit (y-axis) and its corresponding *CF* (x-axis). Observe that it is better for an agent to adopt a partial level of cooperativeness instead of being fully cooperative or self-interested in order to maximize its profit. Other agents' Profit-*CF* curves also follow a similar phenomenon.

Table 1: Comparison of two coalition formation mechanisms

No. of Jobs	No. Feasible Coalitions	Total Profit Ratio	Benefiting Agents(%)
10	4 vs 9	2.93	70%
20	9 vs 16	2.30	70%
30	12 vs 26	2.15	83%
40	16 vs 32	2.02	77%
50	20 vs 43	2.25	68%

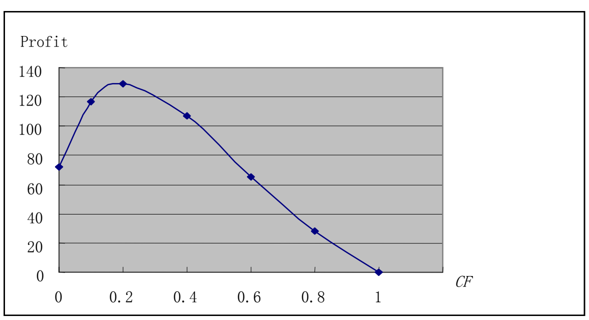

Figure 1: Profit versus *CF* curve

7. Conclusion

Experimental results show that our two-level approach outperforms the one-level approach in terms of total profits as well as the individual profit of most participating agents. It also suggests an intermediate level of cooperativeness toward negotiation yields higher profit than the extremes. Note that although our approach increases the total profit of the system and the individual profit of most agents, there are still a number of agents whose profits decrease under this approach. An interesting extension of this paper is to provide a better payoff distribution protocol among agents so that more if not all agents would benefit from this two-level approach. Another interesting research is to formalize a more sophisticated mechanism which can suggest the degree of cooperativeness an agent should adopt toward negotiation in order to maximize its own profit.

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