# Extending Social Reasoning to Cope with Multiple Partner Coalitions

Nuno David[1], Jaime Simão Sichman[2], and Helder Coelho[3]

[1] ISCTE/DCTI, Department of Information and Technology Sciences, Lisbon, Portugal
Nuno.David@iscte.pt
[2] LTI/PCS/EP/USP, University of São Paulo, São Paulo, Brazil
jaime@pcs.usp.br
[3] DI/FC/UL, University of Lisbon, Lisbon, Portugal
hcoelho@di.fc.ul.pt

**Abstract.** We present a utility-driven rationality and a complementary-driven rationality based model, relative to multiple partner coalitions, motivated by relations of dependence and instrumental goal adoption. For this purpose, we analyze social dependency patterns and its corresponding dependency networks. The networks are used as a source of quantitative and qualitative information with which an agent is able to choose the best set of partners and adequate proposals to form coalitions. An e-commerce example is presented, showing the usefulness of the mechanism in real world multi-agent systems.

## 1 Introduction

In some classes of multi-agent systems (MAS), the notion of autonomy usually suggests that agents do not necessarily attempt to do what is requested of them. This so-called non-benevolence assumption is frequently undertaken from two divergent points of view: (1) a quantitative utility oriented perspective, from which the most obvious examples are game theoretic models (e.g. [9]), or (2) a socio-psychological perspective, from which we may refer to the theory of dependence and social power [1][2]. Common to both perspectives is the problem around the choice of partners and proposals for coalition formation. With respect to the first approach, choice of partners and proposals has been fundamentally associated with the classic principle of economic rationality (maximizing the agent's expected utility as suggested by decision theory, (e.g. [3])). As for the second approach the literature is not so extensive. Sichman and his partners [5][6] adopt a pure complementary-driven rationality and propose a taxonomy of *dependency situations* as a criterion for choosing partners susceptible to accept proposals of coalitions. Nevertheless, the latest research does not consider multiple partner coalitions and the taxonomy is solely based on the agents' goals, beyond the set of possible plans, actions and its corresponding costs, which are required for an effective proposal of coalition.

In this paper, we extend the *social reasoning mechanism* [6] and present both a utility-driven rationality (quantitative) and a complementary-driven rationality (dependence) based model, relative to multiple partner coalitions, motivated by relations of dependence and instrumental goal adoption [1][2]. To achieve this aim, we analyze social dependency patterns and model its corresponding dependency networks with the concepts of *and-* and *or-dependencies* [1] and *inverse dependence relations*. Such networks are utilized as a source of quantitative and qualitative information with which an agent is able to decide about the best set of partners and adequate proposals in order to form multiple partner coalitions. Specifically, we advocate that a preliminary selection of adequate offered goals, plans and actions with respect to a proposal is intimately related to qualitative notions of dependency situations between partners. On the other hand, the final selection of actions to be effectively proposed to the partners depends closely on quantitative measures of dependence between partners. We conclude with a practical example in the field of e-commerce in the Internet. The example involves coalitions of companies in the software industry, where the adoption of each other's "service packages" for software reuse is a strategic advantage.

## 2 The Social Reasoning Mechanism

The social reasoning mechanism allows an agent to reason about the capabilities of others in order to answer such questions as whether his goals and plans are feasible and/or to assess how he stands in relation to other agents in the agency. Consequently, an agent must have a data structure where this information about the others is stored. Such data structure is called an *external description* - a private data structure that holds for every agent, including himself, a corresponding entry describing the *goals* an agent wants to achieve; the *actions* an agent is able to perform; the *resources* an agent is able to use; and the *plans* an agent wants to execute, making use of any actions and resources in order to achieve a certain goal.

We start by assuming a finite set of agents $Ag$. The agent $ag_o \in Ag$ is a generic agent, designated *object* agent, whose social properties are going to be analyzed by a *subject* agent. It is quite often the case when the subject and the object of social reasoning analysis are one and the same, and we will consider this fact hereinafter, i.e., the agent $ag_o$ represents both the *subject* and *object* agents. The external description of the object *agent* $ag_o$, regarding some third party *agent* $ag_t$ **entry**, is defined as follows: $Ext_{ag_o}(ag_t)=_{def} \{G_{ag_o}(ag_t), A_{ag_o}(ag_t), R_{ag_o}(ag_t), P_{ag_o}(ag_t)\}$, where $G_{ag_o}(ag_t)$ is a set of goals, $A_{ag_o}(ag_t)$ is a set of actions, $R_{ag_o}(ag_t)$ is a set of resources and $P_{ag_o}(ag_t)$ is a set of plans (we do not analyse resources dependencies but see [6] for a preliminary analysis). A plan $p=(id_{goal}(p),I(p))$ that supposedly achieves some goal given by its goal identity $id_{goal}(p)$ comprises a set of instantiated actions $I(p)$, each one of them $i \in I(p)$ corresponding to some action given by its instantiated action identity $id_{action}(i)$. These actions needed by a plan do not necessarily belong to every agent's set of controlled actions and thus an agent may *depend* on others in order to carry out a plan and attain a particular goal.

In the present work, we use two quantities in the external description: the importance given by the *third party* agent $ag_t$ to each one of his goals $g \in G_{ag_o}(ag_t)$, denoted by $w_{ag_o}(ag_t,g)$, and the cost given by the *third party* agent $ag_t$ to each one of his controlled actions $a \in A_{ag_o}(ag_t)$, denoted by $c_{ag_o}(ag_t,a)$. Notice that the expected cost for each instantiated action in a plan depends on the set of costs given by all agents that are able to execute the action in the agency. From the point of view of the *object* agent $ag_o$, an action is said to be *available* if there is, at least, one *third party* agent $ag_t$ represented in his external description $Ext_{ag_o}$ that is able to perform it (maybe the object agent himself). The predicate $feasible_{ag_o}(p)$ is true if for every instantiated action in the plan $p$ the corresponding action is available. If a plan is feasible, some needed actions and the corresponding costs may be controlled by some agents but not by others. Therefore, plan expected costs are calculated dynamically and are not explicitly represented in the external description. If a plan is not feasible its expected cost will be undefined.

## 2.1 Inverse dependence relations

We adopt a definition of dependence based on the notion of *action-dependencies*. Let $E_{ag_o}$ be the set of all agents represented in the external description $Ext_{ag_o}$ of *object* agent $ag_o$. We say an *object* agent $ag_o$ has an *action-dependency* relative to a plan $p$ and an action $a$, if the *object* agent $ag_o$ is not able to perform the action but there is one other *third party* agent $ag_t$ member of $E_{ag_o}$ who is able to perform it:

$$a\_dep(ag_o,p,a) \equiv_{def} \exists (i \in I(p))\, (id_{action}(i)=a \wedge a \notin A_{ag_o}(ag_o) \wedge \exists (ag_t \in E_{ag_o})\, (a \in A_{ag_o}(ag_t))) \,. \quad (1)$$

An *object* agent $ag_o$ has a dependency on a *third party* agent $ag_t$, in regard to a specific goal $g$, according to the plans the *object* agent thinks the *source* agent $ag_s$ has, iff (1) the *object* agent $ag_o$ has the goal $g$ in his set of goals $G_{ag_o}(ag_o)$; (2) there is a plan for goal $g$ in the set of plans $P_{ag_o}(ag_s)$ that the *object* agent thinks the *source* agent $ag_s$ has, and (3) the *object* agent $ag_o$ has, at least, one action-dependency corresponding to some instantiated action in the plan for which the action is available in the set of actions $A_{ag_o}(ag_t)$ that the *object* agent thinks the *third party* agent $ag_t$ has, i.e. the *third party* agent is able to perform the action according to the *object* agent's beliefs:

$$\begin{aligned} dep\_on(ag_o,ag_t,g,ag_s) \equiv_{def} & \exists (g \in G_{ag_o}(ag_o),\ p \in P_{ag_o}(ag_s)) \\ & (id_{goal}(p)=g \wedge \exists (i \in I(p),\ a \in A_{ag_o}(ag_t))\, (a\_dep(ag_o,p,a) \wedge a=id_{action}(i))) \,. \end{aligned} \quad (2)$$

Dependency situations (dep-sits) are based on the distinction between social cooperation and social exchange [2] and local and non-local believed dependencies [6]. An object agent $ag_o$ is Mutually Dependent on a third party agent $ag_t$ for some goal $g$, according to the plans the object agent thinks the source agent $ag_s$ has, if the object agent and the third party agent depend on each other for goal $g$, according to the plans the object agent believes the source agent has. While a **M**utual **D**ependency between the object agent $ag_o$ and the third party agent $ag_t$ interprets a bilateral dependency concerning the same goal $g$, a **R**eciprocal **D**ependency translates a bilateral dependency in regard to two different goals $g$ and $g'$:

$$\begin{aligned} MD(ag_o,ag_t,g,ag_s) &\equiv_{def} dep\_on(ag_o,ag_t,g,ag_s) \wedge dep\_on(ag_t,ag_o,g,ag_s) \,. \\ RD(ag_o,ag_t,g,g',ag_s) &\equiv_{def} dep\_on(ag_o,ag_t,g,ag_s) \wedge dep\_on(ag_t,ag_o,g',ag_s) \wedge g \neq g' \,. \end{aligned} \quad (3)$$

Moreover, if the object agent $ag_o$ concludes there is a mutual dependency with the third party agent $ag_t$ for goal $g$, according to his own set of plans, but he can not reach the same conclusion using the set of plans he believes the third party agent has, then there is a Local Believed Mutual Dependency: $LBMD(ag_o,ag_t,g) \equiv_{def} MD(ag_o,ag_t,g,ag_o) \wedge \neg MD(ag_o,ag_t,g,ag_t)$. However, if the object agent also reaches the same conclusion using the plans he believes the third party agent has, he will infer a Mutual Believed Mutual Dependency (MBMD).

**Table 1.** Dependency situations as seen by the subject/object agent. Column headers indicate dependencies inferred according to the object agent's set of plans and line headers according to the plans the object agent thinks the third party agent has: Mutual Believed Mutual Dependencies, Local Believed Mutual Dependencies, Mutual Believed Reciprocal Dependencies, Local Believed Reciprocal Dependencies and Unilateral Dependencies.

| $P_{ag_o}(ag_t)$ \ $P_{ag_o}(ag_o)$ | $MD(ag_o,ag_t,g,ag_o)$ | $RD(ag_o,ag_t,g,g',ag_o)$ | $dep\_on(ag_o,ag_t,g,ag_o)$ | $\neg dep\_on(ag_o,ag_t,g,ag_o)$ |
|---|---|---|---|---|
| $MD(ag_o,ag_t,g,ag_t)$ | MBMD (1) | LBRD (2) | UD (3) | IND (4) |
| $RD(ag_o,ag_t,g,g',ag_t)$ | LBMD (5) | MBRD (6) | UD (7) | IND (8) |
| $dep\_on(ag_t,ag_o,g,ag_t)$ | LBMD (9) | LBRD (10) | UD (11) | IND (12) |
| $dep\_on(ag_o,ag_t,g,ag_t)$ | LBMD (13) | LBRD (14) | UD (15) | IND (16) |
| $\neg dep\_on(ag_t,ag_o,g,ag_t)$ | LBMD (17) | LBRD (18) | UD (19) | IND (20) |

As shown in the table, the referred taxonomy of dep-sits is a very general one. A detailed analysis on the referred set of dep-sits may look for further composition of local dependencies. Suppose that some object agent finds himself in situation number eleven (11). He will infer a Unilateral Dependency (UD) with the third party agent. Yet, the third party agent is also unilaterally dependent on him according to the plans he believes the third party agent has. This may as well be an incentive for cooperation or social exchange. Even though the object agent and the third party agent plans must be necessarily different (considering $E_{ag_o}(ag_o)=E_{ag_t}(ag_o) \wedge E_{ag_t}(ag_t)=E_{ag_o}(ag_t)$) each agent thinks that he depends on the other according to his own plans. The crucial point to note is that a single third party agent dependency on the object agent, inferred according to the plans the object agent thinks the third party has, assigns some sort of social (strategic) power to the object agent over the third party agent as well. In fact, if the object agent finds some sort of dependence on the third party agent, according to his own plans, he might be open to influence the third party agent to collaborate by using his power over what he thinks the third party agent beliefs are. Note that even if one or both agents do not believe that the other's plans are right (e.g. do not achieve the intended goals), they might be open to collaborate in order to attain their own goals. This does not necessarily breaks a principle of sincerity assumption: both agents may be aware of the fact; still, they believe the other party beliefs are wrong and theirs are right.

We call a third party agent dependency on the object agent inferred according to the plans the object agent thinks the third party has, a Remote Believed Inverse Dependency: $RBID(ag_o,ag_t,g) \equiv_{def} dep\_on(ag_t,ag_o,g,ag_t)$. Conversely, we call a third party agent dependency on the object agent, inferred according to the object agent's set of plans, a Local Believed Inverse Dependency: $LBID(ag_o,ag_t,g) \equiv_{def} dep\_on(ag_t,ag_o,g,ag_o)$.

## 3 Dependency and Strategic Reasoning

Usually, after a proposal, there may be three subsequent basic outcomes: the potential partner accepts the proposal without further demands; rejects the proposal; or makes a counter-proposal in order to reach an agreement, which may partially satisfy all parties involved. In effect, the principal vehicle for carrying out negotiation activities is the exchange of proposals and counter-proposals. Moreover, to reject an offer and not to make a counter-proposal may well lead the other party to break off negotiation [4]. The initial choice of potential partners should, therefore, be viewed in *strategic* terms. Not only should the proponent have in hands a first valuable proposal, sufficiently strong to lead the potential partner to collaborate, but also be able to control other alternative propositions, which may be needed to deal with the potential partners' further counter-proposals.

Most of existing work in strategic reasoning in MAS has been exclusively based on pure decision utility-based models (e.g. [8]). However, when reasoning about coalition formation in cognitive domains, the commitment to a minimal cost solution associated with a certain set of possible partners does not necessarily contributes to the proponent's predicative power on their intentional decisions and thus their susceptibility to accept proposals of coalition. For this end, prior reasoning on the third party agents' goals and dependencies is needed (social power/bargaining). Assume that some object agent $ag_o$ is pursuing some goal $g_e$ and commits to some feasible plan $p_e$ that we call the object agent's *engaged goal* and *engaged plan*, respectively. If the engaged plan is feasible then all action-dependencies expected costs can be computed since all actions and its corresponding set of costs are available in the agency. In reality, plan choices to achieve a specific goal may depend on a number of criteria such as plan feasibility conditions, number of action-dependencies, and/or instantiated actions (expected) costs. Analogously, two classes of criteria for selection of multiple partners relative to some engaged goal $g_e \in G_{ag_o}(ag_o)$, and engaged plan $p_e \in P_{ag_o}(ag_o)$ are identified, namely, complementary (C) and utility (U) oriented choices:

**(C1) Number of action-dependencies the third party agent originates on the object agent's chosen plan.** Conjunctive dependencies or *and-dependencies* [1] augment the degree of power/dependence between agents. We call *multi-action and-dependencies* to a set of actions if every action makes the same agent dependent on another relative to the same plan. In purely complementary terms, the higher is the number of action-dependencies that make the object agent dependent on the third party agent with reference to the engaged plan, the more the object agent depends on the third party agent. On the other hand, such condition may decrease the number of expected partners in the coalition and thus the overall communication flow.

**(C2) Number of goals that make the third party agent dependent on the object agent.** Prior effective planning and preparation are among the most critical elements to achieve further negotiation objectives. This requires an effort from the proponent agent, not only to specify his objectives and goals, but also to understand the possible partner's perspective and identify his needs and goals. This point is crucial for social exchange, where the object agent must find which third party agent goals originate reciprocal dependencies if coupled with the object agent's engaged goal. The higher is the number of goals that are identified, the larger will be the set of possible alternative proposals. We call the goals that may be offered to a third party agent the object agent's *offered-goals*. Offered goals are captured by the notion of *multi-goal and-dependencies* - the third party agent depends on the object agent for multiple goals. Offered goals comprise any goal $g$ in the set of goals that the object agent thinks the third party agent has $G_{ag_o}(ag_t)$, which make the third party agent $ag_t$ dependent on the object agent $ag_o$, respectively, according to the object agent's set of plans or the set of plans the object agent thinks the third party agent has, i.e., local or remote believed inverse dependencies:

$$\textit{Off-Goals}_{ag_o}(ag_t) \equiv_{def} \{g \in G_{ag_o}(ag_t) \mid LBID(ag_o, ag_t, g) \vee RBID(ag_o, ag_t, g)\}. \quad (4)$$

**(C3) Number of available plans for each offered goal** *Multi-plan or-dependencies* result from multiple action-dependencies within different plans that make the third party agent dependent on the object agent for the same goal. The set of all possible *offered plans* comprises any plan $p$ in the object agent's set of plans $P_{ag_o}(ag_o)$ or in the set of plans that the object agent thinks the third party has $P_{ag_o}(ag_t)$, that may contribute to any offered goal:

$$\textit{Off-Plans}_{ag_o}(ag_t) \equiv_{def} \{p \in (P_{ag_o}(ag_o) \cup P_{ag_o}(ag_t)) \mid \exists (g \in \textit{Off-Goals}_{ag_o}(ag_t))(id_{goal}(p)=g)\}. \quad (5)$$

Interestingly, the existence of *multi-plan or-dependencies* may be a strategically advantage for all parties involved, enriching the range of available solutions, and consequently the possible existence of satisfactory proposals for both parties.

**(C4) Number of actions controlled by the object agent and not controlled by the third party agent for each offered plan.** The set of *offered actions* comprises any action $a$ in the object agent's set of controlled actions $A_{ag_o}(ag_t)$ that make the third party agent $ag_t$ dependent on the object agent $ag_o$ for any offered plan:

$$\textit{Off-Actions}_{ag_o}(ag_t) \equiv_{def} \{a \in A_{ag_o}(ag_o) \mid \exists (p \in \textit{Off-Plans}_{ag_o}(ag_t))(a\_dep_{ag_o}(ag_t, p, a))\}. \quad (6)$$

Notice that there is the case of *multi-plan or-dependencies* with respect to a same offered goal, where for each offered plan there is a **distinct** offered action, and the case where a set of offered plans for a same offered goal hold one **same** offered action. The latest situation is highly valuable since the object agent may offer a number of alternative solutions to the third party agent with a single offered action. Moreover, a unique offered action can also contribute to accomplish multiple offered non-parallel goals, yielding a strong influencing power over the third party agent.

**(U1) The cost each third party agent assigns to each object agent's action-dependency in the object agent's engaged plan.** The choice of a plan has inherently attached an individual internal commitment to the object agent: finding a set of preferred partners, each one chosen from the set of possible partners associated with each action-dependency. For each action-dependency and from the corresponding set of possible partners, the third party agent assigning the lowest cost to the action is chosen among the ones who share the highest degree of dependence. Indeed, even though a proposal may be rejected because of misleading beliefs involving one or both parties or simply disagreement of proposals and its costs, the proponent may hold other alternative possible partners for his action-dependency.

**(U2) The cost of the offered actions.** May be used as a function regulator to the third party agent degree of dependence on the object agent. Suppose the third party agent holds a great amount of dependence on the object agent but the object agent costs for executing his *offered actions* are expected to be very high. Consequently, it may not turn out to be a strategic advantage to collaborate, at least, from the object agent's point of view.

**(U3) The importance of the offered goal(s).** A prioritization of the partners' goals shall be considered. Once again, this situation is more relevant for reciprocal dep-sit cases, as there may be several alternative goals to offer. Here, the strategic value rests, essentially, on which goals to offer when in the first stages of coalition proposal, beyond partner selection activities.

Frequently, negotiation fails to set clear objectives. Hence, when something has to be given, or the other party makes a proposal that rearranges the elements in a settlement, they are not in a position to evaluate new possibilities quickly and accurately [4]. Beyond the search for the best potential partners, there is equally a need to reason around the most adequate corresponding proposals to be sent. For this purpose, a specific social dependency network is established holding all possible offered actions and their costs to every possible offered plan, all possible offered plans to every possible offered goal, all possible offered goals and their importance to every possible partner, and all possible partners for each action-dependency and its corresponding expected cost. The result is a structural network of alternatives that can be used to reason about workable proposals and feasible arguments. Furthermore, when picking up the possible partners with the *highest* and *strongest* dep-sit, there is a good chance of achieving a quick agreement. The *highest* dep-sit is calculated with reference to a partial ordered set of dep-sits (e.g. see [5]). The *strength* accounts for an assessment on the number of the possible partner's *and-* and *or-dependencies* on the proponent. What we need is to quantify the *dimension* of the dependency network.

Different offered actions assign different degrees of power over an agent and thus contribute differently to each possible partner's strength of dependence. We define a function for every third party agent $ag_t$ represented in the object agent's external description and for every action $a$ available in the set of offered actions, adding value to actions contributing to a significant number of plans and goals. We call this function (offered) action strength:

$$\textit{action-strength}_{ag_o}(ag_t,a) =_{def} (\Sigma_i\ N_{plans}(g^a{}_i)\ .\ w_{ag_o}(ag_t,g^a{}_i)) / c_{ag_o}(ag_o,a)) \,. \qquad (7)$$

Here, $g^a{}_i$ is any offered goal for which the offered action $a$ contributes, $w_{ag_o}(ag_t,g^a{}_i)$ is the goal importance as given by the external description third party agent entry, $N_{plans}(g^a{}_i)$ is the number of offered plans for which the offered action $a$ contributes and $c_{ag_o}(ag_o,a)$ is the cost of the offered action as given by the external description object agent entry. The third party agent $ag_t$ dependence strength on the object agent $ag_o$ is defined as the sum of all object agent's possible offered action strengths:

$$\textit{dep-strength}_{ag_o}(ag_t) =_{def} \Sigma_{a\,\in\,\textit{Offer-Actions}_{ag_o}(ag_t)}\ \textit{action-strength}_{ag_o}(ag_t,a) \,. \qquad (8)$$

The first formula considers criteria C2, C3, U2 and U3, adding value to actions that contribute to a high number of offered plans and offered goals. The last criterion acts as a denominator, regulating the third party agent's dependency links importance and number, against the cost of the offered action. Finally, the notion of dependence strength considers the number of possible offered actions, i.e. criterion C4, and ponders and integrates their strength. While the latter definition identifies the most dependent possible partners on the proponent, the former is able to identify the partners' most valued needed actions with respect to selection of adequate proposals.

# 4 Multiple Partner Coalitions

Let $\textit{Action-Dep}_{ag_o}(p_e)$ be the set of all object agent's action-dependencies with reference to his engaged plan $p_e$. For every action-dependency $a^d$ in $\textit{Action-Dep}_{ag_o}(p_e)$ there is a set of possible partners represented in the external description that are able to perform it. Furthermore, each possible partner will probably originate different dependence conditions. We want to find a set of ordered pairs $(a^d, ag_t)$ – action-dependency / best possible partner – where for each action-dependency $a^d$ in $\textit{Action-Dep}_{ag_o}(p_e)$ there is one third party agent $ag_t$ in the corresponding set of possible partners $\textit{Pos-Partners}_{ag_o}(p_e, a^d)$ for which the object agent $ag_o$ sends him a proposal of coalition. This is the problem of multiple partner coalitions associated with criterion C1, which may not be a mere generalization problem from two partner coalitions if communication flow is a critical problem in the system.

## 4.1 Choice of partners

At this point, we define a new strategy to identify third party agents that are susceptible to accept coalition proposals, while trying to decrease the proponent's costs and communication flow. The strategy assumes a sequence of priorities but any other sequence or composition of weighed functions could be used.

Let $\textit{highest-dsit}_{ag_o}:(\textit{superset}(E_{ag_o}), G_{ag_o}(ag_o), P_{ag_o}(ag_o)) \rightarrow \textit{superset}(E_{ag_o})$ be a function where, given a set of agents in the object agent's external description, the object agent's engaged goal $g_e$ and engaged plan $p_e$, returns the subset of agents with the highest inferred dep-sit using the set $\{p_e\}$ as the object agent's set of plans. Also, the function $\textit{n-adep}_{ag_o}:(E_{ag_o}, P_{ag_o}(ag_o)) \rightarrow N$ returns the number of action-dependencies in a given engaged plan $p_e$ that make the object agent dependent on a third party $ag_t$. Assume that the plan $p_e$ is feasible. Then for each action-dependency $a^d$ in the engaged plan $p_e$ there is a non-empty set of possible partners $\textit{PPartners}$ that are able to perform it.

**Definition 1** If $ag, ag' \in \textit{PPartners}$ then $ag' \leq_{partner} ag$ iff:

- $ag' = ag$, or
- $ag' \notin \textit{highest-dsit}(\textit{PPartners}, g_e, p_e) \wedge ag \in \textit{highest-dsit}(\textit{PPartners}, g_e, p_e)$,
- $ag', ag \in \textit{highest-dsit}(\textit{PPartners}, g_e, p_e) \wedge \textit{dep-strength}(ag') < \textit{dep-strength}(ag)$,
- $ag', ag \in \textit{highest-dsit}(\textit{PPartners}, g_e, p_e) \wedge \textit{dep-strength}(ag') = \textit{dep-strength}(ag) \wedge c(ag', a^d) > c(ag, a^d)$,
- $ag', ag \in \textit{highest-dsit}(\textit{PPartners}, g_e, p_e) \wedge \textit{dep\_strength}(ag') = \textit{dep-strength}(ag) \wedge c(ag', a^d) = c(ag, a^d) \wedge \textit{n-adep}(p_e, ag') < \textit{n-adep}(p_e, ag)$.

The relation $\leq_{partner} \subseteq \textit{PPartners} \times \textit{PPartners}$ is reflexive, anti-symmetric and transitive and thus a partial ordered set of possible partners. Let $S_{max}$ be the set in which all of its elements are major elements of $S^c_{max} = \textit{PPartners} - S_{max}$ and hence also maximal elements in $S_{max}$, that is, (i) if $ag \in S_{max}$ and $ag' \in S^c_{max}$ then $ag' \leq_{partner} ag$ and; (ii) for all $ag$

$\in S_{max}$ and $ag' \in S_{max}$, if $ag' \leq_{partner} ag$ then $ag'=ag$. The choice of a partner is defined as follows: $decision_{a\text{-}partner} =_{def} random(S_{max})$.

In conclusion, for each action-dependency $a^d \in$ ***Action-Dep***$_{ag_o}(p_e)$ in the engaged plan $p_e$, the preferred partner is chosen from the corresponding set of possible partners ***Pos-Partners***$_{ag_o}(p_e,a^d)$ among the ones originating the highest dep-sit, with the highest dependence strength, with the lowest action-dependency cost, inducing the highest number of action-dependencies in the engaged plan. If two third party agents share the same dependence conditions and costs, the one who is potentially able to execute the highest number of action-dependencies in the engaged plan is chosen, i.e., partner choices will try to decrease communication flow, still preventing weak dependent agents from overcoming strong dependent ones.

## 4.2 Choice of Proposals

### 4.2.1 Offered Goals

Suppose that the object agent infers a mutual dependency (locally or mutually believed) with the preferred partner. A logical and immediate proposed offered goal is the one that originates the mutual dependency. In reality, except for unilateral dependencies, the set of chosen offered goals for the preferred partner $ag_t$, engaged goal $g_e$ and plan $p_e$ results from offered goals that originate the dep-sit:

$$\textbf{C-OGoals}(ag_t,g_e,p_e) \equiv \quad (9)$$

$$\begin{cases} \{g_e\} & \text{if dep-sit}(ag_t,g_e,p_e)=MBMD \text{ or } LBMD \\ \{g' \in \textbf{Off-Goals}(ag_t) \mid LBID(ag_o,ag_t,g') \wedge RBID(ag_t,ag_o,g')\} & \text{if dep-sit}(ag_t,g_e,p_e)=MBRD \\ \{g' \in \textbf{Off-Goals}(ag_t) \mid LBID(ag_o,ag_t,g')\} & \text{if dep-sit}(ag_t,g_e,p_e)=LBRD \\ \{g' \in \textbf{Off-Goals}(ag_t) \mid RBID(ag_o,ag_t,g')\} & \text{if dep-sit}(ag_t,g_e,p_e)=UD \\ \varnothing & \text{if dep-sit}(ag_t,g_e,p_e)=IND \end{cases}$$

Notice in the Unilateral Dependency (UD) case that all chosen offered goals result necessarily from the set of plans the object agent thinks the preferred partner has, i.e., Remote Believed Inverse Dependencies (RBID). If there are no such dependencies, this set may be empty, meaning that the preferred partner has zero dependence strength on the object agent. If that is the case, then the object agent holds little or no influencing power over the preferred partner, which illustrates the possible existence of different degrees of influencing power for a same dependency situation.

### 4.2.2 Offered Plans

Beyond the intended effects on the preferred partner, proposed offered plans also play an important role on the proponent's needs, depending on the type of inferred dep-sit. For example, being a mutual dep-sit case, both parties are necessarily pursuing the same and identical goal. Therefore, the offered plan should be feasible in order to meet the proponent's goals, which are also the preferred partner's goals. Notice, however, that the existence of a single plan believed by both parties and originating a Mutual Believed Mutual Dependency (MBMD) implies two conditions: (i) there is a single plan for each set of plans in the external description that originate a mutual dependency; (ii) the two plans are identical. Being this case an exception rather than a rule, proposed offered actions should mostly result from mutually or locally believed plans so as to influence the preferred partner towards the proponents' goals and plans. On the contrary, if there is but a Unilateral Dependency (UD) then all offered plans are necessarily calculated according to the set of plans the object agent thinks the third party agent has. Such plans have little or no impact on the proponent mainly if his engaged goal $g_e$ differs from all goals associated with the set of offered plans.

Let the set $\textit{C-OPlans}(ag_t,g_e,p_e)_l$ be a subset of all offered plans $\textit{Off-Plans}(ag_t)$, calculated according to the set of chosen offered goals $\textit{C-OGoals}(ag_t,g_e,p_e)$, i.e., $\textit{C-OPlans}(ag_t,g_e,p_e)_l \equiv \{p \in \textit{Off-Plans}(ag_t) \mid \exists (g \in \textit{C-OGoals}(ag_t,g_e,p_e))(id_{goal}(p)=g)\}$.

**Definition 2** If $p1, p2 \in \textit{C-OPlans}(ag_t,g_e,p_e)_l$ then $p1 \leq_{plan} p2$ iff:

- $p1=p2$, or
- $feasible(p1)=false \wedge feasible(p2)=true$, or
- $feasible(p1)=feasible(p2)=true \wedge p1 \notin (P_{ag_o}(ag_o) \cap P_{ag_o}(ag_t)) \wedge p2 \in (P_{ag_o}(ag_o) \cap P_{ag_o}(ag_t))$, or
- $feasible(p1)=feasible(p2)=true \wedge p1,p2 \notin (P_{ag_o}(ag_o) \cap P_{ag_o}(ag_t)) \wedge p1 \in P_{ag_o}(ag_t) \wedge p2 \in P_{ag_o}(ag_o)$.

The set $(\textit{C-OPlans}(ag_t,g_e,p_e)_l, \leq_{plan})$ is an ordered set by $\leq_{plan}$. Assume the set of chosen offered plans $\textit{C-OPlans}(ag_t,g_e,p_e)$ to be the set in which all of its elements are major elements of $\textit{C-OPlans}(ag_t,g_e,p_e)^C = \textit{C-OPlans}(ag_t,g_e,p_e)_l - \textit{C-Oplans}(ag_t,g_e,p_e)$. The best feasible offered plans are the ones believed by both agents. Local believed plans are also preferred to non-local believed plans.

### 4.2.3 Offered Actions

Let $\textit{C-OActions}(ag_t,g_e,p_e)_l$ be the subset of all offered actions associated with the set of chosen offered plans, i.e,
$\textit{C-OActions}(ag_t,g_e,p_e)_l \equiv \{a \in \textit{Off-Actions}(ag_t) \mid \exists (p \in \textit{C-OPlans}(ag_t,g_e,p_e))(\exists (i \in I(p))(id_{action}(i)=a))\}$.
Assume that $\textit{max-strength}_a$ is the maximum action strength value in $\textit{C-OActions}(ag_t,g_e,p_e)_l$. The set of chosen offered actions $\textit{C-OActions}(ag_t,g_e,p_e)$ are those members of $\textit{C-OActions}(ag_t,g_e,p_e)_l$ that share the highest action strength.

In conclusion, the preferred offered action is chosen from the object agent's set of controlled actions associated with (1) offered goals originated by the highest dep-sit; (2) feasible and a convenient source set of plans; (3) the maximum observed action strength. The final proposal for each preferred partner $ag_t$, relative to the object agent's engaged goal $g_e$ and engaged plan $p_e$ is therefore:

$$decide_{prop}(ag_t,g_e,p_e) =_{def} \begin{cases} undef & \text{if } \textit{C-OActions}(ag_t,g_e,p_e)=\emptyset \\ (a, P(a), G(P(a))) & \text{if } \textit{C-OActions}(ag_t,g_e,p_e)\neq\emptyset \end{cases} \quad (10)$$

where,

$$a = random(\textit{C-OActions}(ag_t,g_e,p_e))$$
$$P(a) = \{p \in \textit{C-OPlans}(ag_t,g_e,p_e) \mid \exists (i \in I(p))(id_{action}(i)=a)\}$$
$$G(P(a)) = \{g \in \textit{C-OGoals}(ag_t,g_e,p_e) \mid \exists (p \in P(a))(id_{goal}(p)=g)\}$$

# 5 Example: Multi-Agent Contracts for Software Reuse

Experimentation was the way to evaluate our ideas about the social reasoning mechanism and to check the relevance of the hybrid decision rationality. Since we have limited space we present a piece of a small experiment concerning coalition formation for software reuse. Here a company has a set of projects (goals) and different alternative configurations (plans) of packages (actions) to build its software products. Each project is associated with a given importance and each package with its cost. Companies may be willing to set up a strategically agreement with the others, instead of building service packages from scratch. Suppose there are two agents known to Company A. The external description of Company A is the following:

```
Identity:  <CompA luke.somewhere.org 1090>          Goals:   SecureBrowser (90) / WordProc (100)
Actions:   EnglishThesaurus (10) / MultiLingThesaurus (12) / TCPPack (32)
Plans:     WordProc:= MultiLingThesaurus, HtmlEditPackS1.1, GraphEditPack.
           WordProc:= EnglishThesaurus, HtmlEditPackP, GraphEditPack.
Identity:  <CompB zeus.compB.org 1094>              Goals:   EMailClient (55)
Actions:   GraphEditPack (23) / HtmlEditPackS1.1 (25), SEditor (9)
Plans:     EMailClient:= TCPPack, SEditor.
Identity:  <CompC compC.org 1095>                   Goals:   SecureBrowser (110) / DBaseClient (65)
Actions:   SQLPack (4) / HtmlEditPackS1.1 (23)
Plans:     WordProc:= MultiLingThesaurus, HtmlEditPackS1.1, GraphEditPack.
           DBaseClient:= MultiLingThesaurus, SQLPack.
```

The agent CompA will adopt WordProc as his active goal and choose the plan with the least expected cost set of actions. He then builds his dependency networks:

```
The engaged goal is: WordProc (100), my dependency network with reference to goal <WordProc> is:
<CompA>
--------- WordProc (100)
     |--------- WordProc:= MultiLingThesaurus, HtmlEditPackS1.1, GraphEditPack. (Feasible EC:59.0)
     |     |--------- HtmlEditPackS1.1 (EC:24.0)
     |              |******** <CompB 1094> (25.0)
     |              |        | <CompC 1095> (23.0)
     |              |        |----------
     |              | GraphEditPack (EC:23.0)
     |              |******** <CompB 1094> (23.0)
     |                       |----------
     |--------- WordProc:= EnglishThesaurus, HtmlEditPackP, GraphEditPack. (Feasible EC:66.0)
           |--------- HtmlEditPackP (EC:33.0)
                    |******** <CompC 1096> (33.0)
                    |        |----------
                    | GraphEditPack  (EC:23.0)
                    |******** <CompB 1094> (23.0)
                             |----------
The chosen plan is <WordProc:= MultiLingThesaurus, HtmlEditPackS1.1, GraphEditPack.>.
(...)
My possible partners, offered goals, plans and actions for my action-dependencies are:
 HtmlEditPackS1.1 and GraphEditPack
|------
    |<CompB zeus.compB.org 1094> /dep-sit: UD / dep-strength: 1.7 / dep-action cost: 25.0 and 23.0
    |-------
         |EMailClient (55) (RBID)
         |-------
              |EMailClient:= TCPPack, SEditor. (NonLocalSource)
              |---------
                   |TCPPack (32)
HtmlEditPackS1.1
|------
    |<CompC compC.org 1095> / dep-sit: MBMD / dep-strength: 25.6 / dep-action cost: 23.0
    |-------
         |WordProc (110) (MBMD)
         |-------
         |    |WordProc:= MultiLingThesaurus, HtmlEditPackS1.1, GraphEditPack. (BothSources)
         |    |---------
         |    |    |MultiLingThesaurus (12)
         |    |    |------
         |    |WordProc:= EnglishThesaurus, HtmlEditPackP, GraphEditPack. (LocalSource)
         |    |---------
         |         |EnglishThesaurus (10)
         |         |------
         |DBaseClient (65) (RBID)
         |-------
              |DBaseClient:= MultiLingThesaurus, SQLPack. (NonLocalSource)
              |---------
                   |MultiLingThesaurus (12)
The selected partner(s) and proposal(s) are (dep-sit > dep-strength > action-cost > na-deps) :
| Needed action: <HtmlEditPackS1.1>              Chosen Partner: <CompC CompC.org 1095>
```

```
  Offered action: <MultiLingThesaurus>          Offered goals: <WordProc> / <DBaseClient>
| Needed action: <GraphEditPack>                Chosen Partner: <CompB zeus.compB.org 1094>
  Offered action: <TCPPack>                     Offered goals: <EMailClient>
Sending proposals of coalition to <CompC CompC.org 1095> and <CompB zeus.compB.org 1094> ...
```

There were two possible partners for the object agent CompA's missing package HtmlEDITPackS1.1 and one for GraphEditPack. Even though the agent CompB controls both packages, the object agent chose CompC for the first package in the coalition. In effect, CompA holds a significant flexibility for negotiating with CompC: (1) both agents are pursuing the same project and share a Mutual Believed Mutual Dependence (MBMD); (2) CompC's dependence strength (=25.6) is visibly high compared to CompB (=1.7); (2) in fact, CompA is aware that the package MultiLingThesaurus is an important one to CompC in two of his current projects, contributing to a strong dependence strength (WordProc and DBaseClient); (3) ComC assigns a lower cost than CompB to ComA's action-dependency HtmlEDITPackS1.1. Finally, CompC's missing package MultLingThesaurus belongs to a plan believed by both sources, holds the highest action strength in the network and therefore is chosen as one of the final proposals.

One may notice that CompA holds only a Unilateral Dependency (UD) on CompB. However, the power of CompA over CompB is not insignificant, according to the plans CompA thinks CompB has. In effect, CompA may be able to instrumentalize the Remote Believed Inverse Dependency (RBID) with his proposal involving the offered goal EmailCLient and the offered action TCPPack. Below we partially show CompB's dependency networks. He is in fact dependent on CompA for the proposed action TCPack and goal EMailClient. He also infers that he controls CompA's needed action GraphEditPack, according to the plans he thinks CompA has. Once more, Unilateral Dependencies (UD) do not necessarily mean zero dependence strength and negotiation power. Coalitions may in fact take place with different subjective views of the world. Notice that such situation was possible with consistent beliefs about each other's goals and controlled actions, even though they do not share the same plans.

```
Received a coalition proposal (PROP <CompA luke.somewhere.org 1090> (WordProc/GraphEditPack UD EmailClient/TCPPack))
My dependence network is:     <CompB>
                              ---------- EMailClient (55)
                                     |---------- EMailClient:= TCPPack, SEditor. (EC:41.0)
                                           |---------- TCPPack (EC:32.0)
                                                  |----------  <CompA 1090> (32.0)
My possible partners, offered goals, plans and actions for my action dependencies are:
 TCPPack
|------
  |<CompA luke.somewhere.org 1090> / dep-sit: UD / dep-strength: 12.8 / dep-action cost: 32.0
  |--------
       |WordProc (100) (RBID)
       |-------
           |WordProc:= MultiLingThesaurus, HtmlEditPackS1.1, GraphEditPack.(NonLocalSource)
           |---------
           |     |HtmlEditPackS1.1 (25)
           |     |------
           |        |GraphEditPack (23)
           |        |------
           |WordProc:= EnglishThesaurus, HtmlEditPackP, GraphEditPack. (NonLocalSource)
           |---------
                 |GraphEditPack (23)
(. . .) I will accept the proposal because I do not have a better partner.
```

# 6 Conclusions

There may be different degrees of influencing power for a same dependency situation. Inverse dependencies are valuable tools for reasoning strategically on the partners' needs and proposals. The network of inverse dependencies establishes a structural network of alternative proposals with relevant qualitative and quantitative information about possible courses of action to the proponent. The dimension of such social dependency network may be used strategically as a quantitative measure for selecting partners and proposals to form coalitions.

Our analysis and experimental results suggests that dependence based choices of partners and proposals are obligatorily integrated issues. Furthermore, while the choice of a goal with respect to a proposal is closely related to the set of observed dep-sits, the choice of relevant actions is related to quantitative measures of dependence. This means that it is essential to make an assessment on the set of available proposals before choosing adequate partners to form a coalition. Such view may be essential on a number of negotiation and brokering protocols involving multicasting (e.g. contract net protocols [7]) and in large and open networks (e.g. the Internet). The proponent is able to concentrate his efforts from the start on the possible partners that are more susceptible to accept his proposals, decreasing the amount of control and content information exchange and, possibly, the time to find the most suitable partners in the agency.

One interesting result concerns the proponent's power of influencing a third party agent to form a coalition even though he may not believe the third party is dependent on him according to his own plans, but only according to the plans he believes the third party has. This is common and fundamental in real world applications, since the other agents' plans play an important role in any negotiating project. For example, one can not imagine two aircraft companies negotiating without considering both companies' carriers in the final coalition.

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