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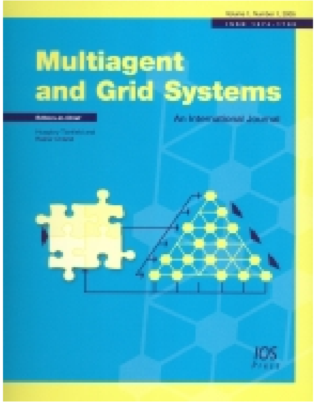

A flexible and reasonable mechanism for self-interested agent team forming

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Abstract

As social entities, intelligent agents need to collaborate with others regardless of whether they are cooperative or self-interested. Compared with cooperative agents, collaborations among self-interested agents are more complex and dynamic due to the selfish features. Self-interested agents are impelled to cooperate with others by their individual goals. In an agent team composed of self-interested agents, "common" goals of agents may change to be conflict as the environment changes. Especially in open and dynamic environments, if factors such as agent goals, task requirements and resources have been changed, a selfish agent may need to modify or even relieved the collaboration relationships with its "colleagues". Otherwise the collaboration would be conflict or even harmful to its individual goal. Therefore, it is important to include rational team forming mechanisms in self-interested multi-agent systems. Without a rational team-forming mechanism, agent teams in a system may have unreasonable or outdated compositions which obstruct (agent) team members to purchase profits or cause unnecessary resource consumptions. Focusing on general self-interested multi-agent systems, this paper suggests a flexible team forming mechanism that can enable agents to select team members with reasonable terms and objects. The flexibility of the mechanism enables agents to form more rational teams that can avoid potential benefit conflicts among self-interested team members.

A Flexible and Reasonable Mechanism for Self-interested Agent Team Forming

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December 5, 2007

Abstract

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1 Introduction

A multi-agent system (MAS) is a collection of intelligent agents [22]. An intelligent agent is a reactive, proactive, autonomous and social entity, which performs a given task using information gleaned from its environment [10] [17]. Generally, agents of a MAS can be characterised by whether they are cooperative or self-interested [11]. However, due to the distributed nature of the problem to be solved or the limitations of agent abilities, both cooperative and self-interested agents will often need to collaborate with other agents to achieve their goals [1] [4].

For self-interested agents, collaborations between agents are based on common benefits they can achieve together. This kind collaborative relationship is not as stable as that of cooperative agents. Today, as MAS applications become more and more complex, many multi-agent systems (MASs) need to work in open and dynamic domains [2] [7] [23] [25]. Uncertainties of open application domains bring difficulties to agent team forming in following three major aspects:

- Firstly, in open environments, a MAS may receives various tasks that require agents to possess different resources and skills. Towards changes of task requirements, agent teams in a MAS need to modify their team compositions to achieve tasks;

- Secondly, in an agent team, the criteria for evaluating the importance of team members is associated closely with their contributions in the completion of tasks. In open environments, it will be difficult to evaluate the importance of agents since task requirements and agent abilities are changeable;
- Finally, in an open environment, goals of team members (agents) are changeable. As the goals of team members change, keeping collaborations with other members may obstruct an self-interested agent to achieve its individual goal.

In open environments, "there is no single type of organisation that is suitable for all situations [8]". Therefore, in MAS research, it is an important issue to develop a rational team forming mechanism for MASs. Generally, a team-forming mechanism can enable agents to form and reform teams automatically, and to avoid unreasonable or outdated team compositions in MASs. Towards challenges brought by open environments, a number of researchers try to find an optimal mechanism for dynamic team forming and member selection. Abdallah, Shehory and Tambe proposed mechanisms to form agent teams based on skills of agents that are required for task completion (see [1], [21] and [24]). This kind of mechanisms are efficient for cooperative MASs. But in self-interested MASs, individual agents' willingness and goals are another important factor to be considered during team forming. The research on team forming for self-interested agents generally focuses on the problem of forming one-shot teams, which is also called short-term teams, for individual tasks. In this kind of mechanisms, agents come together when they need to handle some tasks, and their relationships will be terminated after tasks have been accomplished. Obviously, one-shot teaming will arouse frequent grouping and regrouping among agents, and unfortunately, each grouping/regrouping will consume some resources, such as communication resources, computation resources, etc. resources. To overcome the weakness of one-shot teaming, Rathod and desJardins proposed several stable-team forming strategies for self-interested MASs [18]. These strategies cite human organisation styles (i.e. humans always tend to prefer working with people they know and trust) into MAS organisation formations, and try to make self-interested agents form long-term relationships to cut team forming consummations. However, for many self-interested MASs, agent goals or willingness are changeable and uncertain. A long-term relationship is very hard to be kept after the goals of team member agents are changed.

In this research, we develop a mechanism that enables self-interested agents to flexibly choose team durations and members. Factors, such as agent historical performances, task requirements and resource constraints, are considered in the mechanism. For open environments, the flexible team forming and member selection mechanism will be more suitable for self-interested agents applications. It enables more dynamic and reasonable collaboration between agents and reduces unnecessary consumptions and benefit conflicts brought by team forming. However, due to the highly uncertainties of most open environments, analysis and evaluation of dynamic factors is not very easy. It is impossible to find a fixed standard for factors such as "how good an agent performance is". Regarding this point, in the mechanism introduced in this paper, fuzzy rules are hired to evaluate factors related with team forming. Through this way, an agent can dynamically select collaboration durations and objectives according to the result of fuzzy evaluations, and choose collaboration manners more flexibly.

The rest of this paper is arranged as follows. In the second section, the MAS structures and some important definitions and assumptions in this research are introduced. Section 3 presents the advantages, disadvantages and suitable areas of long-term and one-shot teams. The flexible team forming mechanism is introduced in Section 4. In Section 5, experiments that compare the flexible mechanism with one-shot and long-term team forming is presented. Some related works of this research are presented and compared in Section 6. Finally, the conclusions and further directions of this research are presented in Section 7.

2 System Architecture and Problem Definition

Various MAS applications may have different system structures. In this research, the MAS environment is set up to demonstrate and analyse the team forming and member selection mechanisms. Hence, the system structure is set up toward assisting agent communication and task allocation. Some simplifying assumptions and definitions, which can avoid adding the scheduling and task decomposing problems, are also made, and only elementary agents and task models are included in the MAS. However, these models are generic enough to be practical and applicable to a wide range of real applications.

2.1 The System Architecture

The MAS architecture of this research is shown in Figure 1. From this figure, it can be seen that tasks of a MAS are published on the *Task Board* of the system, and will be removed from *Task Board* after been taken by an agent or agent team (AT). Published tasks are accessible to all individual agents and agent teams (ATs) of the system. Agents can enter and leave the system according to their willingness. However, agents have to publish and remove their registration information on the *Agent Board* of the system before they enter and leave the system. The registration information records the skills and status (see Subsection 2.2) of an agent.

Agent abilities are limited. To perform tasks beyond its ability, an agent

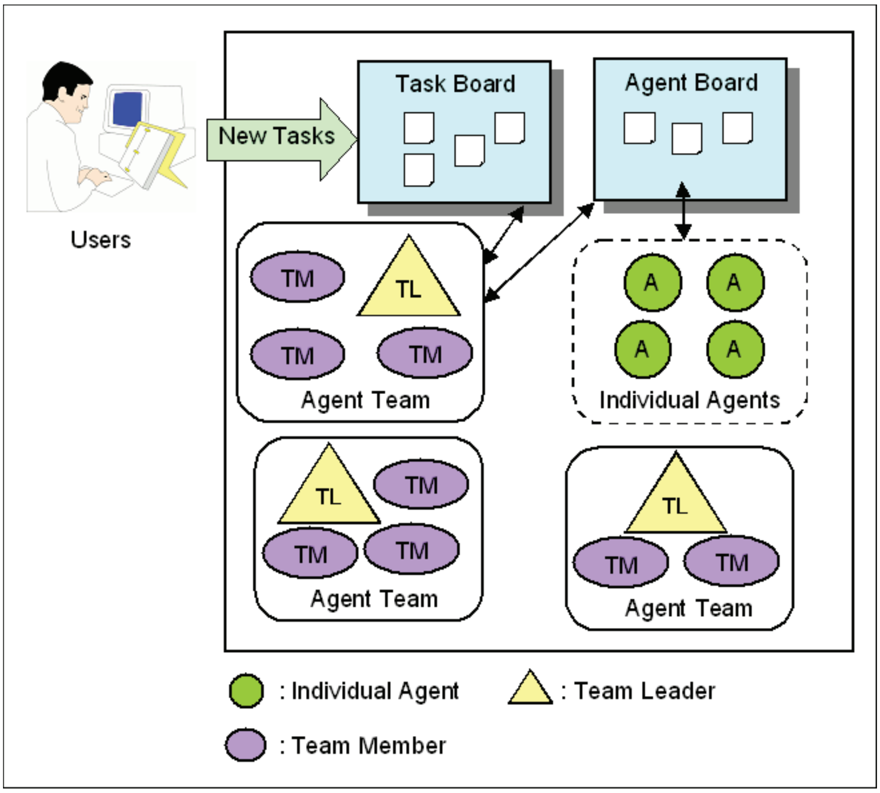

Figure 1: The System Architecture

needs to collaborate with other agents through joining or forming a team. Each AT is composed by one (and only one) Team Leader (TL) and several Team Members (TMs). After an agent joins an AT, it can get payments from the AT and at the same time it needs to work for the AT for a certain period. The payment and serving term are described in the contract (see Definition 3) between the Team Member (TM) and the TL.

2.2 Definitions and Assumptions

In this paper, all agents are assumed to possess a set of resources, and all tasks are required to be accomplished by using the resources of agents. Agents in this paper are self-interested. Their goals are to achieve as much as possible awards through accomplishing. However, due to resource limitations, agents have to collaborate with others to execute tasks together (by forming teams).

In this subsection, some important definitions are given. All of these definitions are under the assumptions which are presented in the previous paragraph.

Definition 1 A task is formally defined as $t_i = \langle w_i, R'_i \rangle$, where w_i is the reward gained by an agent/agent team if task t_i is accomplished by that agent/agent team; R'_i is the set of resources or skills, which are possessed by agents of the system, required by task t_i. A task can only be assigned to one agent or AT.

Definition 2 An agent is formally defined as $a_i = \langle g_i, R_i, s_i \rangle$, where g_i is a set of individual goals of agent a_i; R_i is the skills and resources possessed by agent a_i; s_i is the status of a_i, where $s_i = (v_a, v_p, t)$. s_i represents whether agent a_i is performing a task and participating an AT. Meanings of different s_i values are listed in Table 1. The names and meanings of v_a, v_p and t are listed as following:

Availability v_a : v_a presents whether an agent is performing a task. $v_a = 0$ when the agent has no task (available); $v_a = 1$ when the agent is performing a task (not available);

Position Parameter v_p : v_p presents whether an agent is an individual agent, TL or TM. $v_p = 0$ when the agent is individual; $v_p = 1$ when the agent is a TM of an AT; $v_p = 2$ when the agent is a TL of an AT.

Contract Ending Time t : t is the contract ending time of an agent (also see Definition 3).

Note: R'_i in the definition of *task* is different from R_i in the definition of *agent*. R'_i denotes the required resources of a task; R_i denotes the possessed resources of an agent.

Table 1: Status of an Agent

s_i **value**	**Status of agent** a_i
(0, 0, 0)	Performing no task; has no AT.
(1, 0, 0)	Performing a task; has no AT.
(0, 1, 0)	Has a one-shot contract as a TM; performing no task currently.
(1, 1, 0)	Has a one-shot contract as a TM; performing a task currently.
(0, 1, t)	The TM of an AT for period t; performing no task currently.
(1, 1, t)	The TM of an AT for period t, performing a task currently.
(0, 2, 0)	The TL of an AT; performing no task currently. (It is assumed that the TL cannot quit from its AT and let t value of a TL equal to 0.)
(1, 2, 0)	The TL of an AT; performing a task currently.

Definition 3 A *Contract* c_{ij} is an agreement between TL a_i and TM a_j. It can be defined as $c_{ij} = \langle t_{ij}, p_{ij}, S_{ij} \rangle$, where t_{ij} is the contract ending time; p_{ij} is the penalty that the TL or TM has to pay if it breaks the contract and terminates the cooperation relationship before t_{ij}; S_{ij} is a set of payment that a_j can gain through serving the AT. S_{ij} can be described as tuple $\langle sc_{ij}, sd_{ij} \rangle$. sc_{ij} is the payment that TM a_j can gain for each task completed by the AT, when a_j directly participates in the task. sd_{ij} is the dividend that TM a_j can share for each task completed by the AT, when a_j does not actually participate in that task. For contracts between the TL and TM of a one-shot team, t_{ij}, p_{ij}, and sd_{ij} equal to 0.

Definition 4 An Agent Team is a set of agents. It can be formally defined as $AT_i = \langle MS_i, TR_i \rangle$, where MS_i is the set of agents that currently are TMs of AT_i; TR_i is the capacity of the whole AT. Here, it is assumed that $TR_i = \sum_{j|a_j \in MS_i}(R_j + R_i)$, where R_i and R_j are resources possessed by the team leader and team members, respectively. In the other word, the capability of an AT is the sum of its TMs' capabilities and TL's capability. It is also defined that $\forall i \neq j : MS_i \cap MS_j = \emptyset$, which means an agent can only participate in one AT.

Definition 5 A *Contributor Set* $CS_{ij}(CS_{ij} \subset MS_i)$ of Agent Team AT_i is the set of agents that participate in performing task t_j, where t_j is a task of agent team AT_i. For a one-shot team, the CS equals to MS_i of the team (also refer to Definition 4).

Definition 6 For Agent Team AT_i, a *Member Contribution* mc_{ijk} is the contribution of agent a_k, where $a_k \in CS_{ij}$, in performing task t_j ($t_i = \langle w, R'_i \rangle$). mc_{ijk} equals to w/N, where N is the size of CS and w is the task reward.

3 One-Shot and Long-Term Team Forming

After presenting the system architecture and some important definitions, Introductions and comparisons of the one-shot and long-term team forming mechanisms are presented in this section.

3.1 One-Shot Teams

One-shot team strategy is widely applied in many MAS applications. In this strategy, agents of the system do not have a team initially. When a task t_i is published in the *Task Board*, agents start to bid on the new task. The system facilitator will choose (or randomly select) a bidder to assign the task. After the agent bided the task successfully, it becomes a TL and starts to look for collaborators according to the task requirement R'_i. Finally, the AT will disband after t_i is accomplished.

Generally, the one-shot team strategy includes following processes. (Here, it is assumed that the agents of the MAS cannot achieve the task individually.)

1. The system facilitator of the MAS publishes a new task t_i ($t_i = \langle w_i, R'_i \rangle$) on the *Task Board*;

2. Agents, whose $g < w_i$ and s=(0, 0, 0) bid on t_i;

3. The system facilitator awards t_i to agent $a_j (a_j =< g_j, R_j, s_j >)$. At the same time, a_j becomes the TL of agent team AT_j and modifies its s_j to (0, 2, 0). At this movement, $TR_j = R_j$;

4. a_j searches the *Agent Board* to look for agents with status (0, 0, 0), which can provide the lacking resources R, where $R \subseteq (R'_i - R'_i \cap TR_j)$;

5. a_j finds a required agent a_p, where $R_p \subseteq (R'_i - R'_i \cap TR_j)$;

6. a_j sends a contract c_{jp} to a_p, where $sc_{jp} \leq (w_i - g_j) \cdot sizeOf(R_p)/sizeOf(R'_i - R_i)$;

7. a_p accepts c_{jp} if $sc_{jp} \geq g_p$ or rejects c_{jp} if $sc_j p \leq g_p$;

8. If c_{jp} is accepted by a_p, $TR_j = TR_j \cup R_p$, and a_p modifies its status to (0, 1, 0);

9. Goes to Process (4) until $TR_j = R'_i$;

10. AT_j starts to perform t_i; the TL and TMs of AT_j modify their statuses to (1, 1, 0) and (1, 2, 0), respectively;

11. AT_j accomplishes t_i; agents of AT_j modify their statuses to (0, 0, 0) and are released from the team.

One-shot teams always keep loosely coupled relationships among agents as default. This feature is very suitable for dynamic MAS application domains. However, many dynamic applications are not that dynamic. For example, the new tasks may have some similarity, and their requirements might be similar (which means that they may just need similar ATs). In this case, frequent grouping and regrouping are not very necessary, especially each grouping will consume some system resources.

3.2 Long-Term Teams

The long-term team forming mechanism is different from the one-shot team forming mechanism. In the long-term team forming mechanism, the AT will not be dissolved after perform tasks. In the contrary, the TL of the team pays TMs some payments to keep the cooperation relationships, even if the TM does not contribute on a task accomplishment. The major motivation of the TL to keep long-term TMs in a team is to reduce the communication time that is used in searching TMs and forming teams, so as to bid on tasks as quick as possible. The long-term team strategy normally includes following processes.

1. TL a_i finds several free agents, whose status values are (0, 0, 0), from the *Agent Board* and sends them contracts in order to form a team with them. Agents modify their statuses to (0, 1, t_{ij}) if they accept the contracts. In this case, agent team AT_i is formed successfully;

2. TL a_i searches the *Task Board* for a suitable task and bids on task $t_k(t_k = \langle w_k, R'_k \rangle)$, where $R'_k \subseteq TR_i$ and $w_k \geq \sum_{j|a_j \in MS_i}(S_{ij} + g_i)$ (also refer to Definition 1-4).

3. If t_k is bided successfully, TL a_i assigns t_k to TM $a_p, a_q a_n$, where $R_p \cup R_q ... \cup R_n$ is the minimum set that satisfies $R'_k \subseteq R_p \cup R_q ... \cup R_n$. At the same time, $a_p, a_q a_n$ modify their statuses to $(1, 1, t_{ip}), (1, 1, t_{iq}), (1, 1, t_{in})$. Also, for this task performance, the *Contributor Set* CS_{ik} (refer to Definition 5) will be $\{a_p, a_q, ..., a_n\}$;

4. $a_p, a_q, ..., a_n$ modify their statuses to $(0, 1, t_{ip}), (0, 1, t_{iq}), ..., (0, 1, t_{in})$ after t_k is accomplished;

5. TL a_i awards TM a_m ($a_m \in AT_i$) with $(sc_{im} + sd_{im})$ if $a_m \in CS_{ik}$, or sd_{im} if a_m is not in CS_{ik};

In addition, if the TL a_i or TM a_p wants to terminate the contract before the contract ending time t_{ip}, they may process following two steps.

1. a_i/a_p terminates c_{ip} with a_p/a_i, and pays p_{ip} to a_p/a_i;

2. a_p is released from AT_i, and its status is modified to (0, 0, 0).

Hiring long-term teams can greatly reduce the system consumption caused by grouping and regrouping. However, most current long-term team forming strategies cannot figure out when agents should form long-term teams, which agents should be included in, and how long the relationships should be kept. For self-interested MAS applications, keeping unnecessary long-term cooperation relationships could be very dangerous and harmful for the overall performance of the system.

4 Flexible Team Forming Mechanism

From the comparison of last subsection, it can be seen that both long-term and one-shot teams have some advantages and disadvantages. One-shot teams are suitable for dynamic tasks, i.e. requirements of various new tasks are totally different. On the other side, long-term teams possess advantages when tasks are "stable" or similar. For self-interested agents, the durations of teams should not be fixed on a certain term. Take human society as an example. A company may sign different contracts (with different durations and conditions) with different employees. According to the performances of employees and statuses of the market, the company could also modify employees' contracts. For MASs, it is also necessary to have a flexible team forming mechanism, which can enable team leaders to choose different collaboration durations with agents according to the changing trend of task-requirements and agent performances. In this section, a flexible team forming mechanism is introduced. In the mechanism, valuableness and availability of agents are evaluated. Then, team leaders will find out required members and choose proper collaboration durations and cost according to the evaluation results.

4.1 Team Member Performance Evaluations

In general, agents that are always contribute on performing tasks and can bring many benefits to the team are the most valuable members of an AT. These agents should be kept into the team for a long term. In contrary, the AT should not include agents that seldom contribute for the team. In this mechanism, two factors, which are *Utilization Ratio* (ur) and *Contribution Ratio* (cr), are used to evaluate the valuableness of a TM.

Definition 7 *Utilization Ratio* ur_{Mk} ($ur_{Mk} \in [0, 1]$) is the frequency that a TM a_k has participated in the most recent M tasks of the agent team AT_i. It can be calculated by Formula 1. The value of parameter M is chosen by TLs or assigned by users. TLs can also adjust M values according to environment situations and team performances.

$$ur_{Mk} = \sum_{j=1}^{M} \frac{1}{M} \quad (j | a_k \in CS_{ij}) \tag{1}$$

Definition 8 *Contribution Ratio* cr_{Mk} ($cr_{Mk} \in [0, 1]$) is the ratio that TM a_k has contributed to the agent team AT_i in the most recent M tasks, and it can be found out by using Formula 2 (also refer to Definition 6).

$$cr_{Mk} = \frac{\sum_{j=1}^{M} mc_{ijk} \quad (\ k | a_k \in CS_{ij})}{\sum_{j=1}^{M} w_j} \tag{2}$$

The following example shows how to evaluate TMs through ur and cr. Suppose that $t_1 =< 40, R'_1 >, t2 =< 50, R'_2 >$ and $t_3 =< 60, R'_3 >$ are the most recent three tasks accomplished by agent team AT_i. a_p, a_q, a_r and a_s are TMs of AT_i. TMs that participate in the three tasks are $\{a_p, a_q\}, \{a_p, a_r\}$ and $\{a_p, a_q\}$, respectively. According to Equation 1 and 2 , it can be found that the ur and cr values of a_p, a_q, a_r and a_s are:

a_p: $ur_{3p} = 1$, $cr_{3p} = \frac{(40/2+50/2+60/3)}{(40+50+60)} = 0.5$

a_q: $ur_{3q} = 0.67$, $cr_{3q} = \frac{(40/2+60/3)}{(40+50+60)} = 0.33$

a_r: $ur_{3r} = 0.33$, $cr_{3r} = \frac{50/2}{(40+50+60)} = 0.17$

a_s: $ur_{3s} = 0$, $cr_{3p} = 0$

Comparing the ur and cr values of the four TMs of AT_i, it can be seen that a_p is the most important member of AT_i. a_p frequently participated in recent tasks and contributed the most benefit to the team. On the other hand, a_s did not participate in recent tasks and do not contribute to AT_i.

4.2 System Agent Resource Evaluations

With ur and cr, the TL can evaluate the contribution of a TM. However, to make reasonable contracts with a TM, the TL also need to evaluate whether it is easy to find similar agents (possess similar resources and skills) in the MAS. In this mechanism, *Agent Resource Availability* (ara) is the parameter defined to evaluation agent resource availability in the MAS.

Definition 9 *Agent Resource Availability* ara_k: ara_k is the ratio of available agents (do not have a team/task) that possess same or more resources than TM a_k. It can be calculated as Formula 3. In this formula, N_{av} is the available agent number of the MAS.

$$ara_k = \sum_{s_i=(0,0,0)}^{R_k \subseteq R_i} \frac{1}{N_{av}} \qquad (3)$$

For example, suppose that a_k is a TM of AT_i. Currently, there are ten out of twenty available agents in the MAS possess same or more resources than a_k. Hence, the *ara* value of a_k is: $ara_k = 0.5$.

4.3 Flexible Member Selection by Using Fuzzy Rules

According to the value of the three evaluation parameters introduced in last subsection, in this mechanism, TLs use a fuzzy method to determine collaboration durations and cost with their TMs.

4.3.1 Input and Output Parameters

In the fuzzy method, *ur*, *cr* and *ara* are input parameters. The output parameters are *Contract Term ct* and *Commission Amount ca*. They are defined in Definition 10 and 11, respectively.

Definition 10 *Contract Term* ct_k is the parameter to denote the duration that the AT should keep agent a_k. It is an output parameter that needs to be identified through the fuzzy method. The working range of *Contract Term* is in $[0, MAXTERM]$. MAXTERM is a constant defined in the MAS. It denotes the maximum term that an agent can be kept in an AT.

Definition 11 *Commission Amount* ca_k is the parameter to denote the maximum commission that the AT should pay to agent a_k in order to keep it in the team. It is an output parameter that needs to be identified through the fuzzy method. The working range of *Commission Amount* is in $[0, MAXPAY]$.

MAXPAY is a parameter decided by TLs. It denotes the maximum payment that an AT can afford to keep a single agent as a TM.

4.3.2 Membership Functions for Input Parameters

For *ur*, four linguistic states are selected and expressed by appropriate fuzzy sets. They are *Never* (N), *Seldom* (S), *Medium* (M) and *Frequent* (F). The other input parameter *cr* also has four linguistic states, which are *None* (N), *Little* (L), *Medium* (M) and *Huge* (H). The trapezoidal [3] fuzzy membership function is adopted here to define fuzzy memberships of these five fuzzy sets. The membership functions are defined from Formulae 4 to 7, respectively. They are also depicted in Figure 2.

$$F_{Never}(x)/F_{None}(x) = \begin{cases} 1 - 5x & x \in [0, 0.2] \\ 0 & x \notin [0, 0.2] \end{cases} \tag{4}$$

$$F_{Seldom}(x)/F_{Little}(x) = \begin{cases} \min(1, 10x - 1, 4 - 10x) & x \in [0.1, 0.4] \\ 0 & x \notin [0.1, 0.4] \end{cases} \tag{5}$$

$$F_{Medium}(x) = \begin{cases} \min(1, 10x - 3, 7 - 10x) & x \in [0.3, 0.7] \\ 0 & x \notin [0.3, 0.7] \end{cases} \tag{6}$$

$$F_{Frequent}(x)/F_{Huge}(x) = \begin{cases} \min(1, 10x - 6) & x \in [0.6, 1] \\ 0 & x \notin [0.6, 1] \end{cases} \tag{7}$$

For *ara*, three linguistic states are selected, which are *Rare* (R), *Some* (S), *Many* (M). The membership functions for *ara* are defined from Formulae 8 to 10 and Figure 3.

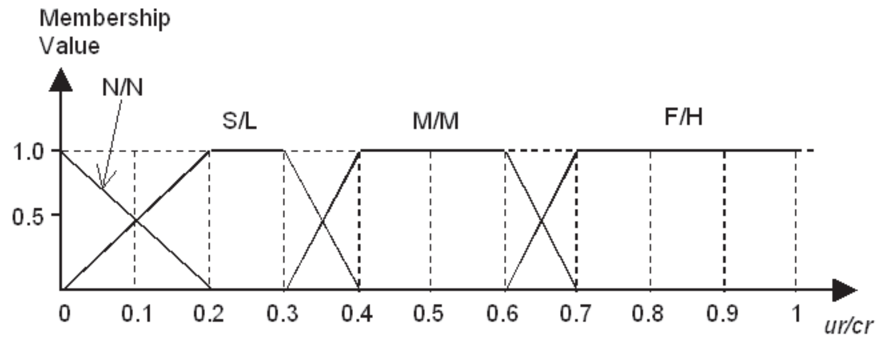

Figure 2: Fuzzy Membership Functions for *ur/cr*

$$F_{Rare}(x) = \begin{cases} 1 - 4x & x \in [0, 0.4] \\ 0 & x \notin [0, 0.4] \end{cases} \tag{8}$$

$$F_{Some}(x) = \begin{cases} \min(5x - 1, 3 - 5x) & x \in [0.2, 0.6] \\ 0 & x \notin [0.2, 0.6] \end{cases} \tag{9}$$

$$F_{Many}(x) = \begin{cases} \min(1, 5x - 2) & x \in [0.4, 1] \\ 0 & x \notin [0.4, 1] \end{cases} \tag{10}$$

4.3.3 Membership Functions for Output Parameters

There are two output parameters,which are *Contract Term* (ct) and Commission Level (cl) in the fuzzy method. For ct, four linguistic states are selected, which are *Long* (L), *Medium* (M), *Short* (S) and *No* (N). For cl, *High* (H), *Medium* (M), *Low* (L) and *No* (N) are chosen as linguistic states. Fuzzy membership functions of above fuzzy sets are defined from Formulae 11 to 14 and described in Figure 4.

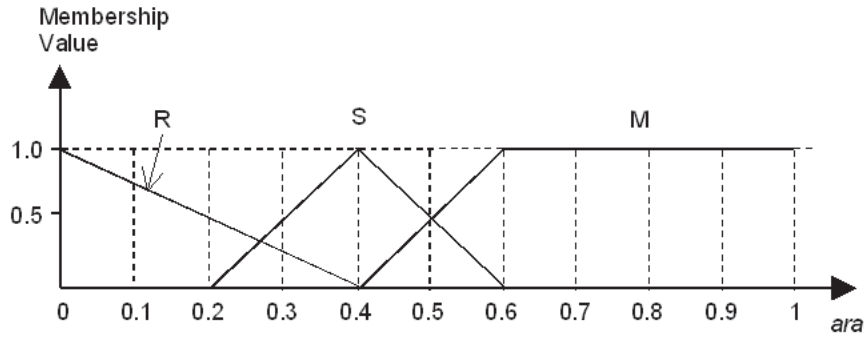

Figure 3: Fuzzy Membership Functions for *ara*

$$F_{No}(x) = \begin{cases} 1 - 10x & x \in [0, 0.1] \\ 0 & x \notin [0, 0.1] \end{cases} \tag{11}$$

$$F_{Short}(x)/F_{Low}(x) = \begin{cases} \min(1, 10x, 4 - 10x) & x \in [0, 0.4] \\ 0 & x \notin [0, 0.4] \end{cases} \tag{12}$$

$$F_{Medium}(x) = \begin{cases} \min(1, 10x - 3, 7 - 10x) & x \in [0.3, 0.7] \\ 0 & x \notin [0.3, 0.7] \end{cases} \tag{13}$$

$$F_{Long}(x)/F_{High}(x) = \begin{cases} \min(1, 10x - 6) & x \in [0.6, 1] \\ 0 & x \notin [0.6, 1] \end{cases} \tag{14}$$

4.3.4 Fuzzy Rule Base

A fuzzy rule base is a matrix of combinations of each of the input linguistic parameters and their corresponding output parameters. The rule base in this mechanism is as Table 2.

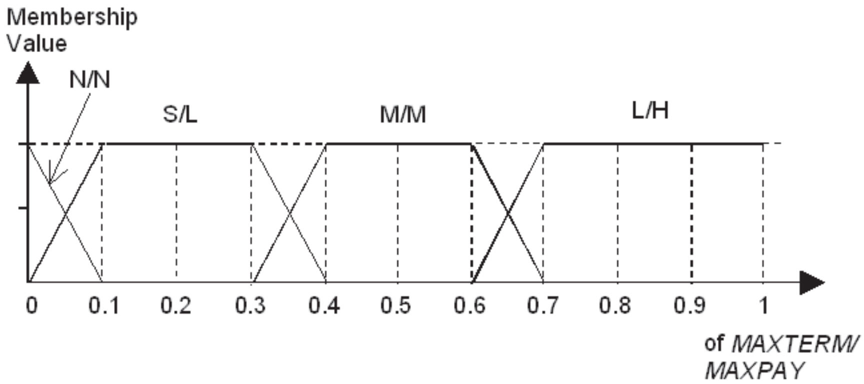

Figure 4: Fuzzy Membership Functions for ct/cl

Table 2: Fuzzy Rule Base Matrix

ara	**R**				**S**				**M**			
$ur\backslash cr$	**N**	**L**	**M**	**H**	**N**	**L**	**M**	**H**	**N**	**L**	**M**	**H**
N	N,N	M,L			N,N	N,N			N,N	N,N		
S	M,L	L,L	L,L	L,M	N,N	S,L	M,M	S,M	N,N	N,N	S,M	N,M
M		L,M	L,M	L,H		M,L	M,M	L,M		S,L	M,L	M,M
F		L,M	L,H	L,H		M,M	L,M	L,H		L,L	L,L	L,M

4.3.5 Determination of Output Membership Values and Defuzzification

Each entry of the rule base is a rule, which is defined by *ANDing* two linguistic input parameters to produce an output combination, in the form of: *IF(F(ur)=*α AND *F(cr)=*β AND *F(ara)=*γ) THEN *(F(ct)=*δ) AND *F(cl)* = η), where $\alpha \in \{Never, Seldom, Medium, Frequent\}$, $\beta \in \{None, Little, Medium, Large\}$, $\gamma \in \{Rare, Some, Many\}$, $\delta \in \{Long, Medium, Short, No\}$, and $\eta \in \{$*High, Medium, Low, No*$\}$. In this mechanism, AND (min) operator [5] is used to combine the membership values together . Hence, the output membership value $\mu_{\delta/\eta}(v)$ can be calculated by Formula 15.

$$\mu_{\delta/\eta}(v) = MIN(\mu_{\alpha}(ur), \mu_{\beta}(cr), \mu_{\gamma}(ara)) \tag{15}$$

With the output membership, the output values can be determined by tracing the membership values for each rule back trough the output membership functions. Finally, *centroid defuzzification* method [5] is hired to find out the output value. In *centroid defuzzification*, the output value is calculated by Formula 16, where $\mu(v_i)$ is the i^{th} output value, v_i is its corresponding output value, and k is the number of fuzzy rules which are activated.

$$DF = \frac{\sum_{i=1}^{k}(v_i \cdot \mu(v_i))}{\sum_{i=1}^{k}\mu(v_i)} \tag{16}$$

5 Experiments

To analyse the performance of the flexible team forming mechanism, some experiments are executed to compare it with one-shot and long-term team forming. In this section, experiment results are presented to compare one-shot team forming mechanism, long-term team forming mechanism and flexible team forming

Table 3: *a1* and *a2* in the Experiment

ID	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8	r_9	r_{10}
a1	0	1	0	0	0	0	0	0	0	0
a2	0	0	1	0	0	0	0	0	0	0

mechanism.

5.1 Experiment Setup

To simulate the scenario introduced in Section 2, the experiment environment is described as follows:

5.1.1 Agents:

In the experiments, ten kinds of resources (i.e. r_1, r_2, ..., r_{10}) are defined to be possessed by agents. Each agent possesses one or more than one kind(s) of resources (out of the ten kinds of resources). For example, Table 3 shows two agents in the experiment, i.e. *a1* and *a2*. *a1* and *a2* possesses resource r_2 and r_3, respectively.

The intentions of agents are to earn as much as possible award through accomplishing tasks of users. Agents need to contribute their resources to accomplish tasks.

5.1.2 Tasks:

Tasks in the experiments are composed according to Definition 1. Each task has a reward and a set of required resources. For example, Table 4 shows two sample tasks, i.e. *t1* and *t2*. The reward of *t1* is w=40. To accomplish *t1*, an agent team needs to (at least) possess resource r_1, r_2, r_3 and r_7. The reward of *t2* is w=60. To accomplish *t2*, an agent team needs to (at least) possess resource r_3 ,r_4, r_7, r_8, r_9 and r_{10}.

Table 4: Sample Tasks

ID	r'_1	r'_2	r'_3	r'_4	r'_5	r'_6	r'_7	r'_8	r'_9	r'_{10}	**Reward**
t1	1	1	1	0	0	0	1	0	0	0	40
t2	0	0	1	1	0	0	1	1	1	1	60

In the experiments, tasks are recorded in a *Task File*. Agents receive incoming tasks from the user through reading *Task Files*. Then, agents execute these tasks by using three different team forming mechanisms, i.e. (1) the one-shot team forming mechanism, (2) the long-term team forming mechanism, and (3) the flexible team forming mechanism, respectively.

5.2 Experiment Executions and Results

To evaluate the flexible team forming mechanism, two sets of experiments are executed. These two experiments compare the performances of the three team forming mechanisms in two scenarios: (1) let fixed agents process unfixed tasks; (2) let unfixed agents process a set of fixed tasks.

5.2.1 Experiment One:

In Experiment One, ten agents (a_1, a_2, ..., a_{10}) are included in the MAS. These agents possess one of the ten resources (r_1, r_2, ..., r_{10}), respectively. Various numbers of tasks are input to the MAS. The agents form teams and execute tasks by using the three team forming mechanisms, respectively. Through this experiment, we want to compare the performance of the three team forming mechanisms toward different numbers of tasks.

In Experiment One, there are two output parameters, which are used to compare the effectiveness and rationality of the three team forming mechanisms. These two parameters are *Agent Searching Times* (AST) and *Agent Earned*

Reward (*AER*):

- *AST* is the times that a team leader needs to search for required agents to accomplish the tasks. In general, the higher *AST*, the more communication cost the team leader needs to spend on searching agents.

- *AER* is the total reward that each individual agent earned. In Experiment One, *AER* is used to evaluate the rationality of an agent team organisation. It is because that the possessed resources of different agents are different. In such a situation, a one-shot team has an ideal organisation because all its team members contribute to task executions and there is no resource redundancy in the MAS. Hence, in Experiment One, *Agent Earned Rewards* (*AERs*) of one-shot team members are considered as the benchmark of team organisation rationality. Agent teams that have closer *AERs* with one-shot teams are considered as more rational.

The results of Experiment One are shown in Figure 5 and Table 5. Figure 5 compares the Agent-Searching Times (*ASTs*) of the three mechanisms. From this figure, it can be seen that the flexible team forming mechanism always has the least *AST*. On the contrary, the *AST* of one-shot team forming is much higher than both long-term and flexible team forming. In addition, as the number of tasks increases, the *AST* of the one-short team forming mechanism increases much faster then the other two mechanisms. This result shows that the communication consumption in the one-shot team forming mechanism is the highest. This is because that agent teams in the one-shot team forming mechanism are disbanded when each task is accomplished, and then, the team leader needs to regroup a new team for the new task. On the contrary, the long-term team forming mechanism and the flexible team forming mechanism keep the whole team or part of a team after each task is accomplished. Hence, they can have less communication consumptions.

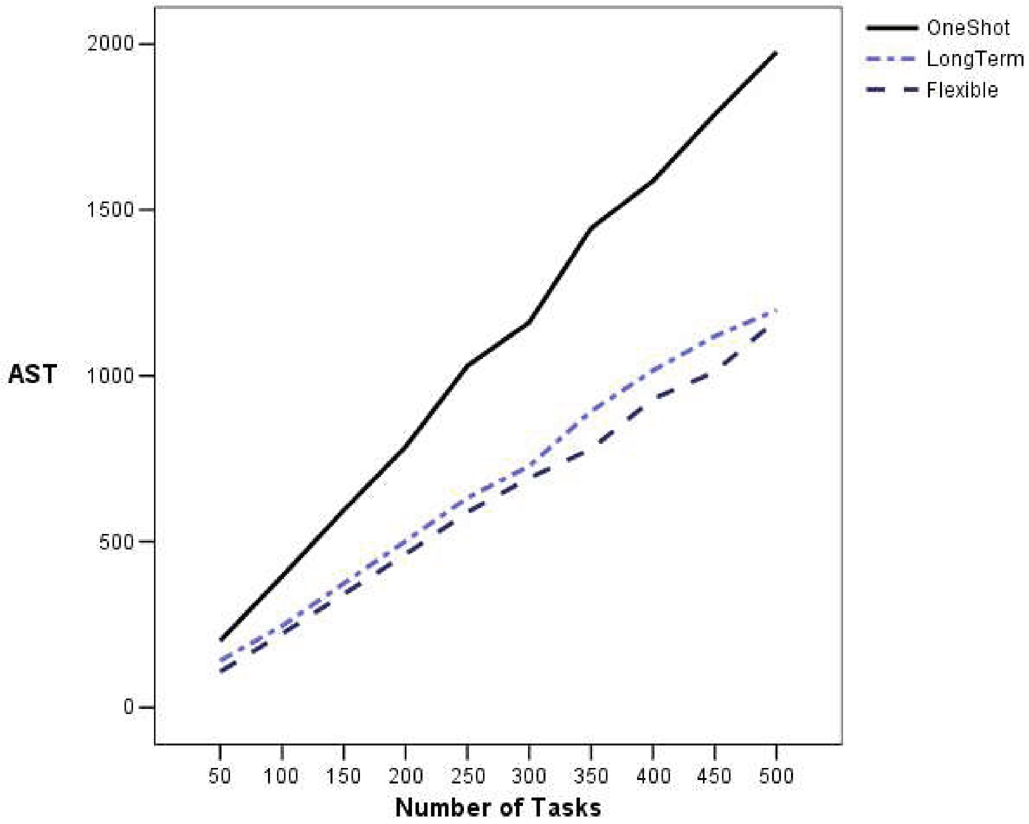

Figure 5: Agent Searching Times Comparison

The *AERs* of the three mechanisms are listed in Table 5. From the data in Table 5, it can be seen that the *AERs* of flexible teams are closer to the *AERs* of one-shot teams in most situations. Hence, the flexible teams have more reasonable organisational structure than that of long-term teams.

5.2.2 Experiment Two:

In Experiment Two, agents are included in the MAS to process a set of tasks that contain five tasks. The resource requirement and the task reward of the five tasks are shown in Table 6. In Experiment Two, we firstly let ten agents (a_1, a_2, ..., a_{10}), which are same as agents in Experiment One, to process the five tasks by using the three team forming mechanisms. Then, we include more agents that possess the same resource with a_1 to the MAS, and let agents of the MAS to reprocess the same task set by using the three team-forming mechanisms.

Reward Rate (*RR*) is the output parameter of Experiment Two. The *RR* of an agent represents the reward that the agent has received in participating each task. The *RR* of an agent a_k can be calculated by using Formula 17, where AER_k is the total reward that a_k has received, CS_{ij} is the *Contributor Set* of each task (refer to Definition 5), M is the size of a task set.

$$RR_k = \frac{AER_k}{\sum_{j=1}^{M} 1 \quad (j|a_k \in CS_{ij})} \tag{17}$$

The result of Experiment Two is shown in Figure 6. This figure shows the difference of the three team forming mechanisms as duplicated agents (agents with the same resource as a_1) are added in the MAS. In the one-shot teams and the long-term teams, the *RR* of a_1 does not change after more agents with the same resource as a_1 are added in the MAS. a_1's *RR* in long-term teams is lower than a_1's *RR* in one-shot teams. It is because that long-term teams may keep "unnecessary" team members. By using the flexible team forming mechanism,

Table 5: The List of Agent Earned Rewards

Agent	Mechanism	Number of Tasks									
		50	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
a1	**Flexible**	220	422	772	1171	1277	1565	1832	1992	2171	2513
	OneShot	220	430	770	1040	1290	1550	1830	2060	2170	2550
	LongTerm	237	443	738	990	1178	1534	1870	1964	2158	2484
a2	**Flexible**	228	505	661	1016	1304	1486	2069	2119	2205	2563
	OneShot	230	520	670	1050	1330	1530	1860	2120	2210	2590
	LongTerm	244	497	700	990	1297	1436	1768	2201	2165	2557
a3	**Flexible**	256	481	776	809	1350	1488	1797	1928	2497	2385
	OneShot	260	490	780	820	1390	1530	1840	1890	2260	2430
	LongTerm	288	452	802	925	1312	1641	1873	1866	2105	2342
a4	**Flexible**	248	456	855	1064	1429	1453	1875	1773	2376	2301
	OneShot	260	440	730	1080	1230	1470	1920	1810	2480	2330
	LongTerm	254	504	728	1182	1253	1494	1985	1846	2436	2273
a5	**Flexible**	255	409	642	1069	1238	1449	1751	1999	2307	2354
	OneShot	250	410	670	1070	1270	1500	1770	2050	2390	2410
	LongTerm	283	477	684	1012	1254	1486	1784	2122	2361	2497
a6	**Flexible**	287	533	813	947	1161	1424	1584	1865	2089	2354
	OneShot	260	550	830	960	1170	1450	1620	1930	2100	2260
	LongTerm	219	571	888	1009	1313	1473	1756	1905	2210	2268
a7	**Flexible**	241	526	670	1019	1269	1617	1831	1985	2346	2617
	OneShot	240	530	680	1030	1280	1320	1830	2010	1280	2700
	LongTerm	246	511	663	1042	1351	1430	1834	1907	2487	2612
a8	**Flexible**	231	580	782	905	1289	1262	1707	1965	2332	2411
	OneShot	240	510	820	910	1310	1330	1720	2010	2360	2500
	LongTerm	254	480	836	939	1381	1313	1610	1958	2477	2625
a9	**Flexible**	309	503	743	970	1327	1312	1919	2102	2174	2561
	OneShot	320	520	760	1010	1340	1330	1960	2130	2210	2620
	LongTerm	263	518	743	922	1358	1389	1803	2095	2124	2685
a10	**Flexible**	226	537	737	889	1157	1555	1585	1842	2162	2326
	OneShot	230	550	740	890	1190	1600	1600	1860	2230	2370
	LongTerm	238	499	656	950	1105	1416	1666	1905	2138	2540

Table 6: The Five Tasks in Experiment Two

ID	r'_1	r'_2	r'_3	r'_4	r'_5	r'_6	r'_7	r'_8	r'_9	r'_{10}	**Reward**
t1	1	1	1	0	1	0	1	0	0	0	50
t2	1	0	1	1	0	0	1	1	1	1	70
t3	0	1	1	0	1	0	1	0	0	1	50
t4	1	0	1	0	1	0	0	0	0	1	40
t5	0	1	1	0	1	0	1	1	1	0	60

the RR of a_1 decreases as more agents (with the same resource as a_1) are added in the MAS. This denotes that the flexible team forming mechanism will adjust agents' rewards as the agent resources changes. Therefore, the result of Experiment Two shows that the flexible team forming mechanism is more suitable for open environment than the other two mechanisms.

From the results of the Experiment One and Experiment Two, it can be seen that the flexible team forming mechanism is more suitable for self-interested agents and open environments. It can enable agent teams to keep valuable team members according to their performance and changing of environments. Furthermore, agent teams can adjust their long-term member selection standards through modifying the member evaluation parameters. Therefore, comparing with one-shot and long-term team forming, the flexible team forming mechanism can enable self-interested agents form more rational teams in open environments with less communication consumptions.

6 Related Work

Team forming is an important issue in MAS research. It is a subbranch of agent coordination and organisation. In [8], Horling and Lesser reviewed most important agent organisations in current MAS applications. Characteristics of different organisations are evaluated in that paper. They also introduced *agent*

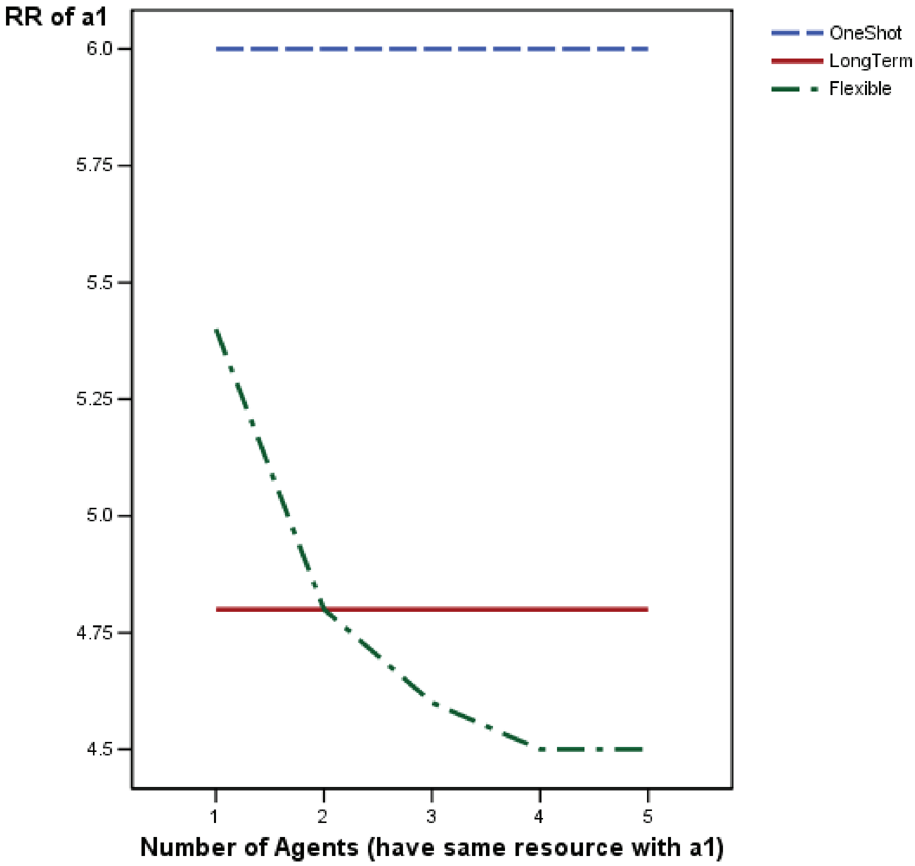

Figure 6: Reward Rates Comparison

team as a kind of typical multi-agent organisations, and pointed out that team organisations have increased communication consumptions as a main drawback.

Communication consumptions and computational complexities of several classic team forming and coordination strategies [9] [16] [25] were evaluated by Pynadath through using the COMmunicative Multiagent Team Decision Problem (COM-MTDP) model [15]. COM-MTDP borrowed *economic team theory* [12] [27] and provided a generic framework that evaluates team forming and coordination strategies. Through the evaluation results obtained by Pynadath, it is obvious that dynamics of joint goals, domain constrains and task requirements would greatly increase communications within a team.

Gaston evaluated multi-agent organisational performance by using social network theories [6]. Through several experiments, Gaston demonstrated that MAS organisational performance were impacted by the underlying social network structure.

A common feature of Pynadath and Gaston's methods is that they all cited sociologic theories. Especially in recent years, more and more MAS researchers realised the benefit of citing human organisational theories into multi-agent team forming. Market-base approaches, such as auction [20], voting [13] and contract nets [26], have been applied in many MAS applications. These approaches are especially suitable for self-interested MASs. However, in most current market-based approaches, the collaboration terms between agents are normally short (even one-shot). This feature could aggravate communication consumption problems. Toward shortcomings of market-based approaches, Rathod proposed a stable team forming strategy for self-interested agents [18]. This idea is also cited from human society. Rathod also suggested to adopt different team strategies in different working domains or situations. However, how to select and automatically refresh different team strategies were not introduced in Rathod's paper.

Comparing with above related researches, the mechanism presented in this paper focuses on features of self-interested agents and tasks. In the mechanism, agent and environment evaluations are included in team forming processes. Collaboration terms between agents are based on these evaluation results. The flexible team forming mechanism can reduce communication consumptions and avoid unreasonable collaboration relationships in agent teams. These advantages have been approved in the experiments of Section 5. From the experiment result, it can be seen that the mechanism presented in this paper has lower communication cost than one-shot team forming, but the rationality of team organisations is closer to optimal.

7 Conclusions and Future Work

As a social entity, self-interested agents need to collaborate with others in most multi-agent environments. Unreasonable team forming mechanisms could cause benefit conflicts between agents, or lead to unnecessary system consumptions. Focused on challenges brought by dynamic application domains, many AI researchers suggested hiring long-term or one-shot team forming mechanisms in MASs. However, both of these two kinds of mechanisms had advantages and disadvantages. Focused on features of self-interested multi-agent systems, advantages and disadvantages of one-shot and long-term team forming mechanisms were evaluated in this paper. Furthermore, a flexible team-forming mechanism was introduced. This mechanism could enable agents to automatically evaluate the performance of other agents in the system, and to select team members with reasonable terms and costs according to the evaluation result. In the flexible team forming mechanism, factors related with agent performance and task requirements were considered as evaluation factors. Through evaluating these factors, team compositions were more reasonable and could avoid some potential benefit conflicts between team members.

In the future work of this research, more factors will be taken into account through related evaluations. Also, the agent organisations discussed in this paper are in very simple team structures. However, in many MAS applications, more complex organisation structures, such as congregation [3], could be included in MASs. In addition, another trend of this research is to hire reputation based methods [14] and social network analysis techniques [19] in team forming mechanisms.

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