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Enhancing Coalition Formation in Multi-Agent Systems When Agents Plan Their activities

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Abstract. In a multiagent system, coalition formation is a coordination method for agents aiming to form groups of interest. In this paper, we focus on the particular context where agents are self-interested and plan their activities. We develop a new coalition formation model that uses the plans of the agents to guide the search for the coalitions and analyzes the coalition proposals already suggested by other agents in order to derive their preferences. This eases the negotiation for the coalitions. We analyse and develop the constraints that should be enforced on self-interested agents in order to form suitable coalitions which guarantee significant solution concepts. In addition, we detail in this paper our coalition formation mechanism, we experiment and evaluate it.

Keywords. Multiagent Systems, coalition formation, plans

Introduction

This paper addresses the coalition formation problem in multi-agent systems. It focuses mainly on self-interested agents operating in a system where the agents cannot reach their objectives individually. However by putting their resources together, a group of agents will be able to perform a set of tasks which no agent of the group can perform by itself.

In such a context, autonomous agents have to find partners with which they will share the achievement of the bundles of tasks they want to perform, i.e. bundles which have high ranks in their preference orders [1,4]. In order to do so, agents need means of coordination. This article focuses on coalition formation, a coordination mechanism which allows agents to form groups of interest to achieve conjointly tasks, which could not have been performed individually.

Our approach uses the plans of the agents to coordinate their actions and form suitable coalitions. In most coalition formation methods, when negotiating their coalitions the agents focus mainly on the immediate tasks to be executed, in order to decide which

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coalitions to form. Agents relegate the negotiations of the coalitions for their subsequent tasks to later stages of the coordination process.

This paper deals with this issue and proposes a new coalition formation model which is based on two principles:

1) It uses the plans of the agents to guide the search for the coalitions to be formed. We show the significance of not only taking into account the immediate actions of the agents in the coalition formation process and introduce new concepts, one of which is the *action desirability*.

2) It analyzes the coalition proposals already suggested by other agents in order to derive their intentions and thus facilitate the negotiations for the coalitions.

Action-relationship analysis can improve coalition search. In particular, the existence of action relationships (e.g. dependencies between actions) raises dependencies between the plans of the agents which perform them. When these dependencies exist, it is preferable that agents identify them early, since such knowledge can favor coalitions and promote compromise.

This article is structured as follows. Section 1 presents the problem; Section 2 presents the solution concepts of our model; Section 3 describes the coalition formation process; Section 4 presents the experimental evaluation, the results and their analysis; Section 5 describes a related work and lastly Section 6 provides a conclusion.

1. Problem Formulation

This section defines the coalition formation problem and describes the example used to illustrate our model. Consider a set of agents $\mathcal{N} = \{a_1, a_2, ..., a_n\}$, a set of plans $\pi = \{p_1, p_2, ..., p_{n'}\}$ containing a set of actions $\mathscr{A} = \{b_1, b_2, ..., b_m\}$. The agents in \mathcal{N} need to execute the plans in π . Actions in \mathscr{A} can be combined into sets of actions, which can be negotiated.

The negotiation for coalition formation between agents is performed without any central truthful algorithm or external decision-maker. Each agent makes its own decisions locally with respect to its preferences.

To give an illustrative example, let us consider a carpooling problem, where users want to move from one city to another and want to share their means of transportation. Each user formulates to its agent its goals to be achieved, for example, "*I want to go from New York to Boston*" and its constraints, its budget, for instance. The user also gives to this agent its preferences, for instance, "*I do not want to share a car with smokers*". To solve this problem, the agents have to deal with all the constraints and preferences of their users in order to enable them to share transportation. Since these agents may be designed by different designers, they have to negotiate the formation of their coalitions. In this context, a coalition will be formed by a set of agents for their users so that they can share a car. Consequently, forming coalitions can lead to a decrease in the unit price of seat, increase the number of the passengers, punctuality, etc.

2. Solution Concepts

Let us begin by recalling some important definitions we use in our coalition formation mechanism.

2.1. Definitions and Notations

Definition 1 A coalition C is a nonempty subset of \mathcal{N} , i.e. $C \subseteq \mathcal{N}$.

Definition 2 A coalition structure CS is a partition of \mathcal{N} , i.e. a set of coalitions $\{C_1, C_2, \dots, C_k\}$ verifying that:

- $\forall l \in [1,k], C_l \subseteq \mathcal{N}.$ $\forall (i,j) \in [1,k]^2, i \neq j, C_i \cap C_j = \emptyset.$
- $\bigcup_{l=1}^{k} C_l = \mathcal{N}.$

We denote u_i as the utility function of agent a_i . This function induces a preference order \succeq_i on coalitions of CS_i : a_i prefers a coalition structure CS to CS' if and only if $u_i(CS) \ge u_i(CS')$, denoted by $CS \succeq_i CS'$. We denote $u_i(CS) = u_i(CS')$ by $CS \sim_i CS'$ and $u_i(CS) > u_i(CS')$ by $CS \succ_i CS'$.

The set of all coalition structures is denoted \mathscr{S} .

Note that a coalition structure is acceptable for agent a_i if it is preferred over, or equivalent to, the reference structure RS, which corresponds to the minimal guaranteed gain of the agent during the negotiation. That is $u_{CS} \ge u_{RS}$.

In order for the agents to know whether they should accept a coalition structure as a solution, they need to be able to compare it with their minimal guaranteed gain during the negotiation. This minimum is the reference state. If there are already formed coalitions, the reference is the current coalitional state.

As mentioned above, the proposed model takes plans as a source of information for the search for the coalitions. Using the same approach in [6], we can represent the plan of an agent as a directed acyclic AND/OR graph.

Definition 3 A directed acyclic AND/OR graph is a graph where nodes are connected by means of AND/OR edges.

A node m which is connected to k nodes $(m_1, ..., m_k)$ by means of AND edges represents an action after which all the actions $(b_{m1},...,b_{mk})$ need to be executed to validate the plan. However, if a node m is connected to k nodes $(m_1,...,m_k)$ by means of OR edges, it suffices that at least one of the actions $(b_{m1}, ..., b_{mk})$ be performed after the execution of the action b_m . Our approach is based on models that use the standard planning algorithm using an accessible and deterministic environment [6,8].

2.2. Plan Analysis

In our model, we use the notion of *action desirability* defined below to allow agents to decide which coalitions will be formed. Each agent computes the desirability of each action that it cannot execute alone and classifies them in descending order. Then, computes the order of the coalitions to be formed. In this section, we describe what are the information derived from the plans of the agents to compute the *desirability*.

2.2.1. The desirability computation

The desirability of an action can be computed at any time using the absolute desirability of this action and the *children-relative desirability*. Before defining the desirability of an action, let us first introduce the concept of *absolute desirability* and *children-relative desirability*. We assume that the plans of the agents are represented as a directed acyclic graphs.

The absolute desirability (AD) of an action is defined without taking into account the current plans of the agents. It is given a priori by the system designer and can be determined according to a number of parameters:

- Agents capable of performing the action: an action that cannot be done by many agents will have a high degree of *desirability*, because the agents are self interested.
- Resources required for the execution of the action: the set of required resources can also be used to determine the *absolute desirability* of the action.
- Semantic information: the system designer can use domain dependent on knowledge to determine the *desirability* of the action since, depending on the field of application, some actions could be more important than others.

Before introducing the concept of *children-relative desirability*, let us introduce the *set of children actions*.

The set of children actions of an action b in a plan p (denoted by Children(b, p)) is the set of actions which are directly connected to b in plan p.

Definition 4 The children-relative desirability (CRD) of an action b in plan p estimates the aggregation of the desirability degrees of the children of b in p. The children-relative desirability is obtained using the AND aggregation function if the action is connected to its children by means of AND edges or the OR aggregation function if it is connected by OR edges.

The parameters of these two functions are the relative desirabilities of the children of the action.

Let AND be the edge type connecting b to its children, and l be the number of children c_q of b in p. Then, the children-relative desirability of b in p, CRD(b,p), is formally defined by the equation:

$$CRD(b,p) = \sum_{q=1}^{l} D(c_q), \forall (c_q, p)$$
(1)

However, since OR edges represent alternatives, it is not expected that all the children actions will be executed. Thus, the *children-relative desirability* of b in p is given by the equation:

$$CRD(b,p) = 1/l \sum_{q=1}^{l} D(c_q), \forall (c_q, p)$$

$$\tag{2}$$

The *children-relative desirability* of an action without children, called a terminal action, is equal to zero. Finally, the *desirability*, *D*, of an action belonging to the plan of an agent reflects the importance of the action with respect to the others of the system. We propose to calculate the desirability, the use of an exponentially decreasing function taking into account the expected time that the action will start to be executed. If we do not consider the time when the actions will start to be executed in the desirability

Action	b_3	b_7	b_8
AD	2	7	3
CRD	0	$5 \times e^{-3}$	0
t	3	2	3
D	$2 \times e^{-3}$	$(7+5\times e^{-3})\times e^{-2}$	$3 \times e^{-3}$

Table 1. Desirability of actions of a_1

computation, one terminal action which is located far from the root in the agents' graph (and possibly having a very late start time) has an equal impact on the final desirability of the root as another action with the same absolute desirability and nearer to the root. It is given by the equation:

$$D(b,p) = \frac{AD(b,p) + CRD(b,p)}{e^{t(b)}}$$
(3)

Where t: is the estimated starting time of the action b. It is computed using a topological sorting in the graph (top-down) considering the elapsed times of the antecedents and siblings' actions [5].

Example 5 Let $\mathcal{N} = \{a_1, a_2, a_3\}$ a set of agents. Each agent of \mathcal{N} has respectively its own plan p_1, p_2 and p_3 . Each plan has a set of actions $p_1 : \{b_3, b_7, b_8\}, p_2 : \{b_1, b_2, b_4, b_6\}$ and $p_3 : \{b_5, b_9, b_{10}, b_{11}\}$.

Let us show how the agent a_1 computes the desirabilities of its actions. Consider that b_7 is connected to the terminal actions b_3 and b_8 with an AND edge. The desirabilities of the actions are computed using equation 3. The CRD is given by equation 1. (cf. Table 1).

3. Coalition Formation Process

The coalition formation process we propose is based on two steps: coalition search and negotiation. In this process we assume that the agents evolve in a system where each agent can perceive the plans of the others, so the concept of *desirability* described previously will be used to derive the preferences of the agents.

3.1. Negotiation

We present in this section a simple protocol we have proposed for the agents in order to negotiate their coalitions. The protocol consists of three phases: initialization of the negotiation, negotiation itself, and transmission of the solution.

1. Initialization of the negotiation and transfer of the actions. The initiator agent a_i informs agents a_j that it is beginning a new negotiation. Each agent a_i asks the other agents a_j to send their actions, and then deduces the set of actions to be performed. a_i selects the coalition structures it wants to propose and gathers these structures in groups. Agent a_i sends coalition formation proposals to the solicited agents a_j .

2. The negotiation. Each solicited agent a_j answers with an acceptance if it is interested in the coalition structure or with a withdrawal if it is not. An agent a_j accepts a coalition structure if the utility it offers is at least equivalent to that of its reference structure.

Let \mathcal{P}_i be the sorted set of coalition structures of \mathcal{S}_i proposed by agent a_i during the process of coalition formation, with an order relation \triangleleft_i such as:

 $\forall (CS_1, CS_2) \in \mathscr{P}_i^2$, $CS_1 \triangleleft_i CS_2$ means that CS_1 is proposed before CS_2 , by a_i . Each agent a_i proposes its proposals following these conditions:

• $\forall CS \in \mathscr{P}_i, CS \in \mathscr{S}_i$, i.e. a_i belongs to the coalition structure that it proposes.

• $\forall (CS_1, CS_2) \in \mathscr{P}_i^2$, $CS_1 \triangleleft_i CS_2 \Rightarrow CS_1 \succeq_i CS_2$ and $CS_1 \neq CS_2$, i.e. the utility of coalitions of \mathscr{P}_i is decreasing following the order \triangleleft_i and a coalition structure is only proposed once.

• $\forall CS \in \mathscr{P}_i, CS \succ_i \{a_i\}$, i.e., each proposed coalition structure is preferred to the reference structure.

• All coalition structures are proposed, following the preference order of the agent derived from its plans.

Once the agent a_i has sent its coalition structures to its preferred agents, it waits for their answers. It possibly receives new coalition structure proposals that a_i will use to update its coalition structures or generate new structures as shown in section 3.2 until a solution is reached or the negotiation fails.

3. Transmission of the solution. Once the last solicited agent has identified an acceptable coalition structure CS' which is approved by all its agents, this agent sends this coalition structure to its initiator agent. This initiator validates CS' and sends it to all its members, which they will accept as the solution for their negotiation and whose utility verifies: $u_i(CS') \ge u_i(RS)$.

3.2. Coalition Search

In the light of its plan, each agent a_i decides on actions it cannot perform alone and computes the *desirability* degree of each of them. In order to form appropriate coalitions, each agent a_i first ranks its actions in decreasing order of *desirability*. Then, the agent a_i can build its own proposals of coalition structures using its own preferences. Once agent a_i has computed the *action desirability* (equation 3), it builds bundles of actions which it sets in partitions using an algorithm for building actions combinations. Agent a_i starts with the action having the highest degree of *desirability*, let us say b_1 , for which it creates the first partition. This partition includes all the action combinations containing b_1 . Then a_i continues to build the following partitions.

Example 6 Let us assume now that the agents have a set of actions $\{b_1, b_2, ..., b_{16}\}$ to be performed in their plans, and that the preferences of a_1 are: $b_7 \succ_1 b_8 \succ_1 b_3$. Agent a_1 will build three partitions $P_{b_7}, P_{b_8}, P_{b_3}$ (respectively for b_7, b_8, b_3), affects in each of its partitions, the action combinations it has generated, and obtains the following results (cf. Figure 1).

However, when a_i receives coalition structure proposals from other agents a_j with $j \neq i$ it should take into account the intentions revealed by these agents in the structures it builds in order to facilitate concessions in the coalition formation process. The generation of these structures is done by a_i based on the preferred actions of the agents a_j . To



Figure 1. Partitions of agent a_1

compute the a_j preferences for these actions, a_i analyzes the coalition structures a_j sent. The preference of a_j for an action b results from the priority and the frequency of b in groups of coalition structures that a_j has sent.

In our mechanism, agents propose their coalition structures with the same utility in a single group of coalition structures.

The priority of an action b, $B_k(b)$, is defined with respect to the group k of coalition structures to which b belongs. It is equal 1, when the action belongs to the first group, 2 when it belongs to the second group etc. As for the frequency of b in a group k, $f_k(b)$, it depends on the number of occurrences of b in the coalition structures of this group. Thus, the preference of a_j for b, denoted $\Delta(b)$, is the ratio between its frequency and its priority:

$$\Delta(b) = \sum_{k \ge 1} f_k(b) / B_k(b) \tag{4}$$

This function induces a preference order \succeq_i on actions. a_i prefers an action b to b'if and only if $\Delta(b) \ge \Delta(b')$, denoted by $b \succeq_i b'$. We denote $\Delta(b) > \Delta(b')$ by $b \succ_i b'$ and $\Delta(b) = \Delta(b')$ by $b \sim_i b'$. When agent a_i receives coalition structures from another agent a_j , these structures may contain combinations of actions not appearing in a_i 's partitions. If a_i is interested in these combinations, it adds them to its partitions. a_i selects only the preferred actions of a_j that might be accepted. The combinations already constructed by a_i are denoted CS_{01}, CS_{02}, \dots

Example 7 (continued) Let us assume now that a_1 receives from a_2 these coalition structures:

 $\begin{array}{l} CS_{21}:(\{a_2,a_1\},\{b_1,b_2,b_3\});(\{a_2,a_3,a_4\},\{b_4,b_5\});(\{a_2,a_4\},\{b_6\})\\ CS_{22}:(\{a_2,a_1\},\{b_3,b_6\});(\{a_2,a_3,a_4\},\{b_2,b_4,b_5\})\\ CS_{23}:(\{a_2,a_3\},\{b_1,b_2\});(\{a_2,a_3,a_1\},\{b_4,b_8\})\\ CS_{24}:(\{a_3,a_1\},\{b_5,b_3\});(\{a_3,a_1,a_4\},\{b_{13},b_8\});(\{a_2,a_3\},\{b_{10},b_2\}) \end{array}$

For instance, CS_{21} is the first coalition structure sent by a_2 to a_1 . In CS_{21} , agent a_2 proposes to a_1 to form a first coalition to carry out the actions b_1, b_2 and b_3 . Both agents a_2 and a_4 will carry out action b_6 and agents a_2, a_3 and a_4 will carry out actions b_4 and b_5 . a_1 computes the preference values of agent $a_2, \Delta_{a_1}^{a_2}$, using the function Δ for each action of a_2 , in order to derive its preferred actions. a_1 obtains $b_1 \succ b_2 \succ b_2 \succ b_4 \succ b_6$.

As a result a_1 updates its previous partitions with the preferred combinations of a_2 which are also desirable for a_1 , and obtains the following new partitions (cf. Figure 2).

Partition P_{b_7} is unchanged since a_2 has not proposed any combination containing action b_7 . To partition P_{b_3} , agent a_1 has added the combination $\{b_1, b_2, b_3\}$ rather than $\{b_3, b_6\}$ due to the preference of agent a_2 for this combination, which resulted from $\Delta_{a_1}^{a_2}$.



Figure 2. Updated partitions of agent a_1

Based on the updated partitions, a_1 builds its new coalition structures that it will propose to the other agents in the following iterations.

This strategy of a_i can be repeated either: (1) individually and for all agents a_j with which a_i interacts, or (2) only for the agents that a_i prefers, or (3) by combining in the same partitions, combinations of actions of all agents a_j with $j \neq i$. This knowledge is very useful for agent a_i to deduce the structures that agents a_j prefer to form, and to accelerate the convergence of the coalition formation process. Moreover, and when needed, agent a_i merges the combinations of actions to form new combinations.

4. EXPERIMENTAL STUDY

4.1. Experimental Settings

We have developed on the platform JADE a multi-agent system that meets the constraints of the context described in the previous section. Agents are developed to perform sets of actions organized in their plans. These are represented by interfaces that implement a set of classes using AND/OR graphs and a set of methods such as computing the *desirability* of each action. To evaluate the proposed protocol, we analyzed its performances observing several parameters: the number of exchanged messages, the size of these messages (the number of coalition structures they contain), the number of coalition structures that have been evaluated and the time of negotiations. Each measure is a mean of 50 different simulations started with the same parameters.

4.2. Experimental Results

4.2.1. Negotiation Time

Firstly, our experimentations have been performed on a system with 100 agents. Each agent a_i implements a random utility function. A strategy based on a *desirability* function to propose their coalition structures and a random probabilistic strategy which consist on sending the coalition structures based on a fixed probability. 100 plans were analyzed with 4 actions to be achieved in each one.

We notice in Figure 3 that the obtained negotiation time in milliseconds with a number of agents between 10 and 100 is growing, due to the number of proposals that agents calculate and exchange for both strategies. However, the search time is acceptable even when the number of agents increases. We notice also that the negotiations runtime by using the probabilistic strategy is larger compared to that based on the *desirability* function, because this strategy allows each agent to send their coalitions sequentially following a preference order, which requires sending a large number of proposals.



Figure 3. Negotiations runtime

4.2.2. Number of proposals submitted and evaluated

In this experimentation, we test the number of proposals submitted and evaluated by the agents.



Figure 4. Number of proposals submitted

Figure 4 shows the number of proposals submitted by agents. We notice that the number of proposals is much larger using the probabilistic strategy. The number of messages sent when using this strategy increases dynamically, due to the incompatibility of the preferences of the agents.

Figure 5 shows the number of proposals evaluated by the agents using the two strategies. We observe that the number of structures evaluated using the strategy based on *desirability* function is smaller compared to the probabilistic function. By analyzing the actions, agents reduce the number of coalitions that will be considered.

4.2.3. Utility ratio obtained by the agents

The following experiments were performed on a system of 20 agents, 15 plans and at least 6 actions in each plan. For a selection set of parameters, 20 experiments are per-



Figure 5. Number of proposals evaluated

formed with an initialization of the utility functions. We have considered the utility obtained by each agent. We are not interested in the exact value of utility obtained, but we compute the relative value of the utility between the minimal guarantee utility u(RS) and the maximal possible utility u(max). We use the ratio r(u), given in equation 5. The value of r(u) varies from r(u(RS)) = 0 to r(u(max)) = 1.

$$r_i(u) = \frac{u_i(CS) - u_i(RS)}{u_i(max) - u_i(RS)}$$
(5)



Figure 6. Utility ratio obtained by the agents

In Figure 6, we observe the utility ratio obtained by agents. We observe that the average utility decreases using the proposed random probabilistic strategy, when the number of proposals sent by the agents decreases. We observe a very good stability of the ratio for the strategy based on a *desirability* function, and decreased only when very low values of proposals are submitted. In general, both strategies behave similarly.

5. Related work

The coalition formation problem has been studied in different contexts. Firstly, it is studied from a static and theoretical perspective in cooperative game theory [10], in which a coalition is defined as a set of agents where each coalition has a valuation which depends on its members. Cooperative game theory focuses on formalizing different solution concepts and does not deal with algorithmic or behavior issues for software agents [11]. \tilde{A} \tilde{A} in a cooperative context, Shehory and Kraus [12] propose a negotiation mechanism to distribute the computation of the coalition values in order to search for the optimal coalition structure. Rahwan et al. [9] propose another algorithm to decrease communication complexity and computation redundancy. Kraus and Shehory [7] present protocols and strategies for coalition formation with incomplete information under time constraints. They focus on strategies for coalition members to distribute revenues among themselves for the request for proposal domain (RFP). Tohmé et al. [13] focus on analyzing the dynamic process of coalition formation by explicitly modeling the costs of communication and deliberation. They have defined an algorithm for sequential action choice when each agent greedily maximizes its stepwise given its beliefs. Although these models have addressed important issues, they only deal with agents' immediate tasks and not with their future tasks. This paper tackles this problem and proposes a model based on the plans of the agents. Brafman et al.[2] introduce a planning games which is a study of interactions of agents in automated planning settings. They extend STRIPS-like models of single-agent planning to systems of multiple self-interested agents. The key point is that each agent in planning games can in principle influence the utility of the other agents resulting in global inter-agent dependency within the system. They define classes of strategic games and solution concepts that capture the context of multi-agent planning. This model provides a rich class of structured games that capture forms of interactions between the agents. However, they do not use the actions of each agent plan to derive what coalitions will be formed and do not deal with the negotiation of such coalitions. In the coalition-planning games, they consider that each agent has its own goals. To achieve its goal, an agent may either need, or just find it cost-efficient, to be assisted by some other agents. They provide computational results by exploiting the structure of a graph called agent-interaction graph in their model. This graph captures the global topology of the direct dependencies between the agents' capabilities. In the same context, Brafman et al.[3] consider the model of planning games with transferable utilities (TU). They have connected the idea of planning games and the classical model of TU coalition games. However, they do not deal with the coalition formation mechanism itself. As a solution concept, they focus on the classical concept of the core.

6. Conclusion

In this paper, we have presented a coalition formation model for self-interested agents. This model uses the plans of the agents and allows them to analyze the coalition proposals already suggested by other agents in order to derive their intentions.

First, we have introduced the concept of *desirability*, in this model, and then we have shown how the *desirability* can be computed using the different plans of the agents involved in the coalition formation process. In this model, we have used the directed

acyclic graphs to represent the plans and show how the *desirability* can be computed. The *desirability* of an action allows agents to decide which coalitions should be first formed and deals with the dependencies between the actions of the agents.

Then, we have detailed our model and explained how an agent analyzes the intentions of the other agents during the negotiation to obtain an acceptable solution.

Finally we have implemented and tested on a multi-agent system the proposed strategy and have compared it to a probabilistic strategy, then we have analyzed the obtained results. We concluded that the strategy based on the *desirability* function allows agents to reduce the number of proposals for the formation of the coalitions while keeping a good utility, which speeds up the process considerably.

In future work, we intend to address several issues, for instance, we intend to model preferences of agents with a more sophisticated formalism like k-additive utility function and adapt our algorithm. One should study additional models for representing the coalition structures when the agents have only a partial view of other agents plans and finally introduce the notion of the dynamic plans in the proposed model and on logical constraints on the coalition structures.

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