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Dependence Graphs: Dependence Within and Between Groups*

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Abstract

This paper applies the two-party dependence theory (Castelfranchi, Cesta and Miceli, 1992, in Y. Demazeau and E. Werner (Eds.) *Decentralized AI-3*, Elsevier, North Holland) to modelling multiagent and group dependence. These have *theoretical* potentialities for the study of emerging groups and collective structures, and more generally for understanding social and organisational complexity, and *practical* utility for both social-organisational and agent systems purposes. In the paper, the dependence theory is extended to describe multiagent links, with a special reference to group and collective phenomena, and is proposed as a framework for the study of emerging social structures, such as groups and collectives. In order to do so, we propose to extend the notion of dependence networks (applied to a single agent) to dependence graphs (applied to an agency). In its present version, the dependence theory is argued to provide (a) a theoretical instrument for the study of social complexity, and (b) a computational system for managing the negotiation process in competitive contexts and for monitoring complexity in organisational and other cooperative contexts.

Keywords: multiagent systems, diversity, dependence, social structures, complexity

1. Introduction

In multiagent domains, most problems arise as a consequence, and in order to reduce the costs, of distributed solutions (cf. Crabtree, 1998; Guttman et al., 1998). Expansion of software agents' applications therefore depends at least in part on the management of complexity in multiagent domains and tasks. Intuitively, complexity is here meant in a structural sense, and it is intended to capture the social structuring of an aggregate of heterogeneous agents endowed with different goals and resources.

Social structures are here viewed as patterns (graphs) of objective relationships of social dependence, according to the dependence theory as proposed by Castelfranchi and his associates (Castelfranchi et al., 1992; Sichman et al., 1994; Conte and Sichman, 1995; Sichman and Demazeau, 2001). We agree with the view (Carley and Krackhardt, 1999) that

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organisational structures do not depend only nor primarily on personnel-personnel relationships, but also on the complex interrelationships among individuals and the environment (cf. the PCANS model, Krackhardt and Carley, 1998). However, we take a more elementary and foundational perspective in order to explore and model the emergence of organisational structures from simple aggregates of heterogeneous agents. Scientists of organisations (e.g., Krackhardt and Carley, 1998) assume organisations as complex structures of interdependencies, where tasks are assigned and commitments made. We share this assertion. However, rather than situations in which tasks are already assigned and commitments made, we aim to model multiagent interdependencies among different agents' goals and actions, and to build up a tool for predicting and simulating their emergence.

The present conception of social structure does not rule out cognition.[1] Quite on the contrary, our approach is foundational in that it aims to model the object of knowledge before modelling the knowledge itself (what-you-know or who-you-know, Carley and Hill (2001)) and the way it is formed. In our view, social structures are but the foundations upon which cognition operates (see Conte and Castelfranchi, 1995). The advantage of this conceptualisation is to provide means for simulating the emergence of dependence graphs from aggregates of heterogeneous agents, and measuring their complexity and fragility (or stability). We are only too aware of the huge body of literature on theories, methods and techniques for exploring organisational structures, and for evaluating their performance (for a thorough analysis and a taxonomy, see Carley and Krackhardt (1999)). Far from providing still another method or technique, we intend to propose a new perspective on the study of organisational structure, as suggested by a specific computational field, i.e. agent and multi agent systems theory.

In this paper, we present an extension of our previous notion of dependence network, applied to a single agent (Sichman et al., 1994), called *dependence graphs*, which is applied to an agency. This new structure allow for the study of emerging social structures, such as groups and collectives, and may form a knowledge base for managing complexity in both competitive and organisational or other cooperative contexts. This was indeed the purpose of both the DEPNET (Sichman et al. (1994); but see for further computational systems, Conte et al. (1998) and Conte and Pedone (1998)) and DEPINT (Sichman, 1998) systems. The expansion proposed in this paper can be incorporated into these systems or any other equivalent system based on dependence theory.

The paper is organised as follows. We discuss the importance of this work in the next section. In the third section, the dependence theory will be summarised and some critical contributions will be both formalised and analysed. In the fourth section, we present the formal description of dependence graphs. We use this notion in the fifth section, to illustrate how the dependence theory can be extended to include multiagent dependence, with a special reference to group and collective phenomena. In the final section, some conclusions will be drawn and ideas for future work will be outlined.

2. Aims

The present development of dependence theory is proposed under the assumption that multi agent dependence has both theoretical and application potentialities.

2.1. Understanding Social Complexity

At the theoretical level, we believe that the theory proposed here is needed to account for the emergence of group and collective structures and more generally for understanding social and organisational complexity. In the last decade or so, much work has been devoted to the study of complexity in the social and organisational sciences (for an informative overview, see Carley (2001a)). However, in much of these works, complexity is but a mere metaphor (Maguire and McKelvey, 1999) of a more precisely defined property of biological and physical systems. Furthermore, complexity is classically viewed as an obstacle for the management and the performance of social and organisational systems.

In this paper, the notion of complexity is closer to that currently shown by computational models of adaptive systems (Holland, 1995), where complexity is seen as a computable property of systems that get adjusted to their environment thanks to emerging, distributed forms of organisation. We will endeavour to show that a collection of autonomous, heterogeneous agents shows computable emerging features of complex systems: spontaneous and adaptive connectivity. As in the agent systems literature, by autonomous agents we essentially mean self-interested agents, i.e. agents endowed with and pursuing their goals. However, these agents are neither utility maximisers nor learning agents. Rather they are AI types of agents, goal-oriented and endowed with a certain degree of planning capacity. As shown in Conte and Sichman (1995), these agents may cooperate and exchange, without being neither perfect bargainer nor learning systems. For this type of agents to want to exchange or cooperate, it is sufficient instead that they form a plan in which the adoption of someone else's goal is a means for the achievement of a goal of their own. Inter-agent connectivity forms the objective ground upon which agents build up actual interactions, partnerships, and even coalitions. To model it provides a tool for predicting/evaluating the activity of any heterogeneous social aggregate, and for speeding up the process of partner seeking in multi agent systems applications. Therefore, our model does not take as input a given organisational design, but rather the agency in which an organised activity may be formed.

Substantially, complexity is defined here as a property of objective dependence relationships emerging in a social aggregate, representing a potential for interactions among the heterogeneous members of an aggregate. Obviously, the higher the number of such relationships over the number of agents involved, and the more complex the social aggregate.

Agents may happen to be involved in incompatible close dependence relationships. As we will see later on in the paper, incompatible relationships are fragile. By fragility, we mean whether or not given dependence relationships are likely to be ≪actualised≫, i.e. to lead to effective interactions among all agents involved.

2.2. Potential Applications

At the level of application, a theory of multiagent dependence is relevant for different agent systems applications. Indeed, the borderline between these fields is ever more uncertain. In fact, organisations may be seen as computational and even intelligent systems in their own right (Carley, 2001b). Furthermore, future organisations will become information sub-societies, i.e. dislocated hybrid systems where humans will interact with more or less intelligent, mobile, sociable and animated software agents (including robots, webbots, avatars).

In cooperative (e.g., organisational) systems, the management of complexity requires (computational) methods for predicting emerging structures within and across organisations (see the notion of horizontal organisations, O'Brien and Wiegand (1998)). In competitive contexts, the process of negotiation is found ever more costly thanks to the spread of (semi-) autonomous and personalised assistants (cf. Maes, 1994; Guttman et al., 1998). How to combine autonomous and personalised benevolence with efficiency? Methods for assessing interdependencies may speed up and optimise the search for partners and the negotiation process to the benefit of society's global communication flow. Ito and Sichman (2000) showed that, for agents to form dynamical coalitions, a good social reasoning mechanism based on social dependence is in the long term more advantageous than blind seeking partners (as used in the Contract Net model).

Consequently, computational models and tools allowing to predict/evaluate the connectivity of an agency is bound to have a strong impact on agent systems applications and thereby on the design and management of organisations.

3. Dependence Theory: Agents' Limited Autonomy

The work presented in this paper proceeds from the assumption that heterogeneous agents endowed with goals, beliefs, able to perform actions and situated in a common world are involved in more or less complex and dynamic networks of relationships. In current agent systems, agents are often conceived of and designed as autonomous. However, they are not completely autonomous: agents may have goals that exceed or differ from their capacities to reach them. In particular, in teamwork, agents' autonomy is intrinsically limited (cf. Conte, 1999).

More generally, socially situated agents may depend on one another to achieve their *own* goals. In terms of the dependence theory, an agent ag_i depends on some other agent ag_j with regard to one of its goal g_k, when

1. ag_i is not autonomous with regard to g_k: it lacks at least one of the actions or resources necessary to achieve g_k, while
2. ag_j has the missing action/resource.

In the rest of this section, the dependence theory as presented in Sichman et al. (1994) on the basis of a pre-existing model developed by Castelfranchi et al. (1992) is summarised. Only the notions relevant for the present exposition will be considered explicitly, namely those of *external description, dependence relations, dependence networks and dependence situations*. For a complete formal expression, see Sichman et al. (1994) and Conte et al. (1998). An alternative formulation is also presented in Sichman and Demazeau (2001). At the end of the section, we also present some additional concepts, called OR-dependence, AND-dependence and CO-dependence, that were presented in Conte et al. (1998), and which will be useful for the development of the next sections.

The present theory evokes a number of related approaches, namely social networks theory (cf. Marwell et al., 1988; Gould, 1993), exchange network theory (see Willer, 1992), the Power-Dependence theory developed by Cook and Emerson (1978), and the work by Pfeffer and Salançik (see Pfeffer, 1981, ch. 4). The reader is addressed to Conte et al. (1998) for a detailed analysis and a confrontation of the present approach with previous ones. Here, suffice it to recall some features that characterise our approach

1. We endeavour to build upon an *elementary* notion of dependence. In our terms, dependence is a not necessarily social notion, in the sense that agent A depends upon all those conditions which allow his goals to be realised. If A is not able to verify these conditions, he is not autonomous. If these conditions can be verified by another agent B, then A is also (but only as a secondary effect) depending on B. This allows to predict dependence network from individual properties, and provide instructions for increasing or reducing dependence among collaborative software agents.
2. Our notion of dependence is *analytical* and is always defined with reference to one given goal of the agent's, rather than to a (sub) set of her goals. This allows for more flexibility in the agent's resulting dependence state, which must be updated after any change in the agent's goal state: if, say, a given goal is dropped, the agent's dependence states may change accordingly.
3. Our notion of dependence is based upon a computational theory of *action*. In our model, an agent depends upon another when she is not able to execute any plan in a set of plans which she believes to realise her goal, while the other agent is able to do so.

3.1. External Description

In order to be able to reason about the others, autonomous agents must have a data structure where this information about the others is stored, despite the possible different internal models they may have. This structure is called *external description*, and it is a private one, i.e., each agent has its own representation of the others. An external description is composed of several entries, each containing the beliefs that a certain *subject agent* has on a particular *object agent* that belongs to the agency (see Sichman and Demazeau (2001) for a complete description of the several roles an agent can play in the social reasoning mechanism).

An external description entry consists of the set of *goals* the object agent wants to achieve, the set of *actions* she is able to perform, the set of *resources* she controls and the set of *plans* she has. A plan consists of a sequence of actions with its associated resources needed to accomplish them. However, an agent may have a plan whose actions or resources do not necessarily belong to her own set of actions or resources. Therefore she may *depend on others* in order to carry on a certain plan, and achieve a certain goal (for the formal notation, see, Sichman et al. (1994) and Sichman and Demazeau (2001)).

As said before, the external description is an agency representation from within an agent's mind. As an example, in the original model G_{ag1} $(ag2)$ *represent the set of goals* $ag1$ *believes that* $ag2$ *has*. The beliefs agents have regarding the others may be neither *necessarily true nor complete*. In order to illustrate the power of the proposed framework, the hypothesis of external description compatibility is adopted as a simplification. This states that any two agents will agree in their representation of a given agent. For some experiments regarding this aspect, please refer to Sichman (1998) and Sichman and Demazeau (2001).

One could ask what relationship holds between the agents' beliefs and the real matters. As one and the same instrument is intended to be employed for both types of representations (mental states and world states), an *objective representation* of the agency is adopted, namely that which corresponds to the mental state of a specific subject agent, assumed as the observer. In order to avoid confusion, as we are interested here in an objective representation. Subscripts referring to the subject agent that were used in the original formalism will be dropped in the rest of this paper, i.e., we will represent the objective representation of ag_2's goals in the previous example by $G(ag_2)$.

Let us denote by $Ext(ag_i) = \{G(ag_i), A(ag_i), R(ag_i), P(ag_i)\}$ the external description entry of ag_i, which respectively means the set of goals, actions, resources and plans that belongs to ag_i. Let us denote as $P(ag_i, g_k)$ the set of plans $p(ag_i, g_k)$ that ag_i has in order to achieve the goal g_k. On the other hand, each plan $p(ag_i, g_k)$ that belongs to the plan set $P(ag_i, g_k)$, is defined as $p(ag_i, g_k) = \{g_k, R(p(ag_i, g_k)), I(p(ag_i, g_k))\}$, where g_k is the goal to be achieved, a (possibly empty) set of resources $R(p(ag_i, g_k))$ used in this plan and a (possibly empty) sequence of instantiated actions $I(p(ag_i, g_k))$ used in this plan. Each instantiated action $i_m(p(ag_i, g_k)) = \{a_m, R(a_m, p(ag_i, g_k))\}$ is composed of an action a_m and a (possibly empty) set of resources $R(a_m, p(ag_i, g_k))$ used in this action, where we have $R(a_m, p(ag_i, g_k)) \subseteq R(p(ag_i, g_k))$.

3.2. Dependence Relations

In our original formulation presented in Sichman et al. (1994) and Sichman and Demazeau (2001), the notions of autonomy and dependence are strictly related to the set of plans $P(ag_q, g_k)$ a subject agent ag_i uses in order to infer them.[2] For brevity, let us use respectively p_{qk} and P_{qk} as a shorthand notations for $p(ag_q, g_k)$ and $P(ag_q, g_k)$.

An agent ag_i is *a-autonomous* (action autonomous) for a given goal g_k, according to a set of plans P_{qk} if there is at least one plan p_{qk} in this set that achieves this goal and for every instantiated action $i_m(p_{qk})$ appearing in this plan the action a_m belongs to her own set of actions $A(ag_i)$. On the contrary, an agent is not a-autonomous for a certain goal if her own set of actions does not include all the actions involved in each of her plans that achieves this goal. Analogously, we define the notion of *r-autonomy* (resource autonomy). Finally, an agent ag_i is *s-autonomous* (social autonomous) if she is both a-autonomous and r-autonomous for this goal. Formally, we have:

$$a_{aut}(ag_i, g_k, P_{qk}) = \exists g_k \in G(ag_i) \exists p_{qk} \in P_{qk} \forall i_m(p_{qk}) \in I(p_{qk}) a_m \in A(ag_i) \tag{1}$$

$$r_{aut}(ag_i, g_k, P_{qk}) = \exists g_k \in G(ag_i) \exists p_{qk} \in P_{qk} \forall r_m(p_{qk}) \in R(p_{qk}) r_m \in R(ag_i) \tag{2}$$

$$s_{aut}(ag_i, g_k, P_{qk}) = a_{aut}(ag_i, g_k, P_{qk}) \wedge r_{aut}(ag_i, g_k, P_{qk}) \tag{3}$$

If an agent does not have all the actions (or resources[3]) to achieve a given goal, according to a set of plans, she may depend on others for this goal. An agent ag_i *a-depends* (action-depends) on another agent ag_j for a given goal g_k, according to a set of plans P_{qk} if

1. she has g_k in her set of goals,
2. she is not a-autonomous for g_k and
3. there is a plan p_{qk} in P_{qk} that achieves g_k
4. at least one action used in this plan is in ag_j's set of actions $A(ag_j)$.

In a similar way, we have defined the notion of *r-dependence* (resource-dependence). Finally, an agent ag_i *s-depends* (social-depends) on another agent ag_j if she either a-depends or r-depends on this latter. Formally, we have:

$$\begin{aligned} a_{dep}(ag_i, ag_j, g_k, P_{qk}) = {} & \exists g_k \in G(ag_i) \neg a_{aut}(ag_i, g_k, P_{qk}) \\ & \wedge \exists p_{qk} \in P_{qk} \exists i_m(p_{qk}) \in I(p_{qk}) a_m \in A(ag_j) \end{aligned} \tag{4}$$

$$\begin{aligned} r_{dep}(ag_i, ag_j, g_k, P_{qk}) = {} & \exists g_k \in G(ag_i) \neg r_{aut}(ag_i, g_k, P_{qk}) \\ & \wedge \exists p_{qk} \in P_{qk} \exists r_m(p_{qk}) \in R(p_{qk}) r_m \in R(ag_j) \end{aligned} \tag{5}$$

$$s_{dep}(ag_i, ag_j, g_k, P_{qk}) = a_{dep}(ag_i, ag_j, g_k, P_{qk}) \vee r_{dep}(ag_i, ag_j, g_k, P_{qk}) \tag{6}$$

3.3. Dependence Networks

If one analyses Eqs. (4) and (5), it is intuitive to say that a *basic dependence relation* means that an agent ag_i needs another agent ag_j to perform an action a_m/to release a resource r_m, that are used in a plan p_{qk} which achieves a certain goal g_k. Let us denote formally, as in Sichman and Demazeau (2001), this basic dependence relation as $basic\_dep(ag_i, ag_j, g_k, p_{qk}, a_m)$.[4]

Whenever an agent infers his basic dependence relations, he can internally represent them in a structure we have called *dependence network*. As an example, let us consider the case where an agent ag_1 has two goals g_1 and g_8. For the first goal g_1, she has two alternative plans, $p_{111} = a_1(\ ), a_2(\ ), a_4(\ )$ and $p_{112} = a_1(\ ), a_5(\ )$ to achieve this goal. On the other hand, for the second goal g_8, she has only one plan, $p_{18} = a_1(\ ), a_7(\ )$ that achieves this goal. Let us also suppose that ag_1 can perform actions a_1 and a_9, but she is unable to perform the actions a_2, a_4, a_5, and a_7, which can be performed respectively by the set of agents $\{ag_2, ag_3\}$, ag_4, ag_5 and by the set of agents $\{ag_6, ag_7\}$. In this scenario, the following basic dependence relations hold:

$$\begin{aligned}
&dp_1: basic_dep(ag_1, ag_2, g_1, p_{111} = a_1(\ ), a_2(\ ), a_4(\ ), a_2) \\
&dp_2: basic_dep(ag_1, ag_3, g_1, p_{111} = a_1(\ ), a_2(\ ), a_4(\ ), a_2) \\
&dp_3: basic_dep(ag_1, ag_4, g_1, p_{111} = a_1(\ ), a_2(\ ), a_4(\ ), a_4) \\
&dp_4: basic_dep(ag_1, ag_5, g_1, p_{112} = a_1(\ ), a_5(\ ), a_5) \\
&dp_5: basic_dep(ag_1, ag_6, g_8, p_{18} = a_1(\ ), a_7(\ ), a_7) \\
&dp_6: basic_dep(ag_1, ag_7, g_8, p_{18} = a_1(\ ), a_7(\ ), a_7)
\end{aligned}$$

The dependence network of ag_1 is presented in figure 1. In the general case, such a network can be much more complicated, as agent can have several goals, with different plans to achieve each of them. Please refer to Sichman et al. (1994) and Sichman and Demazeau (2001) for more examples.

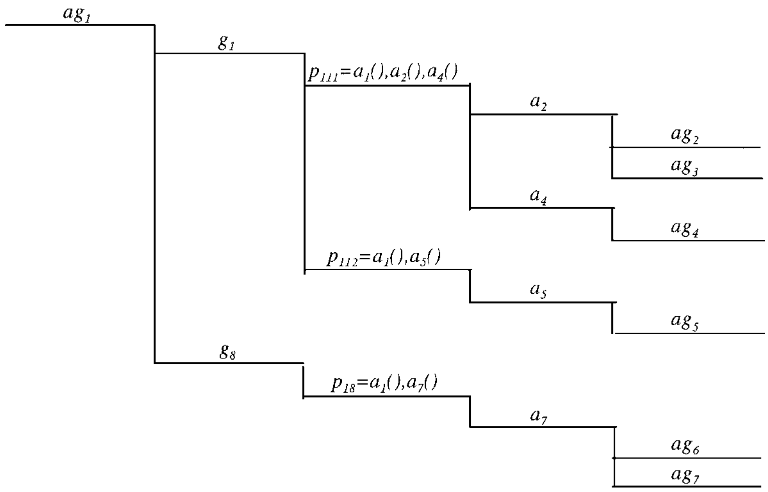

Figure 1. Dependence network.

3.4. Dependence Situations

An agent who has constructed his dependence network can use this information when reasoning about others. For a given goal g_k, an agent ag_i can calculate for each other agent ag_j which is the *dependence situation* relating them for this goal.

In this paper, we classify the dependence situations regarding the *nature*[5] of the dependence. Let us consider two agents ag_i and ag_j. Let us also suppose that agent ag_i has the goal g_k in his set of goals but she is not a-autonomous for it. According to the *nature* of the dependence, there are four different situations that may hold between these two agents, considering ag_i's reasoning mechanism:

1. *Independence*: ag_i infers that she does not a-depend on ag_j for g_k;
2. *Unilateral Dependence*: ag_i infers that she a-depends on ag_j for g_k, but this latter does not a-depend on her for any of his goals;
3. *Mutual Dependence*: ag_i infers that she and ag_j a-depend on each other for the *same goal* g_k;
4. *Reciprocal Dependence*: ag_i infers that she and ag_j a-depend on each other, but for *different goals* g_k and g_l.

The formal definition of these concepts can be found in Sichman et al. (1994) and Sichman and Demazeau (2001). We have used this dependence situations as a decision criterion for choice of partners in the DEPINT systems, details can be found in Sichman (1998) and Sichman and Demazeau (2001).

3.5. OR-Dependence, AND-Dependence and CO-Dependence

In Conte et al. (1998), some additional notions describing multiagent relations have been proposed, called respectively OR-dependence AND-dependence, CO-dependence. In the rest of this section, we will denote a set of agents $\{ag_1, ag_2, \ldots, ag_n\}$ by Ag_j and a set of agent sets $\{Ag_1, Ag_2, \ldots, Ag_n\}$ by AG_j.

3.5.1. OR-Dependence. An agent ag_i OR-depends on a set of agents Ag_j when she holds a disjunction set of dependence relations upon any member ag_k of Ag_j. Any member of the set Ag_j is sufficient but unnecessary for ag_i's goal. For example, in order to have information about how to fill a tax form, any financial expert will do. OR-dependence provides the dependent agent with a number of alternative ways to achieve her goal, among which she shall choose the most convenient. The number of alternatives amounts to the number of agents contained in the set Ag_j. One can notice that *OR-dependence mitigates social dependence*, if only because the probabilities that some agent willing to help is found increase.

Referring to the dependence network presented in figure 1, the notion of OR-dependence is related to the fifth level of the network, i.e., *the possible agents able to perform a single needed action in a particular plan that achieves a certain goal*. In this network, ag_1 OR-depends on the set $\{ag_2, ag_3\}$, because he needs one of them to perform action a_2 to achieve goal g_1, according to plan p_{111}.

We can express an OR-dependence in the following way:

$$\begin{aligned} OR\_dep(ag_i, Ag_j, g_k, p_{qk}, a_m) = {} & \exists g_k \in G(ag_i) \neg a_{aut}(ag_i, g_k, P_{qk}) \wedge |Ag_j| > 1 \\ & \wedge \forall ag_l \in Ag_j basic\_dep(ag_i, ag_l, g_k, p_{qk}, a_m) \\ & \wedge \neg \exists Ag_m Ag_j \subset Ag_m OR\_dep(ag_i, Ag_m, g_k, p_{qk}, a_m) \end{aligned} \tag{7}$$

Briefly, the expression states that an agent ag_i OR-depends on a set of agents Ag_j to perform an action a_m needed in a plan p_{qk} to achieve goal g_k if she is not autonomous for this goal and this set Ag_j has at least two agents on which ag_i depends to perform this action. The recursive definition in the last line guarantees that Ag_j is a maximal set.

3.5.2. AND-Dependence. Sometimes, one and the same agent may depend on a bunch of others for achieving one[6] of her goals. For example, a rogue may AND-depend on a handful of specialised fellows to organise and execute a robbery: a lookout, a skilled driver, etc. While a formal expression of dependence quantity or intensity is under study, here it is necessary at least to observe that ag_i's degree of dependence is a direct function of the costs of the actions (including allowing others to use of one's resources) that ag_i needs to be performed. Therefore, quite unlike the preceding link, AND-dependence will be greater than ordinary dependence, other things being equal.

Referring to the dependence network presented in figure 1, the notion of AND-dependence is related to the fourth level of the network, i.e., *the needed actions to perform a particular plan that achieves a certain goal*. Since different agents may perform a needed action, as was explained in the last subsection, the notion of AND-dependence must be built on OR-dependence. Therefore, we will say that agent ag_i AND-depends on the set of agents' sets AG_j if the following conditions hold:

1. ag_i needs more than one action in order to achieve a certain goal, following a particular plan,

2. for each of these actions a_k, either ag_i OR-depends on a set of agents Ag_k, like explained in the last section, or on the other hand ag_i depends on a single agent ag_k, which will be represented as the singleton $Ag_k = \{ag_k\}$ and
3. AG_j is a set containing these sets Ag_k.

In the network presented in figure 1, ag_1 AND-depends on the set $\{\{ag_2, ag_3\}, \{ag_4\}\}$, because he needs both actions a_2 (which can be performed either by ag_2 or by ag_3) and a_4 (which can be performed by ag_4) in order to execute p_{111} to achieve goal g_1.

Let us denote by $A_n(ag_i, g_k, p_{qk})$ the set of needed actions $\{a_1, a_2, \ldots, a_n\}$ that agent ag_i cannot perform and which are needed in order to execute plan p_{qk}, which achieves goal g_k. We can then express an AND-dependence in the following way:

$$
\begin{aligned}
AND\_dep(ag_i, AG_j, g_k, p_{qk}) = {} & \exists g_k \in G(ag_i) \neg a_{aut}(ag_i, g_k, P_{qk}) \wedge \forall i_m(p_{qk}) \\
& \in I(p_{qk}) a_m \in A_n(ag_i, g_k, p_{qk}) (\exists! Ag_k \in AG_j |Ag_k| \\
= {} & 1 \exists ag_l \in Ag_k basic\_dep(ag_i, ag_l, g_k, p_{qk}, a_m) \\
& \vee \exists! Ag_k \in AG_j OR\_dep(ag_i, Ag_k, g_k, p_{qk}, a_m)) \\
& \wedge \neg \exists AG_m AG_j \subset AG_m AND\_dep(ag_i, AG_m, g_k, p_{qk})
\end{aligned} \tag{8}
$$

Briefly, the expression states that for every action a_m needed by ag_i, there will be either one and only one agent $\{ag_l\} \in AG_j$ able to perform this action or one and only one set of agents $Ag_k \in AG_j$ on which ag_i OR-depends for this action. Once again, the recursive definition guarantees that AG_j is a maximal set.

3.5.3. CO-Dependence. In this case, a set of agents Ag_j depend on ag_i, each for its own goal. The lesser the actions that ag_i can perform simultaneously, the more ag_i will be contended for by Ag_j's members.

We can express CO-dependence in the following way:

$$
\begin{aligned}
CO\_dep(Ag_j, ag_i, P_q) = {} & \forall ag_k \in Ag_j (\exists g_k \in G(ag_k) \neg a_{aut}(ag_k, g_k, P_q) \\
& \wedge \exists p_q \in P_q \exists i_m(p_q) \in I(p_q) basic\_dep(ag_k, ag_i, g_k, p_q, a_m)) \\
& \wedge \neg \exists Ag_l Ag_j \subset Ag_l CO\_dep(Ag_l, ag_i, P_q)
\end{aligned} \tag{9}
$$

4. Dependence Graphs

As one may observe, a dependence network contains all basic dependence relations of a *single agent*. Sometimes, it is useful to represent in a single structure several dependence networks, relating a *set of agents*. In order to do so, we introduce the notion of *dependence graphs*.

Mathematically, a graph G is an ordered triple $(V(G), E(G), \psi_g)$ consisting of a nonempty set of $V(G)$ of vertices (or nodes), a set $E(G)$, disjoint from $V(G)$, of edges (or arcs) and an incidence function ψ_g that associates with each edge of G an unordered pair of (not necessarily distinct) vertices of G (Bondy and Murphy, 1977). Let v_0 and v_n be vertices in a graph.

A *path* from v_0 to v_n of length m is an alternating sequence of $m+1$ vertices and m edges beginning with vertex v_0 and ending with vertex v_n *path* $(v_0, v_n) = (v_0, e_1, v_1, e_2, \ldots, e_m, v_n)$ in which edge e_i is incident on vertices v_{i-1} and v_i, *for* $i = 1, 2, \ldots, m$. A *simple path* from v_i to v_j is a path from v_i to v_j with no repeated vertices. A *cycle* (or circuit) corresponds to the intuitive notion of closed relationship. More formally, a *cycle*(v_i) is a path of nonzero length from v_i to v_i with no repeated edges. A *simple cycle* is a cycle from v_i to v_i in which, except for the beginning and ending vertices that are both equal to v_i, there are no repeated vertices.

When the incidence function ψ_g associates with the edge of G an ordered pair of vertices, the graph is called a *directed graph* (or digraph). In this case, we can propose some new definitions for *directed paths* and *directed cycles*.

A *bipartite graph* is one whose vertices can be partitioned into two subsets X and Y, so that each edge has one end in X and one end in Y. This definition can be extended to n subsets, and the graph is called a *n-partite graph*.

Using these definitions, we can define a *dependence graph*. We will represent the basic notions of our model, agents, goals, plans and actions, as vertices of the graph. Moreover, as a pair of vertices will be linked by a single edge, we will represent a path in a simpler manner, without making an explicit reference to the edges, i.e., we will use *path*$(v_0, v_n) = (v_0, v_1, \ldots, v_n)$ instead of $(v_0, e_1, v_1, e_2, \ldots, e_m, v_n)$.

Formally, a dependence graph $DPG = (V(DPG), E(DPG), \psi_{DPG})$ is a 4-partite directed graph with the following characteristics:

1. the set $V(DPG) = V_{ag}(DPG) \cup V_g(DPG) \cup V_p(DPG) \cup V_a(DPG)$ is the union of the following disjoint sets:
   - 1.1. $V_{ag}(DPG) = \{ag_1, ag_2, \ldots, ag_n\}$ is the set of agents;
   - 1.2. $V_g(DPG) = \{g_1, g_2, \ldots, g_n\}$ is the set of the possible goals these agents may want to achieve;
   - 1.3. $V_p(DPG) = \{p_1, p_2, \ldots, p_n\}$ is the set of plans the agents may use to achieve their goals;
   - 1.4. $V_a(DPG) = \{a_1, a_2, \ldots, a_n\}$ is the set of actions that can be performed by these agents.
2. the set $E(DPG)$ is a set of edges;
3. the function ψ_{DPG}: $E(DPG) \to V(DPG) \times V(DPG)$ is defined as follows.
   - 3.1. $\psi_{DPG}(e) = (ag_i, g_j)$ associates an edge e with an ordered pair of vertices (ag_i, g_j), with $ag_i \in V_{ag}(DPG)$ and $g_j \in V_g(DPG)$ and represents the fact that ag_i has the goal g_j;
   - 3.2. $\psi_{DPG}(e) = (g_i, p_j)$ associates an edge e with an ordered pair of vertices (g_i, p_j), with $g_i \in V_g(DPG)$ and $p_j \in V_p(DPG)$ and represents the fact that goal g_i *is* achieved by plan p_j;
   - 3.3. $\psi_{DPG}(e) = (p_i, a_j)$ associates an edge e with an ordered pair of vertices (p_i, a_j), with $p_i \in V_p(DPG)$ and $a_j \in a_g(DPG)$ and represents the fact that plan p_i needs the action a_j and agent ag_k, can not perform this action;[7]

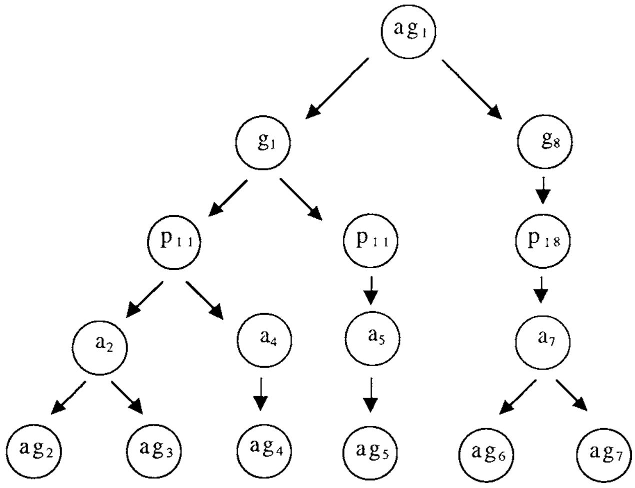

Figure 2. A single agent dependence graph.

3.4. $\psi_{DPG}(e) = (a_i, ag_j)$ associates an edge e with an ordered pair of vertices (a_i, ag_j), with $a_i \in V_a(DPG)$ and $ag_j \in V_{ag}(DPG)$ and represents the fact that action a_i can be performed by agent ag_j.

As an example, the dependence network shown in figure 1 is presented as a dependence graph in figure 2. In a single agent case, like shown in figure 2, the dependence graph results in a tree.

One may notice the following interesting points:

- a basic dependence relation $basic\_dep(ag_i, ag_j, g_k, p_{qk}, a_m)$ is represented in the dependence graph by a $path(ag_i, ag_j) = (ag_i, g_k, p_{qk}, a_m, ag_j)$ of length 4;
- an OR-dependence $OR\_dep(ag_i, Ag_j, g_k, p_{qk}, a_m)$, where $Ag_j = \{ag_j, ag_k, \ldots, ag_l\}$, is represented in the dependence graph by a set of paths $Path(ag_i, a_m) = \{path(ag_i, ag_j), path(ag_i, ag_k), \ldots, path(ag_i, ag_l)\}$, each of them having the following characteristics: (i) the lenght of the path is 4, (ii) the path has the form $(ag_i, g_k, p_{qk}, a_m, ag_x)$ (iii) the initial part of the path, (ag_i, g_k, p_{qk}, a_m), whose length is 3, is identical to all of them and (iv) for each path $path(ag_i, ag_x) \in Path(ag_i, a_m)$, the final part of the path, (a_m, ag_x), of length 1, associates an edge e to a_m and to each of the agents $ag_x \in Ag_j$;
- an AND-dependence $AND\_dep(ag_i, AG_j, g_k, p_{qk})$, where $AG_j = \{\{ag_j, \ldots, ag_k\}, \ldots, \{ag_l, \ldots, ag_m\}\}$, is represented in the dependence graph by a set of sets of paths $PATH(ag_i, p_{qk}) = \{Path(ag_i, a_m), Path(ag_i, a_n), \ldots, Path(ag_i, a_s)\}$, where either one of the following characteristics hold: (i) $Path(ag_i, a_m)$ represents and OR-dependence related to action a_m, like just described above or (ii) $Path(ag_i, a_m)$ has a single element $path(ag_i, a_m)$ which represents a basic dependence relation, as stated above. In both case, however, we have: (i) for each set of paths $Path(ag_i, a_x)$, the length of each $path(ag_i, ag_j) \in Path(ag_i, a_x)$, $Path(ag_i, a_x) \in PATH(ag_i, p_{qk})$ is 4, (ii) any path has the form $(ag_i, g_k, p_{qk}, a_y, ag_x)$ and (iii) the initial part of the path, (ag_i, g_k, p_{qk}), whose length is 2, is identical to all of them.

In the scenario presented in figure 2, the dependence graph represents only the goals of agent ag_1. However, as was stated in the introduction of this section, the interest of dependence graphs is that they can represent goals and dependence relations of *several* agents. In order to illustrate this concept, let us consider again the example presented in Section 3.3, and shown in figures 1 and 2. Let us put forward the following additional hypothesis:

- agent ag_2 has a goal g_2 and a certain plan $p_{22} = a_2(\ ), a_6(\ )$ to achieve this goal, she can perform action a_2 but not a_6. Another agent ag_6 can perform this last action, as well as action a_7, but she needs action a_1 to achieve her goal g_6, according to her plan $p_{66} = a_1(\ ), a_6(\ )$;
- agent ag_4 has a goal g_4 and a certain plan $p_{44} = a_4(\ ), a_7(\ )$ to achieve this goal, she can perform action a_4 but not a_7. As well as ag_6, another agent ag_7 can perform this last action, but she needs action a_9 to achieve her goal g_7, according to her plan $p_{77} = a_7(\ ), a_9(\ )$.

In this scenario, the following additional basic dependence relations hold:

$$dp_7\text{: } basic\_dep(ag_2, ag_6, g_2, p_{22} = a_2(\ ), a_6(\ ), a_6)$$
$$dp_8\text{: } basic\_dep(ag_4, ag_6, g_4, p_{44} = a_4(\ ), a_7(\ ), a_7)$$
$$dp_9\text{: } basic\_dep(ag_4, ag_7, g_4, p_{44} = a_4(\ ), a_7(\ ), a_7)$$
$$dp_{10}\text{: } basic\_dep(ag_6, ag_1, g_6, p_{66} = a_1(\ ), a_6(\ ), a_1)$$
$$dp_{11}\text{: } basic\_dep(ag_7, ag_1, g_7, p_{77} = a_7(\ ), a_9(\ ), a_9)$$

The dependence graph defined for this scenario is represented in figure 3.

As one may notice, the dependence graph is quite a complex structure with lots of paths. In some situations, like the ones that will be treated in the rest of the paper, this structure can be simplified. Let us consider the case where (i) each agent has a *single goal* to achieve

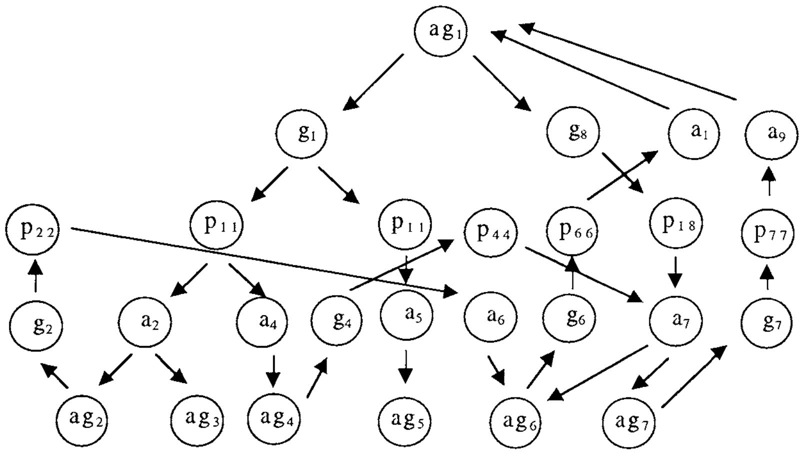

Figure 3. A multi-agent dependence graph.

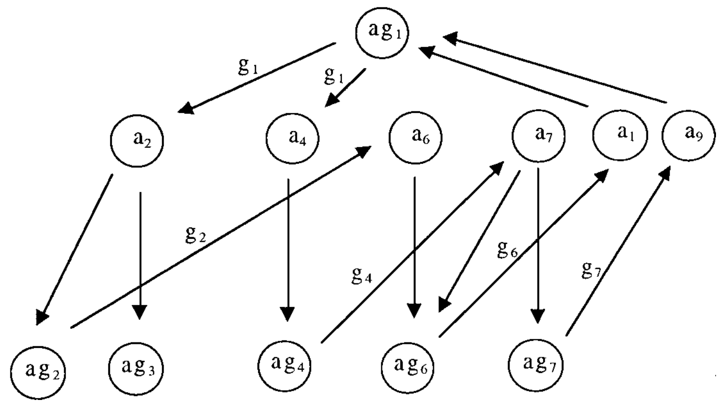

Figure 4. Reduced dependence graph.

and (ii) each agent has a *single plan* to achieve this goal. In this case, we do not need to represent in the graph neither the vertices representing goals nor the ones representing plans, and the set of vertices will be reduced to the union of sets of agents and actions vertices $V(DPG) = V_{ag}(DPG) \cup V_a(DPG)$. Consequently, the function $\psi_{DPG}(e)$ will also be simplified, containing elements like $\psi_{DPG}(e) = (ag_i, a_j)$ and $\psi_{DPG}(e) = (a_i, ag_j)$. As it may be important for the further discussion to identify the agents' goals, we will use them as *labels* of the directed edges linking agents to actions. We will call this representation a *reduced dependence graph*.

As an example of a reduced dependence graph, we represent in figure 4 the same scenario shown in figure 3, with some constraints to adapt to the situation described just above: we suppose that agent ag_1 has only goal g_1 and only one plan $p_{111} = a_1(\ ), a_2(\ ), a_4(\ )$ to achieve this goal.

In figure 4, there are two cycles of the same complexity (same number of paths over the same number of agents involved) starting at vertex ag_1 : $cycle_1(ag_1) = \{ag_1, a_2, ag_2, a_6, ag_6, a_1, ag_1\}$ and $cycle_2(ag_1) = \{ag_1, a_4, ag_4, a_7, ag_7, a_9, ag_1\}$. If we take both cycles, we can observe that a cooperative activity among agents involved could emerge, each agent trying to achieve its goal. Below, we will describe this phenomenon.

5. Multiagent Dependence: A Market Network

The above concepts and the whole set of edges in a dependence graph can be used to describe more or less structured and complex multi agent systems. In particular, different levels of complexity and internal cohesiveness/fragility of a multi agent system can be shown to emerge from some features of the dependence graph described above.

As will be shown throughout this section, rather than a none-or-all notion, multiparty dependence indicates a phenomenon of growing complexity, from loose group-dependence to a more structured and more cohesive collective dependence.

In the remaining of the paper, the notion of agency defined in the previous section, will be replaced by the notion of a *market*. This should not be intended in a strictly economic

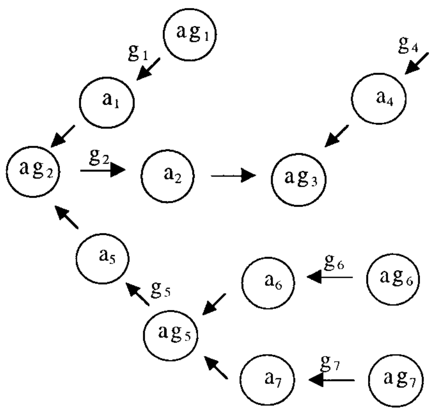

Figure 5. A market dependence graph.

sense, but more generally as a set Ag_i of agents which are non-autonomous with regard to some of their goals. Any member ag_j of Ag_i is characterised by a set of goals $G(ag_j)$ such that ag_j is non-autonomous for at least one goal $g_k \in G(ag_j)$. For simplicity, we will deal with *markets with one-goal single-plan agents*. Therefore, we will use reduced dependence graph to describe them. In figure 5, a market dependence network is shown.

Figure 5 depicts a loose network: no partnership can emerge (no complexity). Let us now see under which conditions the dependence relations may design possible multiagent partneships.

5.1. AMONG-Dependence

Let us look now at figure 6. The graph contains two cycles, $cycle(ag_1) = \{ag_1, a_1, ag_2, a_2, ag_7, a_7, ag_1\}$ and $cycle(ag_4) = \{ag_4, a_4, ag_3, a_3, ag_4\}$ of different complexity: $cycle(ag_4)$ is not so complex, indeed it is relatively easy to manage (two agents in reciprocal dependence). Conversely, $cycle(ag_1)$ is more complex: it contains more than two agents, where each may receive help from someone and may provide help to another. Sociologists (Yamagishi and Cook, 1993) would say that in $cycle(ag_1)$ a "generalised" form of exchange, requiring a rather complex negotiation process, might occur. We will call AMONG-dependence the dependence relationship holding in $cycle(ag_1)$.

More precisely, a set of agents Ag_i can be said to AMONG-depend, or s-depend on one another, where the following three clauses hold:

1. *Dependence clause*—for each ag_j belonging to Ag_i there is at least another agent ag_k upon which ag_j s-depends for her goal;
2. *Utility clause*—there is at least another agent ag_l belonging to Ag_i which s-depends upon ag_j for his goal;
3. *Generalised reciprocity clause*—$ag_k \neq ag_l$.

This last clause excludes the case of a cycle of length 2, i.e., a simple two-party reciprocal dependence.

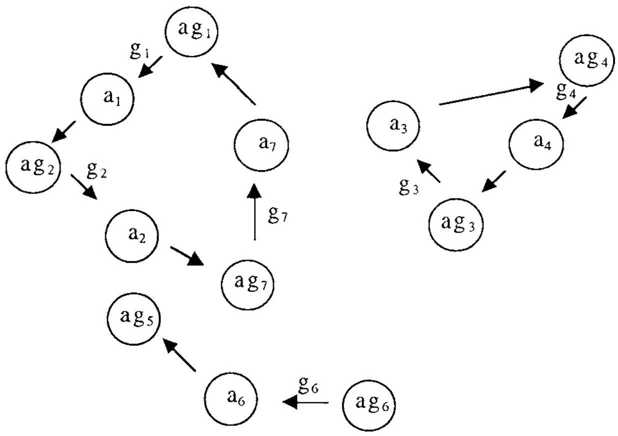

Figure 6. Cooperation cycles.

Obviously, the larger the set of AMONG-depending agents, the more complex the structure and the more difficult the agreement and the coordination.[8]

5.2. *When Does AMONG-Dependence Lead to GROUP-Dependence?*

In figure 6, a simple and ideal case of AMONG-dependence is offered, represented by $cycle(ag_1) = \{ag_1, a_1, ag_2, a_2, ag_7, a_7, ag_1\}$. Under certain conditions, which we are going to examine, an AMONG-depending network may prove fragile, and either split or collapse.

5.2.1. OR-Dependence and AMONG-Dependence. Let us consider what happens if one agent ag_j, belonging to a set of agents Ag_i which satisfies the AMONG-dependence clauses, OR-depends on a subset $Ag_k \subseteq Ag_i$ (cf. figure 7). Here, we have one agent (ag_1) OR-depending on two agents (ag_2 and ag_6) for action a_1. An interesting phenomenon

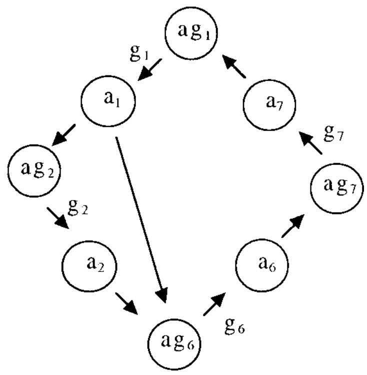

Figure 7. Inequity in AMONG-dependence.

emerges:

If one agent ag_j, belonging to a set of agents Ag_i which satisfies the AMONG-dependence clauses, OR-depends upon a subset Ag_k of Ag_i, there are two or more cycles of different lengths starting at agent ag_j which may satisfy the AMONG-dependence clauses.

In fact, since the AMONG-dependence clauses are by definition satisfied, at least another agent ag_k in Ag_i, different from ag_j, will depend on at least one of the agents upon which ag_j OR-depends. Hence, there will be at least one agent ag_q in Ag_i that is more useful (more required) than dependent (ag_6 in figure 7). Consequently, the dependence graph will have two or more cycles, of different complexity, which may satisfy the AMONG-dependence clauses. In figure 7, for example, these are the two cycles starting at vertex ag_1, $\{ag_1, a_1, ag_6, a_6, ag_7, a_7, ag_1\}$ and $\{ag_1, a_1, ag_2, a_2, ag_6, a_6, ag_7, a_7, ag_1\}$ and both satisfy the AMONG-dependence clauses. The OR-depending agent (ag_1) will have a chance to decide. Its choice will determine whether a sub-group will be formed at the expense of a (subset of) agent(s) (in our case, at ag_2's expense). OR-dependence is an obstacle for AMONG-dependence to lead to group formation. Since OR-dependence reduces the degree of dependence, an OR-depending agent involved in an AMONG-depending network will always be less depending than useful. This introduces an unbalance, or inequity, in the network at the benefit of the OR-depending agent. As will be shown below, unbalance or inequity endangers AMONG-dependence and obstacles group formation.

A special case occurs when the OR-depending agent is useful to the same number of agents that she OR-depends upon:

If the number of agents in the subset Ag_l depending upon ag_j is equal to the number of agents of the subset Ag_k, ag_j OR-depend upon, there are alternative incompatible cycles starting at agent ag_j in all of which AMONG-dependence clauses apply.

In other words, an agent may OR-depend upon as many agents as those depending on her. In figure 8, for example, there are two incompatible cycles starting at vertex ag_1, $\{ag_1, a_1, ag_2, a_2, ag_6, a_6, ag_1\}$ and $\{ag_1, a_1, ag_4, a_4, ag_7, a_7, ag_1\}$, between which the

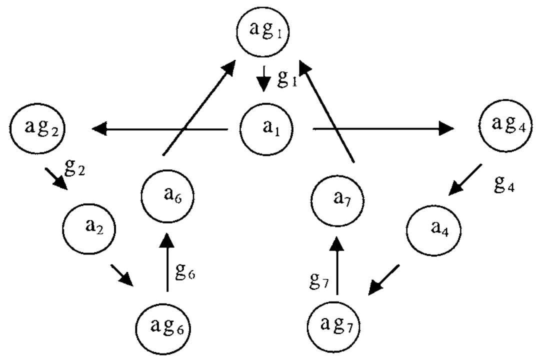

Figure 8. Incompatible AMONG-dependences.

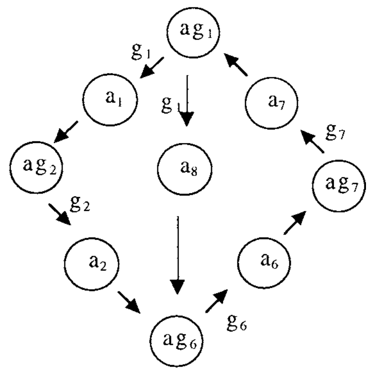

Figure 9. Fragile AMONG-dependence.

OR-depending agent, contended for by the others, will have the power to choose. In either case, OR-dependence disrupts or obstacles AMONG-dependence and consequently, group formation.

5.2.2. AND-Dependence and AMONG-Dependence. Let us consider what happens if we introduce an AND-dependence link (figure 9).

In this case, group exchange can occur only if either one of the agents accepts to give more than she receives (in figure 9, ag_6), or another accepts to obtain less than she needs (in figure 9, ag_1). Again, if at least one agent in the set depends more than it is useful for (inequity condition), the AMONG-dependence is seriously endangered and a fragile agreement is likely to emerge.

If the set Ag_i satisfies the AMONG-dependence conditions, but at least one agent ag_j in Ag_i AND-depends on a set of sets of agents AG_k and $|AG_k| > |Ag_l|, Ag_l$ is the subset of agents depending on ag_j, AMONG-dependence is endangered.

Nonetheless, sometimes AND-dependence may strengthen AMONG-dependence (see figure 10). Here, once more, one can notice two cycles starting at vertex ag_1. However, they are not only compatible but actually inter-dependent (see below, § 5.5): neither $\{ag_1, a_1, ag_2, a_2, ag_6, a_6, ag_1\}$ nor $\{ag_1, a_8, ag_4, a_4, ag_7, a_7, ag_1\}$ can independently form a group. They can only work together.

Given a set of agents Ag_i which satisfies the AMONG-dependence clauses, if there is at least one agent ag_j belonging to Ag_i which AND-depends upon a set of sets of agents AG_k and $|AG_k| = |Ag_l|, Ag_l$ is the subset of agents depending on ag_j, there are two or more compatible cycles, each satisfying the AMONG-dependence conditions.

While OR-dependence always unbalance and endanger AMONG-dependence, AND-dependence is compatible with it when equity is also satisfied, meaning, when the AND-depending agent can give to as many agents as those she can receive from.

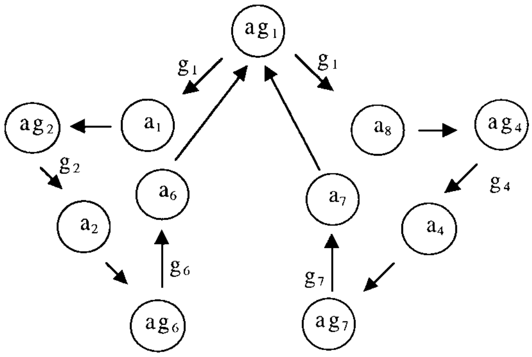

Figure 10. Strong AMONG-dependence.

More generally we can say that AMONG-dependence is likely to lead to group formation when the equity clause is also satisfied, namely when:

> *Equity clause—For all agents ag_j belonging to the set Ag_i of AMONG-depending agents, the subset of agents Ag_k which ag_j s-depends upon is equal to the subset Ag_l of agents s-depending on ag_j.*

When this clause is not satisfied, the AMONG-depending graph is bound to either split or shrink, or group agreement is less likely to occur.

5.3. Group Dependence

AMONG-dependence holding in a set of agents may give rise to GROUP-dependence when the equity condition is satisfied.

When the equity condition applies (all agents depend on others as much as they are needed by others), AMONG-dependence leads to a global network, a potential group structure, since no-one can achieve its goal independent of the others' achievements and actions. This will be called *GROUP*-dependence (but group exchange may also arise from other relationships).[9]

Below, we will distinguish two conceptually different types of group dependence, which can co-exist in real matters.

5.3.1. Decentralised Group-Dependence. Consider the following clause:

> *Egalitarian clause—For all agents ag_j belonging to the set Ag_i of AMONG-depending agents, ag_j depends upon the same number of agents, and is useful for the same number of agents.*

When both the equity and the egalitarian clauses hold, a decentralised structure emerges: none plays a leading role, and all share an equal condition. All the agents involved may find an agreement leading them to receive what they need and provide what they are expected to

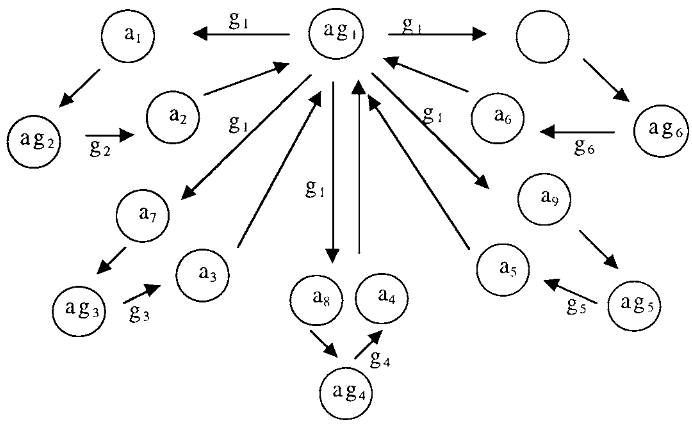

Figure 11. Centralized GROUP-dependence.

deliver. If, and only if, all agents respect the agreement, the group-dependence will actually lead to an effective group partnership. Of course, a complex social process is necessary for the agreement both to be established and to be respected by all members. An example of a decentralised GROUP-dependence can be found in figure 6, if we consider exclusively the set of agents $Ag_i = \{ag_1, ag_2, ag_7\}$.

5.3.2. Centralised Group-Dependence. The fundamental dependence relationship that occurs in group-exchange is *reciprocal* dependence. Agents depend on one another each to achieve their own goals. Both reciprocal and group dependence, in fact, occur quite frequently in competitive contexts, like markets.

An intermediate phenomenon, bridging the gap between group and collective dependence, group exchange and teamwork, is centralised group dependence. Consider the dependence graph presented in figure 11. Here, one agent ag_1 AND-depends on all others to achieve her goal g_1, and all others depend on ag_1 to achieve each its own goal. There is a complete intersection among the set of agents ag_1 AND-depends upon and the set of agents depending upon ag_1.

Centralised GROUP-dependence is a special case of AMONG-dependence in which the egalitarian condition does not apply (although the equity clause does), but there is at least one agent which plays a leading role. The dependence graph is centralised thanks to a multiagent plan owned by one of the agents. All others are complementary for this one to execute her plan. This agent will “hire” all others to achieve this plan. In formal terms, centralised GROUP-dependence occurs in a set of AMONG-depending agents Ag_i when all the following conditions hold:

1. the equity clause is satisfied;
2. there is at least one agent ag_j belonging to Ag_i which AND-depends on a set of sets of agents AG_k, where each element of $AG_k = \{\{ag_p\}, \{ag_q\}, \ldots, \{ag_v\}\}$ is a singleton whose element $ag_q \in Ag_i$ and $|AG_k| = |Ag_i|$;
3. any agent ag_k belonging to Ag_i depends upon ag_j.

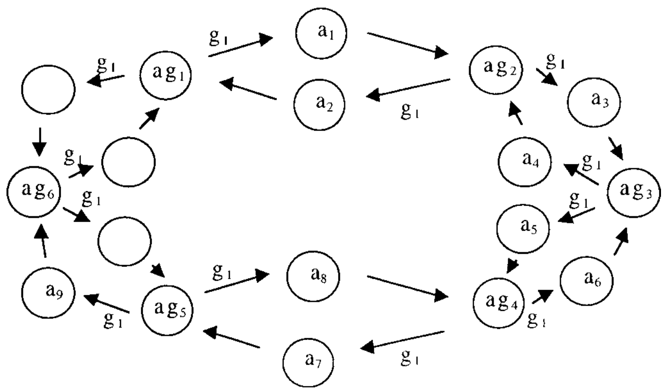

Figure 12. COLL-dependence in teamwork.

In centralised group-dependence a group is likely to be formed and led by one agent which represents the head of the network.

Obviously, if one single agent OR-depends on all others, no group will emerge, but only two agents will form a partnership in exchange (the equity clause is not satisfied). Being the most useful and the least depending agent, the leader of the network would choose her partner for exchange.

5.4. Collective Dependence

Collective dependence is to group dependence what mutual dependence is to reciprocal dependence. The fundamental relationship of dependence is here *mutual* dependence. Rather than a clear-cut distinction, however, group and collective dependence are situated on a continuum. AMONG-dependence graphs vary, among other factors (number of links, decentralised/non-decentralised), according to whether the agents involved share the goals with regard to which they depend on one another, or else pursue different goals. A COLL-dependence (or collective dependence) relationship holds in a set of AMONG-depending agents when each agent depends on all others to achieve a shared goal (cf. figure 12).

Collective dependence therefore leads to a rather cohesive group executing a multiagent plan, i.e. teamwork. All agents are complementary to achieve one and the same goal.

In figure 12, a dependence graph where each agent depends on all others is shown. Such a network is inherent to the team and is based upon the multiagent task that the team is supposed to accomplish. Full collective dependence occurs when the complementary agents share the goal for which they are needed.

In such a case, each member in the set of AMONG-depending agents depends on all others to achieve a common goal.[10] A band of rogues offers a typical example of COLL-dependence.

To sum up, a bunch of agents searching partners for bargain are plunged in a more or less complex dependence graph, where groups and collectives arise. Rather than a clear-cut distinction, the difference between groups and collectives consist of different levels of complexity and cohesiveness of the underlying dependence graph.

Group dependence may occur in market-like contexts. However, it is not yet alike the situation depicted in figure XXX, where each agent depends on all others.

Full collective dependence occurs when the complementary agents share the goal for which they are needed. In such a case, each member in the set of complementary agents depends on all others to achieve the shared goal.

5.5. Inter-Dependent Groups

The situation shown in figure 12 presents analogies with those depicted in figure 10: in both cases there are inter-dependent cycles. Not only single agents, but also groups of agents may be inter-dependent. A group or collective Ag_i may s-depend on any agent ag_k (or set Ag_k), which is *not* a member (or subset) of Ag_i, if at least one agent ag_j belonging to the group Ag_i s-depends for her goal upon ag_k (or set Ag_k). There are two sub-cases.

1. ag_j AND-depends upon the set of sets of agents $AG_k = \{\{ag_k\}, \{ag_q\}, \dots, \{ag_v\}\}$, which contains at least the singleton $\{ag_k\}$ and at least another singleton $\{ag_q\}$ with $ag_q \in Ag_i$. In this case, the group or collective s-depends upon ag_k. Suppose a band of rogues intend to organise a robbery in a bank. Suppose one of bank clerks can give them instructions about how to set the alarm system off. The dependence is here unilateral: all the rogues depend on the clerk, but the latter does not depend on them in return. Consider now the case in which the clerk expects to have a share of the booty. The dependence is bilateral: while the rogues s-depend upon the clerk (information), the latter depends upon the team to succeed (money). An analogous situation occurs in group-dependence. Suppose Maria will lend me one of her new dress for tomorrow party if I lend Alice my elegant purse so that Alice will let Maria use her high-heel shoes. Suppose I need Eva's help for removing a stain from Maria's dress. In such a case the whole group depends upon Eva. If Eva in return depends upon me to get an invitation to the party, she is also depending on the group. Of course, a group may depend on another, as would happen in the previous example if Eva promises to remove the stain on Alice's dress only if Laura does some housecleaning for her, which Laura will certainly do on condition that someone will type her paper... . In such a case, group dependence is bilateral. Any group works on condition that the other does.
2. ag_j OR-depends upon the set of agents $Ag_k = \{ag_k, ag_q, \dots, ag_v\}$, which contains at least the element ag_k and at least another element ag_q with $ag_q \in Ag_i$. Here, the likelihood that Ag_i forms a group is an inverse function of the likelihood that ag_j will enter a partnership with ag_k. Interestingly, ag_j's choice may depend, among other factors, on the relative costs of the action she is expected to do for each group. I may prefer to lend my gloves to Claudia, who can let me wear her dress, rather than give my purse to Alice, who will certainly spoil it.

6. Conclusions

In this paper, a theory of dependence in multi agent systems has been applied to multi agent dependence links among sets of agents, and interdependence among groups of agents.

The approach presented in this paper may have several advantages for multi agent co-ordination and cooperation. First it shows how and why exchange can extend beyond the confines of two-agent relationships, thereby enlarging the possibilities of goal achievement through exchange. Secondly, it models the emergence of objective multi agent structures (dependence networks) of variable complexity in aggregates of heterogeneous agents. Thirdly, factors facilitating or endangering the likelihood of group formation from these structures have been examined to some extent.

The present approach is conceived of as a tool which can be implemented in order to provide multi agent systems with a device to speed up and facilitate the negotiation process, somehow impaired by the growing autonomy and heterogeneity of individual agents. But it is also intended to provide a theoretical instrument for the understanding of complex social systems and their dynamics. One fundamental feature of the approach here presented resides precisely in its strongly dynamic nature: dependence graphs in open systems are intrinsically fragile, since phenomena at the local level (agents' entering or exiting the market) may cause a reconfiguration of the whole graph. At the same time and for the same reason, the dependence theory allows social and collective phenomena to be described and predicted in terms of individuals' heterogeneous features.

Next studies are aimed to:

- Work out a formal model of the quantity of dependence;
- Incorporate the notions here presented in a computational system (e.g., DEPNET), in order to check the efficiency of the model;
- Run simulations to test its predictive power with regard to the emergence of groups and collectives.

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Notes

1. As was objected by one reviewer of a previews draft of this paper.
2. The agent q whose plans are used to infer these notions is called source agent. We show in Sichman et al. (1994) and Sichman and Demazeau (2001) that sometimes it may be useful for an agent to use other agents' plans.
3. In our theory, resources include actions. However, for simplicity only action-dependence will be considered. By definition, actions available in one's repertoire can always be re-used. In case of resource deployment, actions can be set to the non-active value after a to-be-established number of times in which they have been used.
4. In fact, in Sichman and Demazeau (2001) two basic dependence relations are defined, one for actions and the other for resources. For simplicity, we will consider in the rest of the text only action dependencies, and drop the subscript used in the original formulation. This is not a limitation, however, since realising a resource can be modelled as an action.

5. A complementary criterion is the locality of dependence: it may be interesting for ag_i to infer if ag_j is also aware of these dependencies. This criterion is not directly relevant for the present exposition and will not be examined here (however, see Sichman et al. (1994) and Sichman and Demazeau (2001) for a treatment of this aspect.
6. For the sake of brevity, we will ignore multi-party dependence with regard to different goals, which, by the way, is but a multiple two-party dependence. Therefore, in this paper, we consider exclusively the situation where an agent needs more than one action to achieve a certain goal.
7. Agent ag_k is the origin of path to which this edge belongs, as illustrated in the sequence.
8. AMONG-dependence could be quantified as a function of the number of agents belonging to the set of agents involved (and the number of steps that should be realised in order for all agents to receive and give help). However, other variables should be taken into account as will be seen later on in the paper.
9. One interesting source of group exchange is indirect dependence, which bridges the gap between two-party and multi-party dependence. For the specific character of this particular phenomenon, and for the sake of brevity, this issue will not be dealt with in this paper, but will be an object of future work. For a preliminary analysis, however, the interested reader is addressed to Castelfranchi et al. (1992).
10. COLL-dependence need not be decentralised as in figure 12. If there is at least one agent ag_j (or a subset of agents Ag_j) member of Ag_i upon which all others depend upon in order to accomplish their share of the collective task, ag_j (or Ag_j) will play a leading role. A typical example is an orchestra, which is led by one member, the director.

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