

A Social Reasoning Mechanism Based on a New Approach for Coalition Formation

Luís Morgado
Graça Gaspar

DI-FCUL

TR-00-1

March 2000

Departamento de Informática
Faculdade de Ciências da Universidade de Lisboa
Campo Grande, 1700 Lisboa
Portugal

Technical reports are available at <http://www.di.fc.ul.pt/biblioteca/tech-reports>.
The files are stored in PDF, with the report number as filename. Alternatively,
reports are available by post from the above address.

A Social Reasoning Mechanism Based on a New Approach for Coalition Formation

Luís Morgado^{1,2}
lm@isel.pt

Graça Gaspar²
gg@di.fc.ul.pt

¹Instituto Superior de Engenharia de Lisboa, DEEC, Lisboa, Portugal

²Faculdade de Ciências da Universidade de Lisboa, Lisboa, Portugal

Abstract – In order to enable an agent to co-ordinate its activities with other agents and to participate in coalitions, one of the elements to take into account in its conception should be a social reasoning mechanism that allows the agent to reason about the other agents. This paper presents a social reasoning mechanism that extends, in some aspects, the models presented in previous works. Such a model supports the agent’s reasoning concerning other agents, using notions of social dependence. In order to deal with concrete situations, where the agent’s knowledge is limited, a new perspective of coalition formation is presented in which the agents may not have knowledge of all the relevant details to realize their goals. The main concepts underlying the proposed social reasoning mechanism are presented, followed by an overview of the respective formal model, and some aspects related to the implementation of a system based on this model.

Keywords: coalition formation, coalition selection, coordination, distributed artificial intelligence, multi-agent systems, social reasoning.

1. INTRODUCTION

In a society of heterogeneous agents, with different goals and capacities, the agents may not be autonomous to reach some of their goals, that is, they may be unable to carry out some of the necessary activities. To achieve a goal for which it is not autonomous, an agent needs to delegate the accomplishment of activities to other agents of the society. In turn, in a general situation, it cannot be assumed that the agents are benevolent, that is, that they accept to carry out activities for other agents without some counterpart. Therefore, how can an agent obtain that another agent accepts the realization of an activity for its interest or the interest of both?

The theory of dependence [3][4][5] tries to answer this question, and it has been the direction followed by some previous works like those presented in [6][13]. In [13] Sichman presents a social reasoning mechanism based on the theory of dependence leading to a dynamic conception of agent societies. This means that coalitions are formed in a dynamic way whenever the necessity of coordination, to achieve some goal, is identified. However, this has some limitations, which render difficult its use for the resolution of concrete problems, typically of large complexity.

The social reasoning model presented in this paper addresses some of these limitations, being able to be used in societies of agents with different types of organization, and in concrete problems, where the complexity level is typically large, needing therefore an analysis at different levels of abstraction, as proposed in our approach.

In the following, we will present a model of social reasoning that enforces a local perspective of coalition formation, leading to the emergence of nested coalitions. We also discuss several issues related to the implementation of this model, as it is realized in the CADS system. Besides referring the agents’ architecture, communication language and interaction protocol, we also focus other aspects relevant to the operationalization of the model, such as activity scheduling and concurrent access to resources. These two aspects, albeit not being basic for the elaboration of an agent architecture based on the presented model, are of great relevance for the implementation of concrete systems, in order to allow dealing with the time constraints associated with the activities of a plan and with the sharing of resources.

2. MODELS OF SOCIAL REASONING

The models of social reasoning, from which our work derives, draw upon the theory of dependence. According to this theory, dependence and power relations between the agents are the basis to explain how agents interact in order to cooperate and accept to help others.

In [13] Sichman presents a social reasoning model where an agent is able to reason about the other agents to identify the respective dependence situations. For that, an agent uses information about the goals, actions, resources and plans of each agent, which is stored in a data structure called *external description*.

The dependence situations are classified according to two criteria. One criterion depends on the goal being analyzed [12][13]:

- *unilateral*: an agent ag_i infer that it depends on another agent ag_j for a goal g_k , but ag_j does not depend on ag_i ;
- *mutual*: an agent ag_i and an agent ag_j infer that they depend on each other for the same goal g_k ;
- *reciprocal*: an agent ag_i infers that it depends on another agent ag_j for a goal g_k , and the agent ag_j depends on ag_i for another goal g_l , different from g_k .

The other criterion depends on the sets of plans used in the reasoning process:

- *locally believed*: if an agent uses exclusively its own plans when inferring the dependence situations;
- *mutually believed*: if an agent uses its plans and those of the other agent when inferring the dependence situations.

Based on the resulting taxonomy of dependence situations defined, a decision criterion is proposed to choose the most appropriate partners to contact in order to help the agent achieve the goals for which it is not autonomous [11][13].

Another model that uses notions based on dependence relations among the agents is presented by E. Alonso in [1][2]. In this model the agents first recognize how they depend on each other and then negotiate by exchanging offers to reach an agreement where social interlocking commitments are adopted. However the negotiation is a bilateral process not supporting the formation of multipartner coalitions.

Despite the interest of the approaches presented in these works, there are several issues that can be deepened, namely:

- the problem of coalitions formation and selection – how to select the agents to contact in each coalition and how to choose the best coalition to achieve the intended goals;
- the problem of agents’ limitations, either in knowledge or in reasoning – an agent may not know the characteristics of all the agents of the society, and if it knows, the reasoning concerning all that information may not be feasible;
- the problem of reducing the communication effort – to establish a coalition an agent needs to communicate with other agents, this communication effort increases considerably as the number of involved agents increases, therefore it is important to reduce this effort to allow the implementation of concrete systems based on communication channels with limited capacity.

The work of Sichman [13] has been further extended by David [6] to incorporate the notion of *action dependence networks*, based on *and* and *or* dependencies such as multiparty, multigoal, multiaction, alternative plan and alternative partner dependencies. The extensions proposed by David [6][7] present interesting aspects, namely, by proposing new criteria for selecting partners and by supporting multipartner coalitions. However, some aspects of the three problems previously referred remain present, as will be seen later.

In the following sections we will discuss these issues and present a social reasoning model that contributes to address them, as well as other problems related namely to the implementation of real systems. In section 6 is presented one implementation of our model, the CADS system, which supported the simulation in which the

example presented in section 7 is based. This example illustrates the ability and versatility of the proposed model for use in real distributed problem solving activities, within open and dynamic multi-agent system environments.

3. SOCIAL REASONING AND COALITION FORMATION

Let us consider an agent ag_1 and its goal o_1 , for which ag_1 has a plan that involves the accomplishment of the activities a_1, a_2, a_3 . What should ag_1 do, for example, if it doesn't have the capacity to accomplish any of those activities? In that case, the agent will have to delegate to other agents of the society the accomplishment of those activities.

In the social reasoning mechanism proposed by Sichman [13] the agent would try to establish bilateral commitments for each of the activities, just as depicted in figure 1.

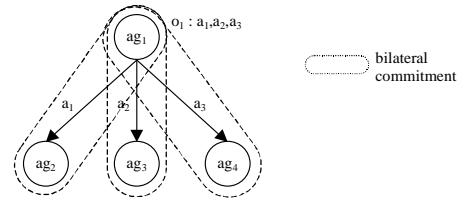


Fig. 1: Delegation of activities through bilateral commitments.

However, this approach has some problems, namely:

- the existence of a coalition of several agents, as a whole, is not explicitly represented, since the focus is on the establishment of bilateral commitments. In this way it is not possible to ponder the global interest of a coalition in order to allow the definition of criteria for coalitions selection, instead of selecting individual partners;
- in the case that the delegation of one of the activities fails after the establishment of commitments for delegation of other connected activities, a way of dealing with the commitments already assumed is not defined.

Another subject that is necessary to take into account has to do with the scope of the agent's social reasoning. Let us consider an agent ag_1 and its goal o_1 , for which this agent has a plan that involves the accomplishment of the activities a_1, a_2, a_3 , being autonomous for a_1 and a_3 and not autonomous for a_2 . Let us consider that another agent ag_2 has the capacity to accomplish a_2 , but to achieve a_2 it needs to accomplish two other activities $a_{2.1}$ and $a_{2.2}$, for which it is not autonomous. In this case a_2 is an activity that cannot be delegated for direct execution, because its accomplishment implies the accomplishment of other

(sub)activities that, in turn, must be delegated. Figure 2 illustrates this situation.

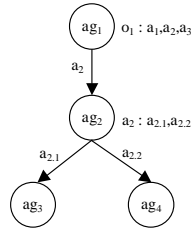


Fig. 2: Indirect delegation of activities.

In a situation like this one, the agent ag_1 would have to reason not only about agent ag_2 , but also about agents ag_3 and ag_4 , and about the dependence situation of ag_2 in relation to ag_3 and ag_4 , and, possibly, in relation to other agents of the society. A reasoning of this type produces an undesirable effect, which is the combinatory complexity of the computation [13]. In this kind of situation an agent must answer two questions:

- Is there any coalition that allows reaching the intended goal?
- in the case of an affirmative answer to the previous question, which agents to contact for the formation of the coalition?

In [8] it is demonstrated that the answer to any one of these questions is a NP-complete problem that, in the general case, cannot be answered in practical terms.

To deal with this problem in the social reasoning model presented by Sichman [13], an agent reasons about its dependence in relation to another agent, but doesn't have the capacity to reason about the dependence situation of this other agent in relation to a third one. On the other hand, the actions are always considered as "atomic" actions, directly executable. Therefore the agent's plans must be completely detailed. The reasoning process uses these completely detailed plans to globally and directly reason about all the other agents of the society.

In spite of this approach limiting the problem of the computational complexity, it also limits the potential for coalition formation in a society. That is, there may exist goals for which an agent is incapable to infer the existence of a successful coalition, despite the fact that there may be agents in the society with the necessary capacities.

4. PROPOSED MODEL

The proposed model is based on a perspective distinct from the previous ones, in which the achievement of a goal may result in a chain of several nested coalitions.

An agent, when reasoning about the other agents to establish a coalition, can adopt two different perspectives:

- a *global perspective*, which corresponds to a reasoning about all the dependence relationships among the agents that can participate in the coalition (including those involved in delegations that are not direct);
- a *local perspective*, in which the agent doesn't know all the details related to the accomplishment of the intended goal, nor does it have knowledge about all the agents of the society.

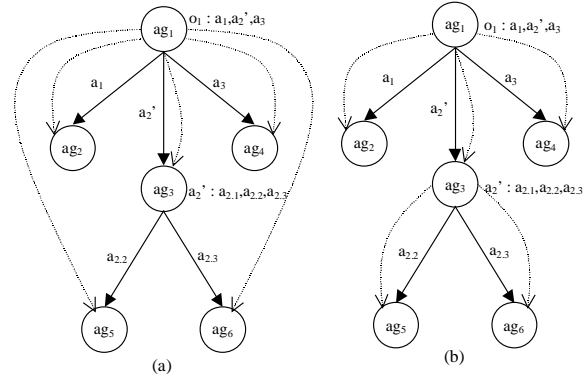


Fig. 3: Different perspectives of coalition formation: (a) global; (b) local.

With an approach based on a local perspective, the achievement of a goal for which an agent is not autonomous may originate, not only one coalition, but a group of nested coalitions that, if succeeded, will have as result the achievement of the initial goal, as exemplified in figure 4.

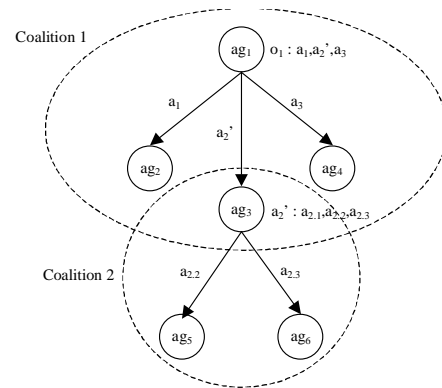


Fig. 4: Nested coalitions.

When adopting a local perspective the computational complexity underlying the social reasoning mechanism is bounded, without limiting the potential of coalitions formation in a society of agents.

Another important aspect of the approach presented in this paper is related to the organization of agent societies. For instance in [6] David proposes an organization based on groups (or agencies), as depicted in figure 5.

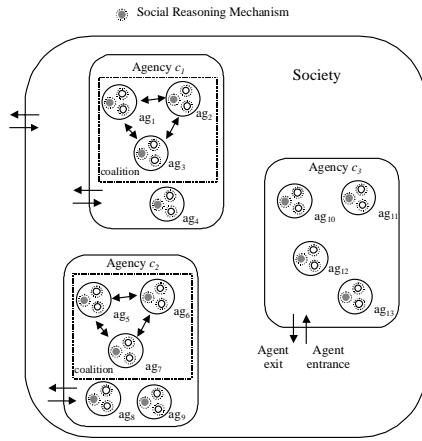


Fig. 5: Society as a group of agencies [6].

When an agent enters the society, it selects one of the groups to join. When joining a group the agent starts by knowing the agent's capacities of that group and, therefore, takes advantage of those capacities to reach its goals. However, the agent knows nothing about the agents of other groups. In order to resolve this problem in [6] it is proposed that an agent can belong, simultaneously, to more than one group. However, when belonging to several groups, the agent needs to know, and therefore communicate with, all the agents of those groups, giving away the potential benefits of organizing a society in groups.

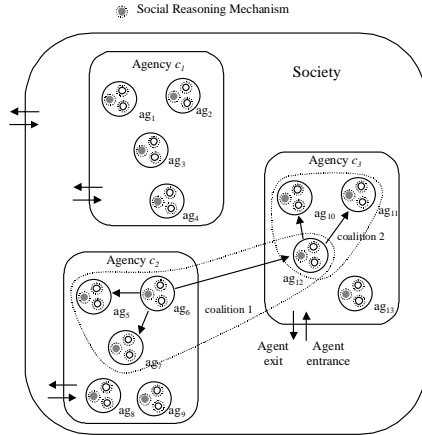


Fig. 6: Nested coalitions involving different agencies.

With our approach an agent doesn't need to know all the agents in a group to take advantage of the capacities of that group. For instance one group may have one or several representatives of the capacities of the group. In this way an agent can join a group and have knowledge of potential capacities of other groups, without needing to join all the groups and to know all the agents in each group. An agent can even establish coalitions involving agents of different groups, without having knowledge about all the agents in the involved groups, just as presented in figure 6. Thus, the coalition formation approach now proposed, by adopting a local perspective,

where the analysis of the accomplishment of the activities can be made at different levels of detail, allows a great versatility in the process of coalitions establishment, namely, supporting the formation of nested coalitions. In this way the agents do not need to have detailed knowledge about the way the involved activities are ultimately accomplished. This approach makes possible the use of a social reasoning mechanism, based on the agents' complementarity, to deal with concrete problems, with diverse organization characteristics.

It is now possible to address the three problems previously referred:

- *coalition formation and selection*: in the proposed model the coalition notion is represented in a explicit way, therefore can be referred to as a whole either in the coalition selection process or in the negotiation process;
- *agents' limitations*: by supporting the formation of nested coalitions an agent does not need to have knowledge of all the agents needed to accomplish the intended goals nor the details of all the activities involved, and does not need to reason about all the agents involved. This is achieved without limiting the potential of coalition formation in a society of agents.
- *reducing the communication effort*: by using a local scope in the social reasoning process an agent does not need to know all the agents necessary to achieve its goals, so the number of agents it needs to contact to establish a coalition is greatly reduced, therefore minimizing the communication effort.

5. COALITION FORMATION

The proposed coalition formation process involves three main elements:

- the existence of a *representation of the agents' characteristics* that supports the underlying aspects of this approach;
- a *social reasoning mechanism* that, based in the adopted representation, allows the agents to elaborate coalition hypotheses, and to choose the most interesting among those several hypotheses;
- an *interaction mechanism* among agents, that supports the establishment of coalitions.

Representation of the agents' characteristics

To reason about the others an agent needs to know their characteristics and must represent this information internally. In [13] Sichman defined formally and implemented the concept of *external description* which stores believed information about the others. This information is represented as a structure that holds for

every agent, including itself, one entry composed of the following elements [12]:

- *goals*: the goals an agent wants to achieve;
- *actions*: the actions an agent is able to perform;
- *resources*: the resources an agent has control upon;
- *plans*: the plans an agent has, using actions and resources, in order to achieve a certain goal.

In this representation the actions are considered “atomic” and directly executable, leading to plans that detail all actions and resources necessary to reach the respective goal. However, this formulation of external description is not adequate to support our model, since it is admitted that the agent doesn’t know the exact way of accomplishment of a goal, that is, the agent doesn’t know in detail all the actions that are necessary to achieve a certain goal, which is not considered in the previous models. Therefore, it is necessary to reformulate the external description. The formulation proposed is based on three main elements to characterize an agent: *goals*, *plans* and *capacities*. Although goals and plans also exist in the previous formulations, their meaning and, essentially, their representation and manipulation is substantially different.

Capacities

Since a formulation based on the notions *action* and *resource* is not adequate to support our model, we need a concept that describes the capacities of an agent in terms of activities that it is able to perform, and the resources it controls. The proposed concept is designated *capacity*. In the context of dependence theory the definition of capacity can be made in a sense similar to *power*, restricted to the accomplishment of activities, in the following way: an agent has a capacity *c* if the agent as the power of *c*. In terms of the proposed model, capacity corresponds to a relationship among an agent and an activity that an agent is able to accomplish, either directly, in the case of primitive activities directly executable by the agent, or indirectly, in the case of non-primitive activities for which the agent has an accomplishment plan, which can imply the delegation of activities to other agents.

Goals

The approaches presented by Sichman and David [13][6] consider the goal adoption process in an instrumental perspective, that is, an agent adopts a goal of another agent since that brings it some benefit, namely, the possibility of achievement of its own goals. However, this adoption is represented in an implicit way, since the agent doesn't add explicitly the adopted goal to its external description. In our approach, this implicit representation is not enough, due to the possibility of indirect delegation. Therefore, in our model, when an agent accepts the delegation of a non-primitive activity, it

explicitly adopts the accomplishment of that activity as one of its own goals. In this way it assumes the responsibility for its accomplishment and it deals with it, as with any of its original goals, using the same reasoning mechanism to identify possible coalitions for its achievement.

Plans

The plans define strategies for action, involving the agents’ capacities, to reach the intended goals. However, in the formulations presented by Sichman and David [13][6] the process of social reasoning is based on actions and resources, and doesn’t consider the possibility to characterize the goals and the respective plans, through different levels of detail successively more refined. This possibility of successive detailing of the plans is of great importance in order to support the formation of nested coalitions for the achievement of a goal, such as proposed in the approach now presented. Therefore, the proposed plan representation is based on a hierarchical structure [10][14], where the plans are characterized by collections of activities that, in turn, can be decomposed. Having this in mind it is possible to define the plans in a hierarchical way, which correspond to strategies of activity realization in order to reach a main goal. An activity can, in turn, correspond to a plan that implies the accomplishment of several other activities. Figure 7 gives an idea of the representation proposed.

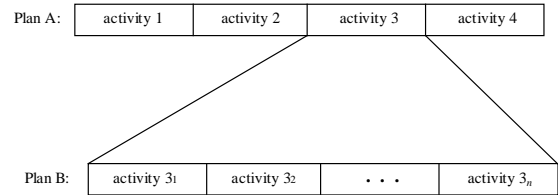


Fig. 7: Representation of plans in a hierarchical way.

Social reasoning mechanism

Once defined the representation that an agent possesses of the other agents, it is now necessary to define the mechanisms to explore that knowledge, designated, generically, by *social reasoning mechanism* [13]. The social reasoning mechanism proposed is composed by three main elements:

- *dependence analysis*: the dependence situations of an agent in relation to the other agents of the society are identified;
- *coalition formation*: based on the identified dependence situations and on the agent's plans, acceptable coalitions to reach the agent's goals are elaborated;
- *coalition ordering*: the elaborated acceptable coalitions are ordered according to defined criteria, in order to allow the agent to choose the most favorable.

Figure 8 gives an idea how these three elements are related.

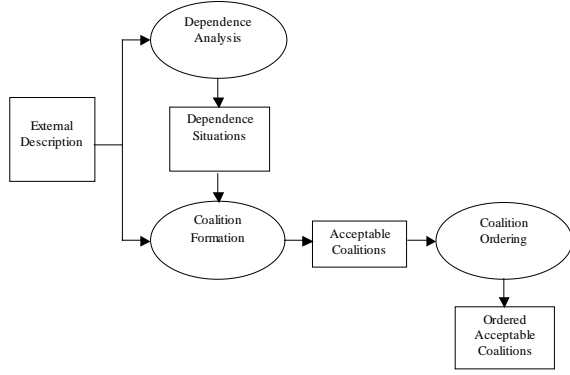


Fig. 8: Social reasoning mechanism of an agent.

The process of *dependence analysis* corresponds to the identification of dependence situations in relation to other agents, for the goals to achieve, and based on the selected plans. To make this possible it is necessary to consider two preliminary aspects: *goal selection* and *plan selection*¹.

The coalition formation is based on the information produced by the dependence analysis process, in terms of goals, plans, and dependence situations. From that, the possible coalitions, which allow reaching the intended goals, are generated. The coalitions resulting from this process are designated *acceptable coalitions*. That group of acceptable coalitions is the input for the *coalition ordering* process, in which the agent evaluate the different coalitions, and order them according to the evaluation criteria.

As a result of this whole process, the agent will have elaborated and ordered, according to an evaluation criteria, a group of coalitions that could allow the accomplishment of the agent' goals. After the completion of this process, in the negotiation phase [9], the selected coalitions will be proposed to the involved agents for their establishment.

Overview of the proposed model formal structure

Having presented an overview of our model, the formal structure of some of the concepts previously presented will now be discussed.

One of the main concepts underlying the proposed model is the *external description* concept that, as above-mentioned, characterizes an agent in terms of goals, plans and capacities. Considering the perspective of an agent ag_i the external description (EXT_{ag_i}) that it has from another agent ag_j is defined as follows².

$$EXT_{ag_i}(ag_j) \equiv_{def} \{GOAL_{ag_i}(ag_j), CAP_{ag_i}(ag_j), PLAN_{ag_i}(ag_j)\}$$

$GOAL$, CAP and $PLAN$ are sets defined as follows.

- $GOAL_{ag_i}(ag_j) \equiv_{def} \{g \mid ext_goal(ag_i, ag_j, g)\}$
- $CAP_{ag_i}(ag_j) \equiv_{def} \{a \mid ext_cap(ag_i, ag_j, a)\}$
- $PLAN_{ag_i}(ag_j) \equiv_{def} \{p \mid ext_plan(ag_i, ag_j, p)\}$

The predicates ext_goal , ext_cap and ext_plan are defined as follows.

- $ext_goal(ag_i, ag_j, g)$: succeeds if g is a goal of ag_j that ag_i knows;
- $ext_cap(ag_i, ag_j, a)$: succeeds if a is a capacity of ag_j that ag_i knows;
- $ext_plan(ag_i, ag_j, p)$: succeeds if p is a plan of ag_j that ag_i knows.

Social autonomy

An agent ag_i is autonomous for a goal g_k based on a plan p_{qk} if and only if ag_i has a goal g_k and is able to accomplish all the activities of this plan. Formally³:

$$gaut(ag_i, g_k, p_{qk}) \Leftrightarrow g_k \in GOAL(ag_i) \wedge (\forall a \in ACT(p_{qk}))(a \in CAP(ag_i))$$

An agent ag_i is autonomous for a goal g_k based on a set of plans of an agent ag_q if and only if ag_i is autonomous for, at least, one of the plans of this set. Formally:

$$GAUT(ag_i, g_k, ag_q) \Leftrightarrow (\exists p_{qk} \in PLAN(ag_q))(gaut(ag_i, g_k, p_{qk}))$$

Social Dependence

An agent ag_i is dependent on another agent ag_j for a goal g_k based on a plan p_{qk} if and only if ag_i has a goal g_k , ag_i is not autonomous for the plan p_{qk} , and the agent ag_j is able to accomplish some of the activities of this plan that ag_i cannot accomplish. Formally:

$$gdep(ag_i, ag_j, g_k, p_{qk}) \Leftrightarrow g_k \in GOAL(ag_i) \wedge \neg gaut(ag_i, g_k, p_{qk}) \wedge (\exists a \in ACT(p_{qk}))(a \notin CAP(ag_i) \wedge a \in CAP(ag_j))$$

An agent ag_i is dependent on another agent ag_j for a goal g_k based on a set of plans of an agent ag_q if and only if ag_i has a goal g_k , ag_i is not autonomous for the goal g_k based on this set of plans, and ag_i is dependent of ag_j for, at least, one of the plans of this set. Formally:

$$GDEP(ag_i, ag_j, g_k, ag_q) \Leftrightarrow \neg GAUT(ag_i, g_k, ag_q) \wedge (\exists p_{qk} \in PLAN(ag_q))(gdep(ag_i, ag_j, g_k, p_{qk}))$$

¹ Not considered in this paper.

² In this paper only an overview of the formal model is presented, a detailed description can be found in [9].

³ ACT represents the set of activities of a plan.

Delegation and coalition

When an agent doesn't have the capacity to carry out some activity to reach one of its goals, it needs to delegate this activity to another agent that might accept to collaborate with it. To facilitate the collaboration the proponent agent can offer some counterparts to the helping agent. Formally, let us consider the set Ag of all the agents of the society, and the set CAG of all the capacities of the agents of the society, defined as follows:

$$CAG \equiv_{def} \{a \mid (\exists ag_i \in Ag)(a \in CAP(ag_i))\}$$

The delegation of an activity a from an agent ag_i to another agent ag_j , offering a set of counterparts o , eventually empty (when the agent has nothing to offer), can be seen as a tuple:

$$(ag_i, ag_j, a, o) \in Ag \times Ag \times CAG \times 2^{CAG}$$

That is, two agents ag_i, ag_j collaborate to reach a goal (the agent ag_i delegates to ag_j an activity a offering as counterparts o). The counterparts are important, because it is through them that the influence power of one agent to the other is reflected. This aspect is directly related with the dependence relations existing between the agents.

Let us consider the set $deleg(ag_i, g_k, p_{qk})$ that represents all the hypotheses of delegation of activities from one plan p_{qk} , by an agent ag_i , to other agents of the society to achieve a goal g_k for which ag_i is not autonomous. Formally⁴:

$$\begin{aligned} deleg(ag_i, g_k, p_{qk}) \equiv_{def} \{ & (ag_i, ag_j, a, o) \mid \\ & gdep(ag_i, ag_j, g_k, p_{qk}) \wedge \\ & a \in ACT(p_{qk}) \wedge a \notin CAP(ag_i) \wedge a \in CAP(ag_j) \wedge \\ & (\forall o_n \in o)(o_n \in CAP(ag_i) \wedge adep(ag_j, ag_i, o_n)) \} \end{aligned}$$

That is, $deleg$ is composed by all the delegation hypotheses for which the agent ag_i is dependent on other agents, whose offered counterparts corresponds to actions that the other agents depend on ag_i .

Coalition

One coalition corresponds to a set of delegation hypotheses, therefore a subset of the set of all the coalition hypotheses, except the empty set. However, some of this sets of delegations are not (valid) coalitions, for instance if they do not consider all the activities needed to achieve the related goal, or if the same activity is delegated to more than one agent. Therefore we need to define which are the valid coalitions.

Let's consider the predicate $colig(c, ag_i, g_k, p_{qk})$ that succeeds if c is a valid coalition to reach the goal g_k using the plan p_{qk} . Formally:

$$\begin{aligned} colig(c, ag_i, g_k, p_{qk}) \Leftrightarrow & (\forall (ag_i, ag_j, a_m, o_m) \in c) \\ & (\forall (ag_i, ag_k, a_n, o_n) \in c)(ag_j \neq ag_k \rightarrow a_m \neq a_n) \wedge \\ & (\forall a \in ACT(p_{qk}))(a \in CAP(ag_i) \vee a \in activ(c)) \end{aligned}$$

In this definition $activ(c)$ represents the set of all the activities of a coalition c .

Once defined the coalition notion, it is now possible to define the set $COLIG$ of all coalitions that, in the agent ag_i perspective, allows to reach a goal g_k based on a set of plans P_{qk} . Formally:

$$COLIG(ag_i, g_k, P_{qk}) \equiv_{def} \{c \mid (\exists p_{qk} \in P_{qk})(colig(c, ag_i, g_k, p_{qk}))\}$$

Based on this set of coalitions an agent can apply a selection criterion to choose the better coalitions to reach its goals. In [9] some new selection criteria are proposed that take advantage of the coalition notion.

6. IMPLEMENTATION OF THE MODEL

The main goal of the implementation that has been made (CADS system [9]) is to allow the realization of concrete agents able to use the knowledge concerning themselves and the other agents, to reach their goals based on predefined plans of execution. In that sense, the social reasoning mechanism is one of the key elements of the agents' internal organization. However, in a broad perspective, other elements may be important, as is the case of perception, execution, and planning, among others. Therefore, a special attention was given to the modularity of the organization proposed, in order to facilitate a possible expansion or adaptation to new circumstances. The importance of the modularity is reinforced by the fact that the agents could present different types of "character", having distinct approaches to the evaluation of plans and coalitions. For instance, an agent can give more importance to the cost of executing the activities, and another agent can value preferentially the duration of the activities. Thus, it is important that specific modules can be altered, or dynamically adapted, without affecting the general operation of the system.

Planning and time

In the context of the social reasoning model presented above, the plans were characterized as collections of activities where the execution order is not relevant. However, when applied to concrete problems, the execution order is typically of great importance. The adopted representation is based on partial ordered plans. Each partial ordered plan is a tuple that consists in a set A of activities, and a set R of order constraints over these activities. Each order constraint has the form $a < b$, which means that the activity a must be concluded before the activity b can start.

⁴ $adep(ag_i, ag_j, a)$ is a predicate that succeeds if ag_i depends on ag_j for the accomplishment of the activity a .

Therefore a plan p for the achievement of a goal g_k is described as follows:

$$p \equiv_{def} (g_k, A, R)$$

For instance:

$(g_1, \{a_1, a_2, a_3\}, \{a_1 < a_2, a_1 < a_3\})$

is a plan to achieve goal g_1 , and is composed by the activities $\{a_1, a_2, a_3\}$, where a_1 must be concluded before a_2 starts, and a_1 must be concluded before a_3 starts.

In this way it is possible to define plans where a total ordering of the activities is not imposed, allowing the formation of distinct execution sequences and, therefore, the formation of distinct coalitions, from which an agent can choose the most suitable. Taking as an example the previous plan, this plan could originate two execution sequences, as schematized in figure 9.

This aspect of partial ordering of the activities has great importance if we consider the fact that the activities of a plan could be accomplished by several agents, and therefore possibly executed in parallel. Therefore, the partial ordering of the activities of a plan is fundamental to allow a larger flexibility in the accomplishment of the activities in a concurrent way.

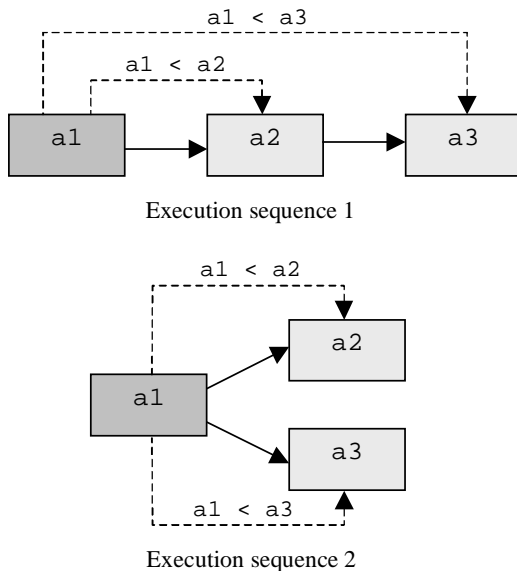


Fig. 9: Possible execution sequences of a plan.

Scheduling of activities

Another aspect of great relevance for the resolution of concrete problems is the issue of time, namely, the beginning and ending points in time of each activity involved in a plan. The presented approach is based on the use of time constraints.

The following aspects are taken into account:

- each activity has associated a certain duration;
- each agent has associated a certain time availability;
- an agent cannot perform several activities simultaneously⁵;
- activities that correspond to the management of resources have their own time availability;
- the goals can have an execution interval associated;
- the order constraints of a plan should be guaranteed.

To support these aspects, for each plan is defined a set of time constraints that should be guaranteed. Those time constraints are reflected in the beginning and ending points of each of the plan activities. In that way, the elaboration of a coalition results in the definition of the beginning and ending points for each activity to be accomplished, as well as the definition of which agent should accomplish that activity. In the coalition establishment process the activities are assigned to the agents with capacity to perform them, maintaining each agent a calendar to record the primitive activities to execute and when. In turn, the non-primitive activities are adopted as goals to reach, which should be executed in between a certain time interval. An agent, when accepting the accomplishment of a given activity, will have its time availability reduced according to the beginning and the duration of that activity, since it is assumed that an agent can't perform activities in parallel.

Agent interaction

Another aspect that an agent's architecture should consider is the capacity to communicate with the remaining agents. The communication allows the agents to exchange information and to coordinate their activities. Since the proposed type of society organization is a decentralized organization, a common memory doesn't exist, and the communication has to be supported on message exchanging mechanisms. The communication among agents is modeled as communication acts that can modify the internal state of the receiving agent, that in turn could lead to the revision of its action plans, or to modify its beliefs.

The interaction model proposed is based on the definition of a communication language among agents, where the interactions are based on message exchanging, whose sequence obeys to well defined rules, specified by a communication protocol [9].

⁵ This assumption was introduced in order to reduce the complexity of the implementation.

7. AN EXAMPLE

To exemplify how the proposed model could be applied to resolve concrete problems, we now present an overview of a simulation that has been made with the CADs system. This simulation consists of a simplification of a situation where several R&D organizations, grouped in communities, collaborate to develop projects in their interest areas. Each organization is represented by one or more agents who interact to reach the goals of the organization represented. The context defined for the simulation is the following:

Two R&D communities are considered, one with interests in the area of database systems and decision support systems, and another with interests in the area of artificial intelligence, in particular in the areas of machine learning and neural networks. The first community (Community A) is composed of two organizations, one specialized in the areas of database systems (DBS) and another specialized in the area of data warehousing (DW). The second community (Community B) represents organizations whose main area of interest is artificial intelligence, and is composed of four organizations, two of them specialized in the area of neural networks (NN), one specialized in the area of machine learning (ML), and a fourth one that acts as a representative of this community (AI).

An organization can be formed by human agents, computational agents, or by agents of both types, however, in the presented simulation context, this aspect is not relevant. In fact, a specific agent represents each of these organizations. Figure 10 illustrates the proposed context.

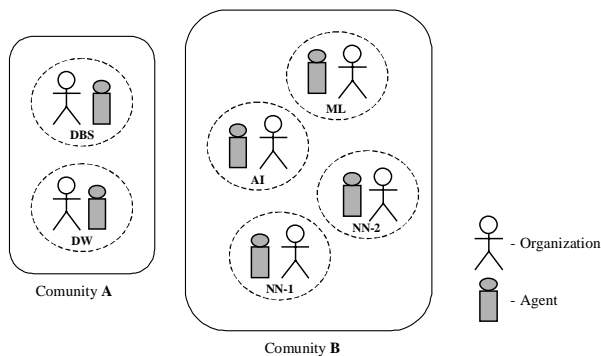


Fig. 10: Base context for the simulation.

Each agent has goals, plans, and capacities. For instance the agent representing the *DBS* organization has the following description:

Identification:	DBS
Availability:	1-1000
Goals:	DecisionSupSystem
Capacities:	DevelopOLAP(SGBD) 500 50, IntegrateDSS 200 20, Software(DBMS) 30 5 1-1000
Plans:	DecisionSupSystem Software(DBMS), DevelopDataWarehouse(SGBD), DevelopDataMining, DevelopOLAP(DBMS), IntegrateDSS 2 < 3, 2 < 4, 3 < 5, 4 < 5, OLAPSystem Software(DBMS), DevelopOLAP (DBMS)

Fig. 11: Description of agent DBS.

Each agent, after being activated, establishes communication with the other agents of the society to obtain the information needed to reason about the different hypotheses of achievement of its goals. When an agent has this information, it can identify its dependence situations in relation to the other agents of the society. To understand this process, let us consider agent's *DBS* perspective to achieve the goal *DecisionSupSystem*. We must note that, in the context of the proposed system, the societies of agents are dynamic, so the agents can enter and leave at any instant. Therefore, initially agent *DBS* tries to contact with agents representing the other communities, as is the case of agent *AI* which represents the community **B**. In the case of community **A** there is no representative, so agent *DBS* must contact all community's elements, in this case just agent *DW*.

In this situation, taking into account the agents' characteristics, each of the agents infers the dependence situations represented in figure 12.

After the several coalition hypotheses have been identified and ordered, it is then possible to begin the negotiation process in order to establish one coalition that allows agent *DBS* to reach the intended goal. As a result of this process a first coalition is established (figure 13).

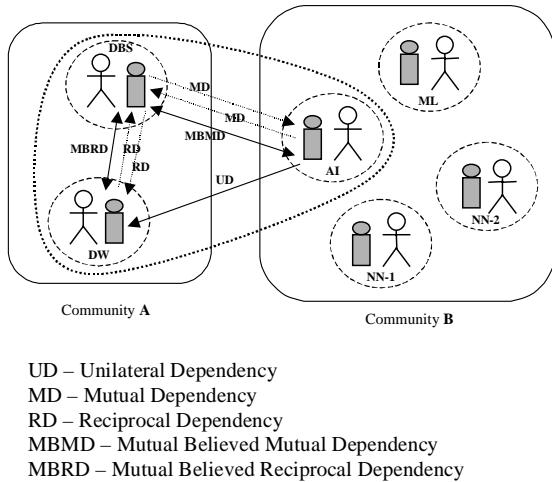


Fig. 12: Identified dependence situations.

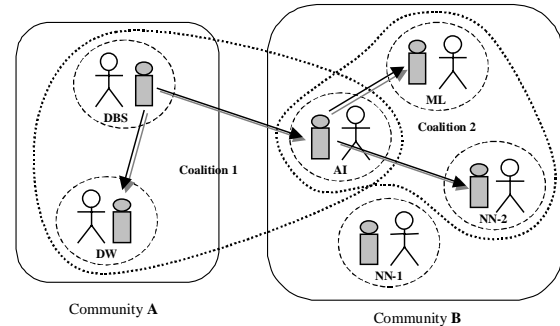


Fig. 15: Nested coalitions.

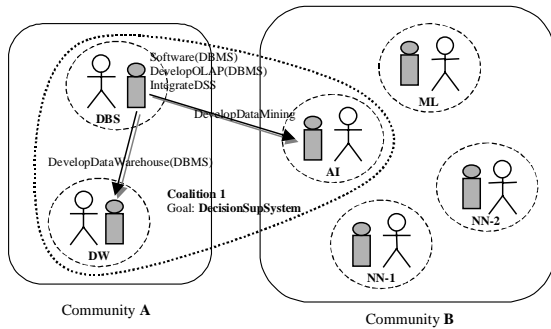


Fig. 13: First coalition established.

In this coalition, agent *DBS* chose to delegate the activity *DevelopDataWarehouse* to agent *DW* and to delegate the activity *DevelopDataMining* to agent *AI*, executing itself the other activities of the plan⁶.

When the coalition is established, agent *AI* verifies that the activity *DevelopDataMining* is a non-primitive activity, adopting it as one of its goals. Therefore, agent *AI* will try to establish a coalition to reach that goal. The result is the establishment of a second coalition, as presented in figure 14.

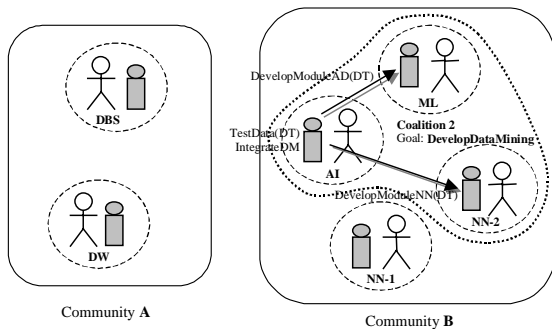


Fig. 14: Second coalition established.

The global result of the simulation is the establishment of two nested coalitions that allow reaching the *DBS* organization's goal, of developing a decision support system. The two nested coalitions are presented in figure 15.

In spite of the relative simplicity of the presented example, it shows some important characteristics of the implemented system. We can see how the agents, interacting in a spontaneous and dynamic way, form and establish coalitions to reach their individual goals, taking advantage of the complementarity existing among them, as proposed in the theory of dependence, which is the base for the proposed social reasoning model. It is also possible to observe how the proposed model supports the formation of nested coalitions, allowing to reach goals in a gradual and dynamic way, without the need of a previous detailed definition of how to reach them. Furthermore the *DBS* agent doesn't need to contact all the agents of community *B*, substantially reducing the communication effort associated to the whole process of coalition establishment.

8. CONCLUSIONS AND FURTHER WORK

In this paper a model of social reasoning was presented, that extends in some aspects previous models. In that model a local perspective of coalition formation is adopted, in which an agent doesn't need to have knowledge of all the details necessary to reach its goals. To achieve that, a new definition of external description is introduced supporting the description of goals, plans and capacities at different levels of abstraction. In this way, reaching a goal can originate the formation of different nested coalitions. In turn, the non-primitive activities are adopted, in an explicit way, as goals of the agents to which they were delegated, allowing a larger autonomy of the agents in their accomplishment, as well as a significant decrease in the global communication effort. Another fundamental aspect of the presented model, is the representation of coalition as a base notion, in an explicit form. Therefore, it is possible to analyze and negotiate a coalition as a whole. Also, it facilitates the modularization of the social reasoning mechanism, to allow the definition

⁶ The plan to reach the goal *DecisionSupSystem* is described in figure 11.

of criteria for coalition evaluation and selection in a integrated and dynamic way.

Several areas are of great interest for future developments of the social reasoning model presented, namely the possibility of commitments revision to handle possible failures of nested delegations.

Other aspects such as the scalability of the model and time/cost complexity of the coalition formation process are of great relevance, and we plan to address them more deeply in future work. However, the proposed model already partially considers these aspects by supporting the definition of execution constraints to limit the number of valid coalitions that an agent must consider.

9. REFERENCES

- [1] Alonso, E. - *An Uncompromising Individualistic Formal Model of Social Activity*. In Working Notes of the 2nd UK Workshop on Foundations of Multi-Agent Systems (FoMAS-97), 1997.
- [2] Alonso, E. - *How Individuals Negotiate Societies*. - In Proceedings of the 3rd International Conference on MAS, ICMAS'98, IEEE, 1998.
- [3] Castelfranchi, C., Miceli, M., Cesta, A. - *Dependence Relations Among Autonomous Agents*. In Proceedings of the 3rd European Workshop on Modelling Autonomous Agents in a Multi-Agent World (MAAMAW '91), 1991.
- [4] Castelfranchi, C. - *Modeling Social Action for AI Agents*. Invited paper. In International Joint Conference of Artificial Intelligence - IJCAI'97, 1997.
- [5] Conte, R., Castelfranchi C. - *Cognitive and Social Action*. UCL Press, 1995.
- [6] David, N. - *Modeling and Implementing And and Or-dependencies in Social Reasoning*. MSc Thesis, Faculdade de Ciências da Universidade de Lisboa, 1998.
- [7] David, N., Sichman, J., Coelho, H. - *Extending Social Reasoning to Cope with Multiple Partner Coalitions*. In Multi-Agent System Engineering, Proceedings of MAAMAW'99, Springer-Verlag, pg. 175-187, 1999.
- [8] Inverno, M., Luck, M., Wooldridge, M. - *Cooperation Structures*. In Proceedings of the International Joint Conference on Artificial Intelligence - IJCAI'97, 1997.
- [9] Morgado, L. - *Coordenação em Sistemas Multi-Agente: Formação de ligações com base em noções de dependência social*. MSc Thesis, Faculdade de Ciências da Universidade de Lisboa, 1999.
- [10] Sacerdoti, E. - *A Structure for Plans and Behavior*. Elsevier, 1977.
- [11] Sichman, J. - *A First Attempt to Use Dependence Situations as a Decision Criterion for Choosing Partners in Multi-Agent Systems*. In Proc. ECAI'94 Workshop on Decision Theory for DAI Applications, 1994.
- [12] Sichman, J., Conte, R. - *A Social Reasoning Mechanism Based On Dependence Networks*. In Proceedings of the European Conference on Artificial Intelligence - ECAI'94, 1994.
- [13] Sichman, J. - *Du Raisonement Social Chez Les Agents: Une Approche Fondée sur la Théorie de la Dépendence*. Thèse de Doctorat, Institut National Polytechnique de Grenoble - France, 1995.
- [14] Yang, Q. - *Intelligent Planning: A Decomposition and Abstraction Based Approach*. Springer, 1997.