Social Dependence-Based Methods for Coalition Formation in Multi-Agent Systems

FELICITAS MOKOM
University of Windsor
mokom@uwindsor.ca

In multi-agent systems, autonomous and disparate agents may need to assist each other in order to achieve their individual goals. To this effect, they may form coalitions. In social dependence-based coalition formation models, agents form coalitions with others based on their dependencies. Agents must reason about each other and coalitions may involve pairs or multiple agents. Issues such as the dynamic coalitions, predicting their emergence, formalizing the process and exploring agent rationality need to be addressed. This survey contains annotations of research publications describing different approaches used to aid in better understanding of the research.

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1. INTRODUCTION

Autonomous and heterogeneous agents in dynamic environments may be incapable or simply not wish to achieve their individual goals solely. To this effect agents may form coalitions towards providing assistance to each other. Generally, models for coalition formation have been grouped into two types. Utility-based models, such as in game theory [Zlotkin and Rosenschein 1994; Axelrod 1995], explore benefits and the distribution of payoffs where the agents' main objective is to maximize its expected utility. On the other hand, complementary-based models such as those rooted in social-dependence explore the relevance of agents' knowledge and skills and agents select partners based on social and psychological relations. In these models agents are required to reason about their relationships with each other. Castelfranchi et al. [1992] introduced the notion of social dependence via the integration of dependence theory [Coleman 1990] into multi-agent systems. All social dependence-based coalition models are based on their work, often in combination with the notion of social power [Castelfranchi 1990]. This survey summarizes the work done by various researchers in the formation of coalitions using social-dependence based concepts.

The research papers for this survey have been found using Google Scholar, ACM, LNCS and IEEE.

Sichman's [1995] thesis along with the work in Sichman et al. [1994] and Sichman [1998] where coalition formation based on social dependence is introduced, are considered milestones in this survey. There are 5 other milestone papers. David et al. [1999] introduces the formation of multiple-partner coalitions, Panzarasa et al. [2002] attempts the formalization of the entire process using multi-modal logic, An et al. [2007] provides coalition formation algorithms based on transitive dependence, Boella et al. [2008] addresses coalitions and attacks and Grossi and Turrini [2010] is the first attempt to explicitly integrate game theory into social dependence-based coalition formation. The remaining 12 papers are considered important. Of the 20 papers that are the basis for this survey, 7 of the papers found are theoretical while 13 are experimental. The majority of the experimental papers use simulations to test their approach. 10 of the research papers are conference papers, 6 are journal papers, 3 are books from lecture notes in Computer Science and 1 is a Ph.D. thesis.

The first paper used in the survey research was written in 1994. There were 7 additional papers written in the 1990s. There were 12 papers written in the 2000s, including the last paper that was written in 2010.

The first set of research papers illustrate various social reasoning mechanisms used in the coalition formation process. The next set of papers explore coalition formation between pairs of agents. The next group presents papers dealing with coalitions formed among multiple partners. The last 2 papers integrate the notion of attacks into coalition formation and combine game theory with social dependence methods respectively. The survey has been structured in a maner that allows the progressive view of the subject area from the agents' reasoning process about who to partner with, to the formation of simple coalitions (between pairs) and ultimately to the formation of multiple-partner coalitions.

All the papers found derive concepts from the work in the first paper on social reasoning by Sichman et al. [1994]. There are 4 papers that explicitly deal with dynamic coalition formation which addresses issues that arise when agents can enter and leave the environment at will or change their plans. Formalization of the entire coalition process is attempted by 2 papers. There are 2 papers that explicitly present algorithms for finding social dependence-based coalitions. An attempt to incorporate utility into social dependence is made by 4 papers culminating in the integration of game theory by Grossi and Turrini [2010].

Grossi and Turrini's [2010] study combining game theory and social dependence, hints at the possibility that combining aspects from both concepts might be the next trend for coalition formation research. The authors note that social dependence-based models for coalition formation are criticized for their lack of a mathematical foundation which can be fulfilled by incorporating aspects of game theory.

2. SURVEY OF RESEARCH

2.1 Social Reasoning Mechanisms

The research papers in this section present studies depicting different ways in which agents can represent information with regard to dependencies on each other in a society. The agents' primary objective is to use this information to reason about others in the environment in order to determine who to approach for the formation of a coalition to achieve its goal. The majority of the papers are an extension of the concepts in the first paper by Sichman et al. [1994]. The last paper was written in 2007.

2.1.1 *Social Reasoning via external descriptions and dependence situations.* In order to take advantage of each others abilities and to adapt to a changing environment, agents need the capability to reason about each other. In the absence of such a mechanism, an agent would not know who to approach for help or how to adjust its existing relationships when agents enter or leave an environment. Sichman et al. [1994] appear to be the first researchers to address the ability of agents in a multi-agent system to reason about each other as a result of how they depend on each other in a domain independent way.

The authors refer to previous work by Yu and Mylopoulos [1993].

The authors criticize the study by Yu and Mylopoulos [1993] for being domain dependent.

Sichman et al. [1994] utilize Castelfranchi's [1990] notion of social power within multi-agent systems and Castelfranchi et al.'s [1992] social dependence concepts, to define a social reasoning mechanism involving *dependence relations* and *dependence situations*. The model is based on dynamic coalition formation, where agents depend on each other for the accomplishment of goals in an environment where they may enter and leave at will. An agent maintains information about other agents in the agency in data structures called *external descriptions*, which it uses to figure out agents that it depends on and agents that depend on it, and how to cooperate or exchange help with such agents. An *external description* structure contains an agent's goals, the actions it can perform, resources it controls and the plans it uses in the achievement of its goals. These plans may involve the use of resources and actions that are controlled and carried out respectively by other agents, in which case, the agent depends on others to execute the plan.

Sichman et al. [1994] describe the notion of *dependence situations* that relates two agents and a goal. They identify three possible types of dependence situations, namely *mutual dependence*, *reciprocal dependence* and *unilateral dependence*. Mutual dependence refers to agents depending on each other for the same goal (cooperation), while with reciprocal dependence, they depend on each other for different goals (exchange). Both dependence situations can be either *locally believed* or *mutually believed* distinguishing between an agent that uses only its own plans to reason about others, and one that uses both its own plans and that of others for the reasoning process. The third case, *unilateral dependence*, refers to a one-way dependence between agents, where the first agent depends on the second to achieve a goal without the second agent depending on the first for the achievement of any of its goals. Ultimately, these dependence situations assist agents in selecting partners that are more likely to accept a proposal for coalition formation.

Sichman et al. [1994] state that their model was used to implement a simulator called *DEPNET*.

Sichman et al. [1994] claim that *DEPNET* figures out dependence relationships and dependence situations between agents, building a network of dependencies for an agent.

Sichman et al. [1994] state that their model reduces communication between agents because agents do not need to contact each other every time an action or resource is needed. Additionally agents are able to reason about who they depend on and also who depends on them.

2.1.2 *Incorporating utility-based reasoning using AND/OR trees.* In deciding who to cooperate with, agents are often driven by their dependencies and the utility of the association, that is, what they would gain relative to what it would cost them. According to Alonso [1998] existing studies have not considered dependence combined with cost and benefit in the social reasoning process.

The author refers to previous work by Sichman et al. [1994].

The author criticizes Sichman et al.'s [1994] model for the absence of a formalization for weak dependencies defined as the situation when an agent prefers to cooperate with another to achieve a goal even though it is capable of achieving it alone. According to the author incorporating utilities is an initial step in facilitating the consideration of preferences in the reasoning process.

Alonso [1998] presents a formal model for agents cooperating towards achieving their goals using Castelfranchi et al.'s [1992] social dependence concepts combined with utility-based rationality. In the model AND/OR trees are built for each agent's specific goals and sub-goals or plans down to the level of actions while utilities for actions are computed with respect to the cost and benefit of their intended plan. The cooperative process begins when agents recognize who they can cooperate with, achieved via the evaluation of their dependencies on each other. Alonso [1998] formally defines two ways that an agent might recognize the need to cooperate with another towards achieving a goal. In the first case the dependency is the result of the presence of a sub-goal that an agent is unable to achieve while another can. In the second, termed a weak dependency, an agent can achieve all its sub-goals but prefers accomplishing its goal via cooperation rather than autonomously. The first case represents a mutual dependency while the second represents a reciprocal one where the preferred agent can be seen as having power over the one that prefers it. In the model, utilities assist in ensuring that cooperation is fair. Mutually dependent agents simply exchange the necessary actions; reciprocal dependency leads to agreements based on maximizing the utility for both agents and if an agent has power over another then the agreement will be driven by the utility of the dominant agent.

Alonso [1998] does not describe any experiments conducted.

Alonso [1998] does not present any results.

Alonso [1998] claims that his model is uncomplicated and formally defines weak relationships thus increasing the cooperative space. He also states that the model provides agent's with the ability to calculate agreements that are fair.

2.1.3 *Incorporating utility-based reasoning by extending external descriptions.* In the selection of partners for the achievement of their goals, autonomous agents have usually been built to use either a quantitative approach or a qualitative one, but not both. The quantitative approach which is utility-based, as in game theory, studies ways to maximize the agent's expected utility while in the complementary-based qualitative approach, such as dependence and social power, agents select partners based on social or psychological relations. Both perspectives are important in partner selection because in the real world effective partner selection would require considering both one's utility as well as preferences and social relations. David et al. [1999] address the problem of combining a qualitative and a quantitative approach to coalition formation.

The authors refer to previous work by Zlotkin and Rosenschein [1994], Sichman et al. [1994] and Sichman and Demazeau [1995b].

The authors criticize the work by Zlotkin and Rosenschein [1994] for its limitation to a quantitative approach to coalition formation. Sichman et al. [1994] and Sichman and Demazeau [1995b] are criticized for their limitation to a qualitative approach to coalition formation.

David et al. [1999] present a model that extends Sichman et al.'s [1994] social reasoning mechanism which permits an agent (*subject*) to represent some properties of others *(objects)* in the environment and use it to reason about their susceptibility to assist it in achieving a goal. The *external description* data structure used by each *subject* agent to store information about *object* agents is extended to include a weight property and a cost property. The weight property represents the significance given to each goal by the object agent. The cost property denotes the cost given by the object agent to each of its actions. The cost of a plan is the sum of all costs associated with all the plan's actions depending on the costs given by the agent's involved, and is calculated dynamically since it depends on the feasibility of the plan. David et al. [1999] introduce *inverse dependencies* which define dependence from the view of the object agents using dependencies on actions. In their model complementary-based partner selection is based on *offered goals*, *offered plans* and *offered actions* which refer to inverse dependencies based on goals, plans and actions respectively. Utility-based partner selection utilizes information stored in the cost property and the weight property. A function *action-strength* is provided that gives a strength value to an offered action, depending on the number of plans and goals the action contributes to and the significance of those goals. Action-strength values are combined to determine an object agent's dependence strength with a *dep-strength* function.

David et al. [1999] state that they conducted an experiment involving coalition formation for software reuse to test their model. A company's projects represented goals, different configurations represented plans and packages denoted actions. Projects were assigned a significance value and packages were given costs. Companies could form coalitions with others to carry out projects.

David et al. [1999] claim that their results demonstrated different types of dependencies and strengths playing a role in how partners were selected. They claim to have observed that choosing a goal with respect to a proposal is more qualitative-based while action choice is related to dependence based on cost, implying that it is important to access possible proposals before attempting partner selection for coalition formation.

David et al. [1999] state that their approach combines qualitative and quantitative notions in the choice of partners for coalition formation, thus making partner selection more effective.

2.1.4 *Inferring indirect relationships.* According to Morgado and Gaspar [2000] existing studies do not account for agents reasoning about others beyond those they are directly related to. This capability can be expected to facilitate the formation of groups towards solving complex problems.

The authors refer to previous work by Sichman [1995], Alonso [1998], David [1998] and David et al. [1999].

The authors state that Sichman's [1995] model is not easily applicable to real problems that are often complex. The model is criticized for its requirement that the details of all plans be available and for not supporting agents reasoning about others beyond those they directly depend on thus limiting the number of possible coalitions. David's [1998] model is criticized for its requirement that agents know the capabilities of all agents in all groups they belong to, increasing required communication between agents.

Morgado and Gaspar [2000] present a dependence-based social reasoning model for coalition formation where agents reason beyond those they directly depend upon. The authors note that when reasoning about others in a society an agent can use either a *global perspective* or a *local perspective*. An agent reasoning globally is aware of the actions of all agents that can participate in a coalition and can therefore reason about all possible dependencies it needs in the society. An agent that adopts a local perspective can only reason about agents that it directly depends upon and may not be aware of indirect relationships that may result in coalition formation. In Morgado and Gasper's [2000] model agents use a local perspective in reasoning but infer indirect relationships.

To support agents maintaining information about each other Morgado and Gaspar [2000] redefine Sichman et al.'s [1994] *external description* structure to include goals, plans and capacities and clarify that their model has a different notion of goals and plans. Capacities encompass actions an agent can perform and resources within its control, but not in relation to the agent's goals as in Sichman et al. [1994]. According to Morgado and Gaspar [2000], this distinction is to account for the fact that in their model agents do not necessarily know all the necessary actions for a goal, since required actions may be achieved via indirect relationships. If an agent has a capacity for an activity then it can either achieve it on its own, or via the formulation of a plan that involves assigning it to other agents. Another deviation from Sichman et al. [1994] involves the explicit adoption of goals. When an agent agrees to execute an activity on another agent's behalf it adds the respective goal to its own goals resulting perhaps in a revision of its own plans. Finally, plans represent agent capacities for achieving goals involving activities that may depend on other activities. In using the represented knowledge to reason about others Morgado and Gaspar [2000] inherit Sichman et al.'s [1994] concept of *dependence situations*.

Morgado and Gaspar [2000] state that their model was implemented in a system named *CADS*. The system added time and order constraints to the model by restricting the time required for the completion of a plan and enforcing an order for activities. The authors claim that the system was used to generate a simulation of groups of agents forming coalitions towards the development of various projects.

Morgado and Gaspar [2000] claim that their experiments resulted in the formation of coalitions where agent could infer relationships beyond those they were directly related to.

Morgado and Gaspar [2000] state that their social reasoning model, that results in the formation of coalitions with agents indirectly dependent on each other, reduces computational complexity without sacrificing the number of coalitions formed. They claim that communication between agents is reduced because agents only need to reason about those they are directly related to, but can still benefit from activities provided by agents they are indirectly related to.

2.1.5 *Formalizing the agent's social reasoning process.* In order to facilitate understanding how autonomous and heterogeneous agents cooperate towards achieving their individual goals in a social environment. Panzarasa et al. [2002] address the formalization of the entire decision-making process of the agents, from their mental aspects to their interactions with each other.

The authors refer to previous work by Wooldridge and Jennings [1999].

The authors state that their work provides a way for agents to influence the behavior and mental aspects of other agents with regard to collaboration which is a limitation of the work by Wooldridge and Jennings [1999].

Using multi-modal logic, Panzarasa et al.'s [2002] model combines the mental aspects of autonomous agents represented by their beliefs, desires, goals and intentions with social aspects represented by their interactions with each other to formalize how agents decide to cooperate. Agent interactions are defined with respect to their relationships with each other viewed in terms of roles or how roles relate to each other. Prior to the start of the collaborative process agents need to identify potential partners for the accomplishment of a goal. According to the authors agents socially dependent on each other [Sichman 1995], have the capacity to recognize a potential for collaboration. The authors formalize the recognition stage by identifying that social dependence can be brought about by an agent's inability to achieve an objective on its own, an agent desiring to collaborate even when it does not have to, an agent compelled to collaborate due to its role or an agent simply forced into collaboration by other agents. The authors assume that once an agent identifies potential partners it will need to influence them towards the formation of a new group using any form of interaction. To handle situations where agents with the same objectives might be in competition with each other and therefore not desire to collaborate, the authors formalize the notions of *joint intentions* and *joint commitments*. The term *social practical reasoning* is introduced to formalize agents reasoning on their own about how the group goes about achieving the committed objective once the group is formed. Finally the negotiation process whereby agents in a group agree on the appropriate way to achieve the goal is conducted by agents making their intentions known and influencing each other towards adopting their reasoned course of action.

Panzarasa et al. [2002] do not describe any conducted experiments.

Panzarasa et al. [2002] do not present any results.

Panzarasa et al. [2002] state that their formal model covers all aspects of the collaborative process from agents identifying potential partners for collaboration to jointly deciding to form a group. They state that contrary to existing models their work accounts for agents with conflicting mindsets and agents influencing the mindsets of others.

2.1.6 *Social reasoning using fuzzy inference.* When determining agent dependencies, current social reasoning methods are exact rather than approximate. For example, an agent depends on another if it lacks a needed resource that the other can provide. Hsieh et al. [2004] address the drawback that existing social reasoning methods do not support defining a degree of dependency. Another addressed issue is the fact that dependence by itself is qualitative and does not consider the costs involved in partnership formation. These issues limit how an agent organizes its relationships, selects partners and responds to partnership proposals from other agents.

The authors refer to previous work by Sichman et al. [1994] and Sichman [1998].

The authors identify several shortfalls in the social reasoning mechanism presented by Sichman et al. [1994] and Sichman [1998]. First, they state in the model agents ignore goals deemed unachievable. Next, agents can only reason about immediate benefits, missing out on situations when a benefit may exist at a later time. Finally, the authors state that in the model, dependence is considered in qualitative rather than quantitative terms.

Hsieh et al. [2004] integrate fuzzy inference into Sichman et al.'s [1994] social reasoning mechanism. Hsieh et al.'s [2004] model supports the evaluation of agent dependencies, an agent's selection of goals to pursue and plans to carry them out, its selection of needed partners and how it responds to help requests from others, all estimated using a fuzzy inference system.

To estimate an agent's dependency on another for a missing action or resource, Hsieh et al. [2004] introduce three variables: *importance*, *urgency*, and *accessibility*. They introduce a formula where agents use these variables to estimate the degree of dependency, that is, how badly they need an action or resource. A resource that is rare would have a low accessibility value which in turn would increase the degree of dependency. If an agent has only one plan for achieving a goal then needed actions or resources become more urgent especially if the agent considers the goal important. Using the formula, an agent is able to calculate its level of dependence with respect to a specific agent.

The criteria for goal and plan selection for pursuit includes variables for the importance of the goal, the feasibility of the plan, as well as the urgency and cost of missing actions and resources. The fuzzy inference system uses these variables to generate a *priority* value. Basically, the agent selects the goal-plan pair with the highest priority value. Goal-plan pairs that are urgent, important, feasible and have a low cost are more likely to be chosen.

In partnership selection the agent requests help when it identifies other agents possessing its missing actions and resources based on the goal-plan selected for execution. Ultimately, the agent wishes to choose the best partner to send a proposal to. To accomplish this, Hsieh et al. [2004] variables were introduced to consider the cost of missing items, prior history of assistance between agents, the level of dependency between agents, whether needed items are in use by the agent being proposed to and how willing the agent is to help depending on how selfish or generous it is. When fed into the fuzzy inference system, these criteria are used to generate a *possibility* value. A proposal would be made to the agent with the highest possibility value.

When responding to proposals for help from other agents, the agent rejects the proposal if it no longer has the needed action or resource, or it has no information about the other agent. Criteria similar to partnership selection is fed into the fuzzy inference system and the value returned is compared to a given threshold to determine acceptance or rejection by the agent.

Hsieh et al. [2004] state that they built a simulation system that used their social reasoning model to control robots. The system was used to conduct three experiments in societies composed of five agents each. The first experiment compared a society made up of selfish agents, one composed of generous agents and a third made up of normal agents. The summation of the importance and urgency variables was used to determine better performance. The second experiment assumed that the agents trusted each other more by increasing the default value of the variable representing agents prior history of assistance. The final experiment evaluated a society with one generous agent and four normal agents compared to a society of five normal agents.

Hsieh et al. [2004] state that the first experiment showed generous agents obtaining the highest performance, followed by normal agents with selfish agents performing the worst. The second experiment demonstrated increase in performance relative to the increase in trust. Finally, the last experiment demonstrated an 8% decrease in the performance of the generous agent operating among normal ones, while the performance of the normal agents increased slightly by 0.4%.

Hsieh et al. [2004] claim their model enhances the previous social reasoning models [Sichman et al. 1994; Sichman 1998], because integrating fuzzy inference rules allows agents to create a better balance between achieving a goal and its urgency or importance. They also state their model considers additional variables in the reasoning process thus improving the social relationships between agents.

2.1.7 *Social reasoning by combining social dependence and social power* . Autonomous and heterogeneous that collaborate towards achieving their goals may need to reason about the ramifications of belonging to a group which can affect their decision-making process of joining one. An agent needs to understand the rules imposed on how it behaves in order to make adequate decisions about who to cooperate with. According to Carabelea et al. [2005] existing studies also do not distinguish between dependencies based on having the ability to do something and the permission to do it.

The authors refer to previous work by Sichman et al. [1994].

The authors state that the work by Sichman et al. [1994] does not consider when agents collaborate as a result of a prohibition to execute a plan or action towards a goal or the lack of access to a needed resource.

Carabelea et al. [2005] use Sichman et al.'s [1994] social dependence concepts and their approach where information about agents is described in terms of goals, actions, resources and plans, as well as Castelfranchi's [2003] power theory, to formalize how agents reason about joining groups. Carabelea et al. [2005] distinguish between *individual powers* and *social powers* with the former represented by an agents' own goals, actions, resources and plans while the latter is represented by powers obtained via dependence relationships. Within individual powers agents can have *executional*, *deontic* or *full* powers. In achieving an objective, executional power specifies when an agent knows how, deontic power indicates when an agent is permitted to and full powers specify when an agent has both executional and deontic powers, is aware of them and intends to use them. In multi-agent systems individual powers lead to social powers as agents may depend on the powers of others to achieve their objectives. If an agent is aware of its dependence on another for a goal then the other agent is deemed to have *influencing power* over it. To this effect agents can gain new powers through access to the powers of others.

Carabelea et al. [2005] define additional powers that agents can have when they belong to a group. These powers are obtained via standard obligatory behavior or authority specified by roles. Agent relationships within groups are defined in terms of power, dependencies, authority relationships, roles and norms. Agents use these relationships to determine what they would gain or lose in reasoning about joining groups. While certain relationships may restrict an agents' powers others might enhance it. Furthermore if necessary, a group can also calculate the benefits or costs of allowing an agent to join it.

Carabelea et al. [2005] state that they have begun implementation of a system called *MOISE+* that can be used to study agent reasoning about belonging to groups.

Carabelea et al. [2005] do not present any results.

Carabelea et al. [2005] state that their model can be used in the design of a multi-agent system towards predicting how agents will behave in a group. They state that agents in such a system can then reason about the ramifications of being part of group and thus decide on whether to join it. It is also claimed that the model makes it possible for agents to be aware of their limitations with respect to power.

2.1.8 *Social reasoning and transitive dependencies.* In order for an agent to realize its goal it may need the assistance of a second agent. It is possible that the second agent can only provide this assistance with the help of a third agent. An et al. [2007] address how agents can reason about the dependencies of agents that they depend on when forming coalitions. This is important because an agent can only realize its goal if these secondary dependencies are taken into consideration.

The authors cite previous work by An et al. [2005].

An et al. [2007] criticize their previous work An et al. [2005] for only supporting the generation of suboptimal coalitions.

An et al. [2007] introduce the notion of transitive dependence into social reasoning based on agent dependencies [Sichman et al. 1994; Morgado and Gaspar 2000]. In An et al.'s [2007] framework, every agent has goals, plans and actions. Actions combine to make up a plan and plans make up a goal. Agents may work together to achieve some or all of their goals. They introduce the notion of *action dependency* which exists between two actions for an agent if the agent will only perform one action on the condition that the other action be performed in return. The agent may also require that a set of actions be performed in return. In such a case, when all the actions in that set are required the dependency becomes an *and-action dependency*. In the event that only one of the actions in the set are required the dependency is deemed an *or-action dependency*. Action dependency relations are used to describe transitive dependencies between agents.

An et al. [2007] state that they built a simulation composed of agents to test their model in an environment without and-action dependencies and one with and-action dependencies.

An et al. [2007] state that agents were able to reason about transitive dependencies with both types of action-dependencies.

An et al. [2007] claim that to the best of their knowledge, their previous work [An et al. 2005] was the first attempt to explore transitive-based coalition formation.

2.1.9 *Summary.*

Year	Author	Title of Paper	Major Contribution
1994	Sichman, Conte, Demazeau and Castelfranchi	A social reasoning mechanism based on dependence networks.	Introduces external descriptions used by agents to maintain information about each other for calculating dependence situations.
1998	Alonso	How individuals negotiate societies.	Uses AND/OR trees to combine cost and benefit with dependencies in reasoning.
1999	David, Sichman and Coelho	Extending social reasoning to cope with multiple partner coalitions.	Incorporates cost and benefit into external descriptions.
2000	Morgado and Gasper	A social reasoning mechanism based on a new approach for coalition formation.	Redefines external descriptions to support agents reasoning beyond those they directly depend upon.
2002	Panzarasa, Jennings and Norman	Formalizing collaborative decision-making and practical reasoning in multi-agent systems.	Formalizes the social reasoning process combining agent's mental aspects with social dependencies.
2004	Hsieh, Liu, Yu and Hsu	A method in social reasoning mechanism for intelligent agents using fuzzy inference.	Integrates fuzzy inference into external descriptions.
2005	Carabelea, Bossier and Castelfranchi	Using social power to enable agents to reason about being part of a group.	Redefines external descriptions and dependence situations in terms of social power.
2007	An, Shen, Miao and Cheng	Algorithms for transitive dependence-based coalition formation.	Introduces transitive dependencies into social reasoning.

Table I. Major Contributions in Social Reasoning Mechanisms

2.2 Coalition Formation Between Pairs of Agents

In this section we review papers that deal with social-dependence based coalition formation between pairs of agents in a society. These models involve agents that directly depend on each other helping each other to achieve common or different goals. All the papers were written in 1998.

2.2.1 *Forming coalitions in dynamic environments.* Autonomous and heterogeneous agents in dynamic environments may be incapable or simply not wish to achieve their individual goals solely. To this effect agents may form coalitions towards providing assistance to each other. In the formation of these coalitions Sichman [1998] identifies several problems that arise. In order to adapt to the implications of agents entering or leaving the agency at will, agents should be able to determine at any given time their realizable goals so that they do not pursue goals that cannot be accomplished. Agents need the ability to detect inconsistencies in what they believe each other capable of because it cannot be assumed that the knowledge agents possess about each other is always complete and correct. Agents need the capacity to determine the other agents that are likely to join them in pursuing their goals since agents are not expected to be charitable.

The author refers to previous work in group formation for problem solving by Smith [1980] and Wooldridge and Jennings [1994]. He also refers to studies conducted by Yu and Mylopoulos [1993] and Carle et al. [1994] regarding the representation of agent dependencies.

The author claims there is less global communication required among agents in his model compared to Smith's [1980] contract net model and criticizes the studies conducted by Smith [1980] and Wooldridge and Jennings [1994] for their confinement to a formal level. He states that unlike the studies by Yu and Mylopoulos [1993] and Carle et al. [1994] that utilize objective views, his model represents agent dependencies subjectively by taking the agents' perspectives into account.

In this paper, Sichman [1998] presents his design and implementation of the *DEPINT* system that demonstrates coalition formation of agents in a dynamic environment utilizing his social reasoning mechanism [Sichman 1995]. He adopts concepts from Sichman et al. [1994], including the *external description* data structure and *dependence situations.* He introduces *goal situations* used to relate an agent to a specific goal with regard to the agent's plans. Agents utilize both situations to choose partners for coalition formation by inferring the three possible types of dependence situations, namely *mutual dependence*, *reciprocal dependence* and *unilateral dependence.* The situations are also used to identify incompatibility between agents' external descriptions and allow for revision of agent's beliefs about each others abilities at run time. In the model, the author differentiates between what an agent knows and what it believes, by stating that an agent knows its own plans and actions but believes that of others.

Coalitions in the *DEPINT* system can only be formed between two partners and agent behaviors are either *passive* or *active.* When active, the agent uses its reasoning to select a goal, plan and partner if it determines it cannot achieve the goal on its own, and proposes a coalition to another agent. When passive, the user of the system simulates the process and the agent can only accept or reject received proposals. In both cases, belief revision occurs whenever inconsistency is detected.

Sichman [1998] states that he built the *DEPINT* system in a multi-agent system software development environment that supports active agents that communicate with each other.

Sichman [1998] claims that the *DEPINT* system illustrated the dynamic formation of coalitions based on dependencies between agents, the ability of agents to adapt to others entering and leaving the society at will and revise inconsistent information in beliefs they have about each other. He presents examples of successful and unsuccessful coalition formation, as well as belief revision.

Sichman [1998] states that the *DEPINT* system is the first system to use social dependence for coalition formation in a dynamic multi-agent system and also the first to represent how agents depend on each other subjectively. He states that his model supports agent adaptation in dynamic environments, agent ability to determine viable plans and achievable goals and detect inconsistencies between agent representations of each other. He claims that compared to other models, there is little global communication in his system as an agent need only broadcast a message to all the others in the agency once upon entering the agency. All further communication is between an agent and a specific agent it identifies to send a coalition proposal to.

2.2.2 *Utility-based rationality and preference-based partner selection.* Alonso [1998] addresses coalition formation among agents with different goals but common intermediary interests. Since agents are often driven by their dependencies and the utility of the association when deciding who to partner with, he also addresses incorporating utilities into the coalition formation process. Finally, he considers the formalization of the entire cooperative process for better understanding.

The author refers to previous work by Jennings [1992], Sichman et al. [1994] and Wooldridge and Jennings [1996].

The author criticizes Jennings' [1992] model for its restriction to cooperation between agents with common goals based on their needs. Sichman et al.'s [1994] model is criticized for accommodating cooperation between agents with different goals only when it is required. Another noted shortfall is the absence of a formalization for weak dependencies defined as the situation when an agent prefers to cooperate with another to achieve a goal even though it is capable of achieving it alone. The approach is also criticized for its exploration of why interaction occurs between agents without specifying how it does and the presumption that social reasoning can be based on unilateral relationships. In the model by Wooldridge and Jennings [1996], agents with common goals choose partners depending on their needs and/or preferences. However, the model is criticized for its lack of a representation tool for the concept of cooperation based on preferences.

Alonso [1998] presents a formal model for agents cooperating towards achieving their goals using Castelfranchi et al.'s [1992] social dependence concepts combined with utility-based rationality. His social reasoning process is described in Section 2.1.2. The model allows agents to cooperate even in the absence of common goals, as sub-goals for heterogeneous agents might hierarchically lead to different goals. Unilateral relationships where an agent might initiate cooperation with another in the absence of a mutual benefit are not supported. Alonso [1998] introduces the concept of a *pure deal* that represents a sequence of actions to define how agents negotiate cooperation. Agents enter into deals with each other by accepting to execute the respective actions. Utilities assist in ensuring that cooperation is fair and the negotiation process is driven by the dependence situations. Mutually dependent agents simply exchange the necessary actions, reciprocal dependency leads to deals based on maximizing utility for both agents and if an agent has power over another then the deal will be driven by the utility of the dominant agent. Agents are assumed to be honest with regard to the actions they can execute and expected to honor deals that they commit to. In the strategy adopted for negotiation, agents seek to make the most profitable deal which may lead to the proposal and acceptance of a counteroffer. Once an agreement is reached cooperating agents can be regarded as belonging to a group, working together towards the accomplishment of goals or partial goals.

Alonso [1998] does not describe any experiments conducted.

Alonso [1998] does not present any results.

Alonso [1998] claims that his model covers all the steps of the coordination process and is uncomplicated. He states that the model allows coordination in the absence of common goals and formally defines weak relationships thus increasing the cooperative space. Finally he claims that his use of dependence relations clarifies the negotiation stage, which defines the agents' ability to calculate fair deals.

2.2.3 *Simulating the emergence of coalitions from dependence networks* . Autonomous and disparate agents may form coalitions to achieve goals that they cannot or do not wish to accomplish on their own. There is a need to explore how agent relationships influence the emergence of these coalitions and how such emergence can be predicted. According to Conte et al. [1998], this is necessary to better understand coalition formation.

The authors refer to previous work by Willer [1992] based on power-dependence theory and the study by Axelrod [1995] where a game-theory approach is used.

In the power-dependence based exchange network theory presented by Willer [1992], exchange partnerships emerge from the dependencies between agents. This approach is criticized for not supporting the prediction of agent behavior. The authors criticize Axelrod's [1995] game-theory approach for using quantitative rather than qualitative measures in relating agents and relying on hostile relationships to explain how coalitions emerge. Both cited studies are criticized for allowing the system designer to control agent dependencies. According to the authors, dependencies among agents should be brought about by the agents' features.

Conte et al. [1998] use the *MICROdep* system [Veneziano et al. 1996], an extension of *DEPNET* [Sichman et al. 1994] to demonstrate the emergence of coalitions in a society of heterogeneous agents. While *DEPNET* generates dependence networks from agents' individual properties which include agents' goals, actions, resources and plans, *MICROdep* is a simulation that figures out partnerships from the networks. Dependence relations between agents specify the extent of an agent's autonomy with regard to its plans for a specific goal. An agent may depend on every agent in a set of agents *(AND_ dependence)* or on any agent in a set of agents *(OR_ dependence)* to accomplish a goal. Additionally a set of agents may depend on one agent *(CO-dependence)* for the achievement of the same goal. The authors utilize these dependencies to formally define the concept of *negotiation power* that intersects an agent's chances to ask for help with its ability to provide help.

Once *MICROdep* figures out the dependence networks and negotiation powers of the agents, it generates a list of favored partners for each agent and then globally formulates the partnerships. The list of favored partners is generated either with a goal-oriented or a gain-oriented criteria. Regarding a provision of help as a cost and the reception of help as a benefit, goal-oriented agents rank agents in their preference list primarily by benefits and secondarily by costs while gain-oriented agents perform the opposite. In forming partnerships, *MICROdep* requires potential partners to represent each other in their preference lists. Partnerships are extracted by repeatedly selecting pairs of agents with the highest *partnership value (p.v.)* and the lowest *difference between values (d.a.v)* from the preference matrix for all agents. The *p.v.* is computed via the summation of values in respective agents' preference lists while the *d.a.v.* represents the absolute value of the difference in the values.

Conte et al. [1998] state that they performed experiments using *MICROdep* simulations to determine the ability of negotiation power to predict coalition formation and evaluate the difference between goal-oriented and gain-oriented methods for partner selection. They claim to have run simulations with agencies of varying sizes.

Conte et al. [1998] claim that the results demonstrated an analogy between the negotiation power of an agent and how often it appeared in the preference lists of other agents. They state that the analogy was stronger when agents utilized the gain-oriented criteria in generating the preference list, than when the goal-oriented approach was applied. Additionally, Conte et al. [1998] claim that correlations were also observed between an agent's negotiation power and partnership formation as well as partnership value. They state that the results were dependent on agency size, allowing for more predictability as the number of agents increased, with negotiation power being the most predictable aspect. They also claim to have observed that partnership values obtained via the goal-oriented approach were more predictable than those derived with the gain-oriented criteria.

Conte et al. [1998] state that their model demonstrates the emergence of coalitions from dependence relations within an agency and how the formation of these partnerships can be predicted. They state that their model illustrates a method for heterogeneous agents to make rational decisions that differs from models that are utility-based. The authors claim in their model agent dependencies emerge from a description of the agency instead of being controlled by the system designer. They also claim that their model lays the foundation for studying multi-agent partnerships as opposed to partnerships between pairs of agents.

2.2.4 *Coalition formation between agents with different goals and different decision-making strategies .* Partnerships may be formed between pairs of autonomous agents with different goals and different decision-making strategies. Conte and Pedone [1998] address the outstanding problem of understanding how such agents rationally choose partners and how their behavior can be predicted.

The authors refer to previous work regarding rationality in agencies by Conte and Sichman [1995], Conte and Castelfranchi [1996] and Conte and Paolucci [1997].

The authors state that in Conte and Sichman [1995] rationality is determined by agent goals, in Conte and Castelfranchi [1996] it is dependent on different social actions conducted between agents and in Conte and Paolucci [1997] it is context-dependent. They state that their approach is different in that it considers both differing agent goals and decision-making strategies. They do not specifically identify any shortcomings of the previous work cited.

Conte and Pedone [1998] introduce the *PART-NET* system, that uses Sichman et al.'s [1994] notion of reciprocal dependence in the formation of partnerships among disparate agents. Regarded as an exchange, reciprocal dependence refers to a pair of agents depending on each other for the achievement of two different goals. *PART-NET* generates agent structures composed of goals, actions, dependence relationships and a chosen decision-making scheme. Conte and Pedone [1998] identify three different decision-making schemes:

—*substantialist* or *hedonist*: agent decisions are based on the importance of goals.

—*instrumentalist* or *utilitarian*: agents make decisions with the objective of maximizing the difference between receiving help and offering help towards achieving goals.

—*miser*: agent decisions aim to minimize the cost of actions.

Each agent depending on its chosen scheme, selects and orders agents that it is reciprocally dependent upon. The highest ranked agent for the hedonist will help it achieve its most important goal regardless of cost, the best partner for the utilitarian will help it achieve its most important goal that will cost the partner the least and the top ranked agent for the miser will request it's help towards the goal that bears the least cost to it. While misers and utilitarians will give up their most important goals in certain situations, hedonists will not. After generating agent structures, the *PART-NET* simulation forms partnerships by iteratively trimming the matrix of plausible partnerships. When one agent is matched against multiple partners, the agent chooses the match that rewards it the most and cancels the rest. At each simulation step the agent structures are regenerated with costs and benefits recalculated. The simulation ends when no more matches can be made.

Conte and Pedone [1998] state that the *PART-NET* simulation was run to form partnerships and compare the varying influences of the three decision-making strategies both in homogeneous and heterogeneous environments. Homogeneous agencies represented the implementation of a single strategy while in heterogeneous environments there was a mix of strategies.

Conte and Pedone [1998] claim that utilitarians were shown to be more flexible than hedonists who needed more goals and/or agents to obtain higher benefits. In heterogeneous environments, where a mix of decision-making strategies was implemented, although utilitarians initially benefited the most followed by hedonists and lastly misers, hedonists would outperform the others over time. In a homogeneous agency where all agents employed a single decision-making strategy however, hedonists had the highest benefits right from the start. Overall, the authors state that heterogeneous environments produced agents with higher benefits than homogeneous ones. They also claim that their results demonstrated that hedonists are more frequently requested as partners than misers and utilitarians.

Conte and Pedone [1998] claim that their concept demonstrates partnership formation based on different decision-making schemes. They also state that agent structures generated by the *PART-NET* system facilitate qualitative comparisons between disparate agents that form partnerships in an agency.

Year	Author	Title of Paper	Major Contribution
1998	Sichman	DEPINT: Dependence-based coalition formation in an open multi-agent scenario.	Models dynamic coalition formation using social dependence.
1998	Alonso	How individuals negotiate societies.	Combines utility-based rationality, preference-based partner selection and social dependence in forming coalitions.
1998	Conte, Castelfranchi and Veneziano	The computer simulation of partnership formation.	Simulates partnership formation from dependence networks.
1998	Conte and Pedone	Finding the best partner: The PART-NET system.	Explores partnerships formed between agents with differing goals and decision-making strategies.

Table II. Major Contributions in Coalitions Formed Between Pairs of Agents

2.2.5 *Summary.*

2.3 Forming Multiple-Partner Coalitions

The research papers in this section address social-dependence based coalition formation involving multiple partners. The models involve agents that indirectly depend on each other helping each other for the achievement of common or different goals. Some of the papers are extensions of previous models for coalition formation between pairs of agents. The papers range from 1999 to 2009.

2.3.1 *Formalizing the emergence of coalitions from group dependence and the stability of agent plans.* In coalition formation where self-interested agents collaborate for the achievement of their individual goals, Brainov and Sandholm [1999] note that social-dependence based methods so far have been based on bilateral dependence relations between agents. The authors address the formalization of dependence between an agent and a group or a group and an agent. This is important because an agent is just as likely to depend on a group of agents for the achievement of its goal, as it is likely to depend on just a single agent. The authors also address the consequences of an agent making changes to its plans and its effects on other agents that it is collaborating with.

The authors refer to previous work by Sichman et al. [1994].

The authors criticize Sichman et al.'s [1994] for its limitation to bilateral dependence, that is, dependence between two agents.

Brainov and Sandholm [1999] introduce the notion of group dependence, a generalization of Sichman et al.'s [1994] previously defined notion of social dependence between pairs of agents. Group dependence accounts for an agent depending on a group of agents as well as a group of agents depending on an agent. In the context of joint plans, they use transitive dependence to characterize reciprocal dependence, the case when a group of agents depend on another group of agents either via a direct dependency or indirectly via a transitive dependency. In their formalization of a group of agents depending on an agent for a plan, they formalize a group of agents' dependence on an agent for a plan in two scenarios. The first scenario addresses when every agent in the group is required to have the plan in its plan list and the second assumes that all agents in the group do not necessarily have the plan in their plan list but must give their permission to whichever agent among them is fulfilling the plan. In formalizing an agent's dependence on a group of agents for a plan they show that only in acting together can the group of agents help or hurt the agent that depends on them.

To address the stability of agents' plans, or the consequences to agent dependencies within joint plans when an agent changes its plan Brainov and Sandholm [1999] differentiate between *individually stable* and *coalitionally stable* plans. Individual stability disallows an agent, on its own, from deviating from the plan and coalitional stability forces at least one agent to oppose to the deviation of a subgroup of agents in the joint plan.

Brainov and Sandholm [1999] do not describe any conducted experiments.

Brainov and Sandholm [1999] do not provide any results.

Brainov and Sandholm [1999] claim that their model formalizes the notion of group dependence among autonomous agents, where an agent can depend on a group of agents or a group of agents can depend on an agent. They claim that their approach where an agent's ability to influence others is related to specific joint plans is better than game theory approaches which relate an agent's power to a general ability to exert influence, because it covers all forms of interaction between agents.

2.3.2 *Multiple-partner coalition formation using dependence strengths and dependence situations.* David et al. [1999] address the formation of multiple-partner coalitions because prior research has only considered coalition formation between pairs of agents.

The authors refer to previous work by Sichman et al. [1994] and Sichman and Demazeau [1995b].

The authors criticize the work by Sichman et al. [1994] and Sichman and Demazeau [1995b] for not addressing multiple-partner coalitions, assuming coalition formation only between pairs of agents.

David et al. [1999] social reasoning mechanism is presented in Section 2.1.3. According to the authors, the multiple-partner coalition problem involves finding the best possible partner for each of an object agent's action-dependency, taking into account the fact that each possible partner may depend on others. To identify agents likely to accept a proposal for coalition formation, with the additional objective of reducing communication flow between agents, they introduce a function called *highest dep-sit* that finds the subset of agents with the highest dependence situations for an object agent's goal and plan. The partner to propose to is chosen based on the highest dependence situation and dependence strength and the lowest action-dependency cost that carries out the highest number of action-dependencies.

David et al. [1999] state that they conducted an experiment involving coalition formation for software reuse to test their model. A company's projects represented goals, different configurations represented plans and packages denoted actions. Projects were assigned a significance value and packages were given costs. Companies could form coalitions with others to carry out projects.

David et al. [1999] claim that their results demonstrated different types of dependencies and strengths playing a role in how partners were selected.

David et al. [1999] state that their model supports multiple partner coalitions where dependencies are represented by considering pairs of agents and agents depending on them.

2.3.3 *Nested coalitions.* According to Morgado and Gaspar [2000] there are aspects of existing models for social-dependence based coalition formation that can be improved such as how agents choose partners and how to reduce the amount of communication that has to occur between agents. The authors address the problem of agents forming coalitions with those they are indirectly related to.

The authors refer to previous work by Sichman [1995], Alonso [1998], David [1998] and David et al. [1999].

The authors state that Sichman's [1995] model is not easily applicable to real problems that are often complex. The model is criticized for its requirement that the details of all plans be available and for not supporting the formation of coalition among agents that are indirectly related. Another noted shortfall is the fact that the model provides no recourse for situations where the assignment of an activity fails after related activities have been successfully assigned. The approaches used by Sichman [1995] and Alonso [1998] are criticized for being limited to coalitions formed between pairs of agents. David's [1998] model supports agents belonging to multiple groups. However, the authors state that the model's requirement that agents know the capabilities of all agents in all groups they belong to, increases required communication between agents. Finally, the authors identify three aspects that can be improved with all cited studies namely the process to select partners, dealing with agents having incomplete information about each other and reducing agent communication.

Morgado and Gaspar [2000] present a dependence-based social reasoning model for coalition formation where a goal may be achieved via a chain of nested coalitions. With the social reasoning process described in Section 2.1.4, agents infer indirect relationships resulting in the formation of multiple connected and nested coalitions. Once goals, plans and dependence situations are identified, possible coalitions can be formed and later on refined to valid coalitions, that ensure the assignment of all necessary activities and do not include activities assigned to more than one agent.

Morgado and Gaspar [2000] state that their model was implemented in a system named *CADS*. The system added time and order constraints to the model by restricting the time required for the completion of a plan and enforcing an order for activities. The authors claim that the system was used to generate a simulation of groups of agents forming coalitions towards the development of various projects.

Morgado and Gaspar [2000] claim that their experiments resulted in the impulsive formation of nested coalitions without agents in the external coalitions needing to reason about all agents in the nested one.

Morgado and Gaspar [2000] state that their social reasoning model, that results in the formation of coalitions with agents indirectly dependent on each other, reduces computational complexity without sacrificing the number of coalitions formed. They claim that communication between agents is reduced because agents only need to reason about those they are directly related to, but can still benefit from activities provided by agents they are indirectly related to. They also state that their model represents coalitions in such a way that both the analysis and negotiation stages can be combined.

2.3.4 *Analyzing rational choice of multiple partners for coalition formation.* The objective of David et al. [2001] is to represent and analyze the cognition of agents in a multi-agent system in order to predict the decisions made for the formation of multiple-partner coalitions. These analyses and representations facilitate the exploration of how agents make rational choices with respect to their goals, selection of partners and generation of adequate proposals for coalition formation.

The authors refer to previous work by Conte and Pedone [1998].

The authors do not specify any shortcomings of the work by [Conte and Pedone 1998] but state that both approaches are based on some common aspects. They state that while Conte and Pedone [1998] provide some analysis of rational choice at individual and group level, they focus on the individual level.

To evaluate rationality in the decision making process of agents in a multi-agent system, David et al. [2001] use concepts of social dependence relations and dependence situations [Sichman 1998]. They distinguish between *motivation-oriented* rationality where agents make decisions based on how they socially interact with each other often via cooperation or exchange and *utility-based* rationality where agents' decisions are driven by the desire to maximize benefits and reduce costs. Dependence relations are refined to include *inverse dependencies*, which provide a view of dependencies from the dependent agent. The authors describe how offered goals, offered actions and offered plans are derived by an agent identifying an action he can offer another agent towards that agent's plan for a particular goal. In generating proposals and choosing partners, they combine utility-oriented and motivation-oriented rationality and identify that agents using utility-based criteria are driven by their choice of actions regardless of goals while those using motivation-based criteria decide according to their goals. They emphasize the importance of both forms of rationality in a multi-agent system. Multiple partner coalitions are handled by agents choosing partners depending on action-dependencies. Dependence situations are used to analyze motivation-driven choices and a domain-dependent concept called *dependence strength* that takes costs and benefits for actions as well as agent preferences into account for the analysis of utility-driven choices is introduced. In combining agent preferences with costs and benefits the utility-based criteria uses utility and motivation concepts.

David et al. [2001] state that they used a social simulation to test their approach. In the paper, they present an example of rational decision making by agents in an airline transportation carrier system. They describe goals as preferred or available carriers, actions as origin/destination pairs of locations and plans as routes composed of several stops.

David et al. [2001] claim their experiments demonstrated rational agent choices with regard to goals, proposals and partner selection utilizing motivation-based and utility-based criteria both in successful and unsuccessful coalition formation. They claim to have noticed power influence of varying degrees for the same dependence situation and observed different levels of complexity in the search space depending on the order of utility-based and motivation-based criteria.

David et al. [2001] claim that their approach shows how rationality driven by both motivation and utility can be used to analyze social dependency patterns that emerge in multi-agent systems.

2.3.5 *Formalizing the emergence of groups from power and dependence relations.* When self-interested agents coordinate their efforts for the achievement of their individual goals in multi-agent systems, groups emerge. Boella et al. [2004] address the formalization of the emergence of groups as a result of power and dependence relationships. This is important as it helps find inconsistencies in the underlying definitions of the coalition formation process.

The authors refer to previous work by Brainov and Sandholm [1999] and Sichman and Conte [2002].

The authors criticize the decision-theoretic approach used in Brainov and Sandholm [1999] to examine social relations, for inferring group behaviors and their effect on how goals are achieved, making it difficult to calculate their benefits. Conte and Sichman's [2002] study is criticized for not considering concurrency management problems such as goal obstruction.

Boella et al. [2004] present a model of a multi-agent system, that represents the environment in terms of important attributes and values. An assignment of values to all attributes in a given system, results in one possible state of the environment. Agents are represented in terms of the actions they can perform. As a result, feasible states can be formalized using rules that examine preconditions of actions and their effects. These effects include the fact that carrying out an action may obstruct another. Attribute values are deemed compatible when no conflicts arise from actions that are carried out in their state. Boella et al. [2004] define feasible rules and feasible set of rules to accommodate concurrency management in situations where the effect of an an agent action is the activation of multiple rules that may not be compatible with each other. Boella et al. [2004] formalize Castelfranchi's [2003] notion of power and Castelfranchi et al.'s [1992] concepts of dependence using their model. They use tagged graphs based on Sichman and Conte's [2002] concept of dependence graphs, to model agent dependencies. Cooperation is regarded in terms of the agent's goal objective and the actions needed to be performed to meet it. The authors extend their formalized model to include agent intentions and group intentions. Finally, cooperation among groups of agents is formalized.

Boella et al. [2004] do not describe any experiments conducted.

Boella et al. [2004] do not present any results.

Boella et al. [2004] claim their study provides a formalization of agents ability to help or obstruct each other for the achievement of their goals. They also state that their model differentiates between an agent's ability to help another and its intention to do so. Another claim made is that their model facilitates the calculation of the utility or benefits obtained from the behavior of a group. They state that their model addresses concurrency management which has been left out in some prior research done.

2.3.6 *Simulating multiple-partner coalition formation between agents with differing goals and decision-making strategies.* Multiple-partner partnerships may be formed among autonomous agents with different goals and different decision-making strategies. An existing problem is understanding how such agents rationally choose partners and how their behavior can be predicted. According to Monteiro and Sichman [2006], this is important because partner selection is more complex when multiple agents as opposed to a single agent can jointly assist an agent to achieve its goal, particularly when these agents employ different strategies when making decisions.

The authors refer to previous work by Conte and Pedone [1998].

The authors state that their work extends the study by Conte and Pedone [1998] from the formation of partnerships between pairs of agents to partnership formation between multiple agents.

Monteiro and Sichman [2006] present the *PartNET++* system that extends Conte and Pedone's [1998] *PART-NET* system from generating exchange partnerships between pairs of agents to multiple agents. To accomplish this they introduce the notion of *plans* into the system that makes it possible to achieve a goal via the execution of a sequence of actions as opposed to only one action. An agent may then form a partnership with multiple agents where different agents are responsible for performing the actions. To facilitate partnership formation among multiple agents in *PartNET++*, Monteiro and Sichman [2006] represent agent dependencies using social dependence graphs [Conte and Sichman 2002]. In dependence graphs, nodes represent agents, goals, plans or actions and edges can have a positive weight that represents the importance of a goal or a negative weight that represents the cost of an action. An agent has a goal that contains a plan made up of a sequence of actions. Monteiro and Sichman [2006] introduce *social stratification* (STR) and *social intolerance* (INT). STR specifies the maximum number of agents in the agency that can act as mediators in partnerships where agents may indirectly benefit each other. In such cases an agent may not be able to execute an action to benefit a second agent it needs, but can assist a third that in turn helps the second. INT refers to the allowed number of intolerant agents, that is agents that will only act as mediators when assured that all actions towards at least one of their plans will be executed in exchange.

Part of the algorithm used for *PartNET++* is based on Sichman's [1998] *DEPINT* system. Each agent randomly chooses partners towards the accomplishment of one of its goals depending on its strategy [Conte and Pedone 1998] and settings for STR and INT.

Monteiro and Sichman [2006] state that various experiments were conducted to verify that the results obtained from the *PART-NET* system would be repeated for multiple partners. Agencies were generated with varying sizes and each was run 100 times to compute averages and standard deviations. Goal importance and action costs were randomly generated. However, in all experiments conducted INT was set to 1.

Monteiro and Sichman [2006] claim that they were able to duplicate all the results from the *PART-NET* system in the new system except for one. They could not replicate *PART-NET*'s determination that agents in heterogeneous environments obtained better benefits on average than agents in homogeneous ones.

Monteiro and Sichman [2006] claim that their simulation explains the formation of multiple-partner partnerships among agents and provides a test bed for other social theories.

2.3.7 *Coalition formation via chains of exchanges and enforced agreements.* In coalition formation, self-interested agents agree to help each other achieve their respective goals either in the form of cooperation in the case of a shared goal, or exchange when the goals differ. When dealing with exchanges, prior models have been limited to exchanges between two agents ignoring other possibilities where agents might help each other. Sauro [2006] addresses agents reasoning about each other in situations where the exchange involves more than two agents. This reasoning considers both the agents recognition of potential partners as well as the associated costs and benefits. In Sauro [2006], conditions under which these complex exchanges can occur are formalized. In the model, there is no general preference for cooperation over exchange as agents can decide on either form of agreement as they deem suitable. A coalition is formed simply when all involved agents commit to it and can consist of both forms of agreements.

The author identifies previous work by Sichman et al. [1994], Wooldridge and Jennings [1994], Alonso [1998], Sichman and Demazeau [2001] and Castelfranchi [2003].

The author criticizes Wooldridge and Jennings' [1994] for only supporting coalition formation among agents with common goals. He states that the models in Sichman et al. [1994] and Castelfranchi [2003] only support exchanges between pairs of agents. The author states that in his model cooperation and exchange are equally likely as a choice for the agents. This differs from Sichman and Demazeau's [2001] approach where agents prefer cooperation over exchange which is criticized for providing an environment where agents may be forced into a form of agreement by other agents.

In Sauro's [2006] model agents help each other either via cooperation or social exchange [Castelfranchi 2003], without any demands from other agents. Once a coalition is formed, the participating agents are deemed committed and required to abide by the conditions of the agreement. Sauro [2006] defines a multi-agent system in terms of a *power structure* which does not focus on individual agent characteristics, but rather describes the environment in terms of which agents can work together for the achievement of one or more goals without internal conflicts. *Power frames* are introduced to describe possible coalitions that can be formed. To address the fact that all power frames do not lead to valid coalitions, Sauro [2006] introduces formalizations of two properties that must hold for an agreement to occur. The *do-ut-des* property specifies that an agent will only give something if it is assured the benefit of getting something else in exchange. To support indirect exchanges, which are exchanges involving more than two agents, the do-ut-des property uses Conte and Sichman's [2002] notion of dependence graphs. An example of an indirect exchange involves three agents collaborating where the first depends on the second, the second depends on the third and the third depends on the first. The *composition* or *indecomposable do-ut-des* property extends the do-ut-des property by considering a balance between coalition benefits and the associated coalition costs. This results in the formation of small coalitions wherever possible.

Sauro [2006] does not describe any conducted experiments.

Sauro [2006] does not present any results.

Sauro [2006] states that his model extends Castelfranchi's [2003] social dependence theory by supporting coalitions formed from chains of exchanges. He claims that his model supports cooperation and social exchange with equal plausibility. His defined conditions under which valid coalitions can be formed differ from existing solution criteria offered by game theory approaches in two ways. First, since his agents are goal-directed possible coalitions are compared by examining their achievable goals and associated risks without deep analysis of the coalitions themselves. Second, his approach allows the evaluation of whether a coalition can be formed without comparing it to others.

2.3.8 *Coalition formation based on transitive dependencies.* When a second agent requires assistance from a third agent in order to provide help to the first agent, there is a transitive dependency. An et al. [2007] address coalition formation among transitively-dependent agents.

The authors cite previous work by An et al. [2005].

An et al. [2007] criticize their previous work An et al. [2005] for only supporting the generation of suboptimal coalitions.

An et al.'s [2007] introduction of the notion of transitive dependency into social reasoning is presented in Section 2.1.8.In their framework, a coalition represents a group of agents that can perform all actions requested by a particular agent for the achievement of a specific goal. If all transitive dependencies are satisfied then the coalition is deemed feasible. The authors provide two algorithms that can be used by agents to form optimal coalitions, that is, partnerships involving the best partners for the least cost. Given an agent's goal, a set of plans to achieve the goal, abilities of agents in the environment and all action dependence relations, the algorithms return a coalition composed of a group of agents and their respective actions to perform for the achievement of the goal. The first algorithm looks for the optimal coalition for a goal among agents where there is no and-action dependence and the second searches for a coalition in an environment with and-action dependencies. The second algorithm is allowed to complete prior to finding the optimal coalition, thus being an anytime algorithm. With regard to cost of actions, every agent that can perform an action has a minimum offer it would accept in order to perform it. Alternatively, every agent that needs an action has a maximum offer that it can propose for it. Both algorithms employ a four step process to form the coalition. First, for each agent that is requested to perform an action in a plan, the algorithms determine the lowest cost for the action taking into account all action dependencies. Next, for each action in a plan, all agents that can perform it are compared and the lowest cost and the associated agent from the first step is selected. The third step involves the summation of the cost of all required actions in each plan. Finally, the plan with the least cost is chosen and all agents involved form a coalition. In the first step of both algorithms, An et al. [2007] use a directed *dependence graph* to characterize the calculation of the cost to an agent to perform an action taking into account all action dependencies.

An et al. [2007] state that they built a simulation composed of agents to test their algorithms for generating coalitions in an environment without and-action dependencies and one with and-action dependencies. Variables of the environment included the number of agents, the number of actions an agent could perform representing its ability, the number of plans for a goal, probability of action dependency, probability of and-action dependence and or-action dependence. The performance of the algorithms were measured in terms of the average processing time and standardized utility which explored how close the generated coalition was, to the optimal coalition. The authors claim that the algorithms were run with several variations of the variables.

An et al. [2007] conducted experiments in an environment without and-action dependence. They state that as the number of agents increased, the processing time increased faster and faster. They claim to have observed that varying the probability of or-action dependencies had very little effect on processing time for the same number of agents. Processing time also increased with an increase in the number of agents for environment with and-action dependencies. However the rise was almost linear. In this environment, an increase in the probability of and-action dependencies resulted in steady increase in processing time. An et al. [2007] claim in their final observation that the longer the with and-action dependence algorithm was executed, the closer it got to generating the optimal coalition.

An et al. [2007] state that they have provided algorithms for generating optimal coalitions for the achievement of a particular goal. They claim that their algorithm for generating coalitions in environments without and-dependence relations is of polynomial complexity. Although their with and-action dependence algorithm is of a higher complexity and the problem is shown to be NP-complete, the authors claim that the algorithm is efficient. They state that their algorithms are applicable in a variety of domains including supply chain management, automotive and service oriented computing, workflow and multi-agent manufacturing systems.

2.3.9 *Algorithms for coalition formation via chains of exchanges.* Boella et al. [2009] address the problem that arises from the fact that all possible chains of exchanges between goal-directed agents are not attainable concurrently and how coalitions can be formed taking this into account. This is important because knowing which exchanges are not realizable at the same time simplifies the coalition formation process.

The authors refer to previous work by Boella et al. [2005], Sauro [2005], Boella et al. [2006] and Sauro [2006].

The authors state that the work in Boella et al. [2005] did not consider the costs and benefits involved in coalition formation based on exchange. Sauro's [2005] game-theoretic approach is criticized for requiring a comparison between a coalition and all others to verify that it satisfies the criteria for forming a coalition. They do not provide any criticism for the study by Boella et al. [2006], but state that their work elaborates the introduced algorithms and demonstrates examples. The authors do not criticize Sauro's [2006] study which considers both cooperation and exchange but note that it differs from theirs which is restricted to exchanges.

Inspired by Castelfranchi's [2003] concept of social exchanges, Boella et al. [2009] use Conte and Sichman's [2002] notion of dependence graphs to represent possible coalitions among goal-directed agents. Addressing coalition formation only in the form of collaboration via exchanges, a coalition is a subgraph of a dependence graph that has vertices representing agents and AND-edges, labeled with a goal. The AND-edges relate a goal to an agent that wants to achieve the goal and a set of agents willing to assist it. Each coalition requires that each agent must make some contribution towards the goal and the coalition cannot be based on private needs that do not demand collaboration. Coalitions are further confined to agents that give in order to receive, the *do-ut-des* property [Boella et al. 2005], and groups that are indecomposable, the *i-dud* property. Complementary to the power-based approach used in Sauro [2006], Boella et al.'s [2009] i-dud property supports only coalitions formed between agents with different goals. Paths in the graph are used to denote networks of exchanges and the i-dud property which disallows the decomposition of a coalition into smaller coalitions that can be formed on their own, is formalized. Conte and Sichman's [2002] condition that agents collaborate only when they are not self-sufficient is relaxed to allow agents to delegate even actions they are capable of when it makes sense cost-wise. Algorithms are provided to find coalitions and all possible sub coalitions that satisfy the property. The computational complexity of the algorithms are discussed.

Boella et al. [2009] state that they used a game providing a test-bed for exchange of resources between agents to test how their approach restricts the set of permissible coalitions and demonstrate their use of AND-graphs to represent coalitions explicitly. Their chips and boxes game supported four agents, each with two chips and two boxes that could vary between three colors. The goal of an agent was to fill each of its boxes with a chip that had the same color as its box, thus requiring the agents to exchange chips. The authors state that the problem was represented with AND-graphs and the algorithms were applied to find possible coalitions that satisfied both the do-ut-des and i-dud properties.

Boella et al. [2009] state that when applied to their version of a chips and boxes game, their algorithms found all coalitions and sub coalitions that satisfied the do-ut-des and i-dud properties.

Boella et al. [2009] state that their algorithm is tractable because verifying that a coalition satisfies their defined criteria only involves the coalition and its sub coalitions rather than all coalitions in the system.

2.3.10 *Summary.*

Year	Author	Title of Paper	Major Contribution
1999	Brainov and Sandholm	Power, dependence and stability in multiagent plans.	Formalizes the emergence of coalitions from group dependence.
1999	David, Sichman and Coelho	Extending social reasoning to cope with multiple partner coalitions.	Uses dependence strengths and dependence situations in the formation of coalitions between multiple partners.
2000	Morgado and Gasper	A social reasoning mechanism based on a new approach for coalition formation.	Introduces the inference of indirect dependencies resulting in the formation of multiple connected and nested coalitions.
2001	David, Sichman and Coelho	Agent-based social simulation with coalitions in social reasoning.	Analyzes selection of multiple partners for coalition formation.
2004	Boella, Sauro and Torre	Power and dependence relations in groups of agents.	Formalizes the emergence of coalitions incorporating agent and group intentions.
2006	Monteiro and Sichman	PartNET++: Simulating multiple agent partnerships using dependence graphs	Simulates multiple-partner partnerships formed between agents with differing goals and decision-making strategies.
2006	Sauro	Qualitative criteria of admissibility for enforced agreements	Introduces multiple-partner coalition formation using chains of exchanges and enforced agreements.
2007	An, Shen, Miao and Cheng	Algorithms for transitive dependence-based coalition formation.	Provides algorithms for coalition formation based on transitive dependencies.
2009	Boella, Sauro and van der Torre	Algorithms for finding coalitions exploiting a new reciprocity condition.	Provides algorithms for coalition formation involving chains of exchanges.

Table III. Major Contributions in Multiple-Partner Coalition Formation

2.4 Coalition Formation via Attacks

The research paper in this section addresses dynamic coalition formation resulting from the identification of conflicting coalitions. The paper was written in 2008.

2.4.1 *Attack relations due to dynamic dependencies.* Boella et al. [2008] address the problem of creating a model to support reasoning about how coalitions evolve due to agents gaining or losing abilities, or agents entering or leaving the environment. Another problem addressed by Boella et al. [2008], is reasoning about how coalitions attack each other. This notion refers to the identification of conflicting coalitions, such as when an agent belongs to multiple coalitions or when different coalitions are trying to achieve the same goal. This is important because it can affect how coalitions are formed.

The authors refer to previous work by Amgoud [2005].

The authors state that Amgoud's [2005] task-based model for coalition formation assumes that agents do not belong to more than one coalition at a time and is limited in the number of attacks covered.

Boella et al. [2008] generalize Amgoud's [2005] task-based argumentation model for coalition formation by providing a framework based on Sichman and Conte's [2002] dependence network theory. Using argumentation in coalition formation involves reasoning by generating arguments and using them to form coalitions. In Boella et al.'s [2008] model, attacks between coalitions occur when the coalitions have a common goal or when dependencies are added or removed. To support this dynamic property of coalitions, the authors utilize Caire et al.'s [2008] notion of dynamic dependence networks, an extension of Sichman and Conte's [2002] work, which supports the change of dependencies between agents over time due to agent actions. Boella et al. [2008] establish two kinds of dynamic dependencies which they refer to as *positive* dynamic dependency and *negative* dynamic dependency. A positive dynamic dependency refers to the addition of a dependency due to another group of agents gaining an ability while a negative dependency occurs when a dependency is removed by a group of agents as a results of an agent abandoning a goal or losing an ability. Corresponding to Amgoud's [2005] model where attack relations occur because coalitions share a common task, Boella et al. [2008] formalize when coalitions attack each other because they have a common goal. They formalize a second kind of attack where a coalition attacks another by adding or removing a dependency.

Boella et al. [2008] use examples to illustrate reasoning about coalition attacks. They present examples demonstrating attacks via addition or removal of dependencies.

Boella et al. [2008] claim their examples demonstrate a wide of range of attacks among coalitions.

Boella et al. [2008] state that their model is a generalization of a previous model that uses argumentation to form coalitions [Amgoud 2005]. They claim that their model covers more attack relations and can be used to study not only coalition formation but coalition evolution as well.

2.4.2 *Summary.*

Year	Author	Title of Paper	Major Contribution
2008	Boella, van der Torre and Villata	Attack relations among dynamic coalitions.	Addresses coalition formation and attack relations.

Table IV. Major Contribution in Coalitions and Attacks

2.5 Combining Social Dependence and Game Theory for Coalition Formation

The research paper in this section deals with the combination of social dependence and game theory in coalition formation. The paper was written in 2010.

2.5.1 *Coalition formation utilizing social dependence and game theory.* Research so far in coalition formation have usually used the game theory approach and the dependence theory alternatively. However, combining these two approaches can provide dependence theory with the mathematical foundation that has been well established in game theory, and give the game theory approach the ability to analyze agent cooperation given their dependencies. The objective of Grossi and Turrini [2010] is to provide a formal model of both approaches combined. They contend that the aspect of dependence theory that explores use of dependencies to predict agent behavior lacks formal foundations.

The authors refer to previous work where dependence theory and game theory were combined for coalition formation by Bonzon et al. [2009] and Sauro et al. [2009] which they state extends a study that started with Boella et al. [2006].

The authors state that the studies by Bonzon et al. [2009] and Sauro et al. [2009] relate different dependence relations within Boolean games to solution concepts from game theory. They state that these studies are limited to Boolean games and focus on the use of dependence theory to analyze the games. Grossi and Turrini [2010], however, use game theory to formalize certain aspects of dependence theory leading to coalition formation.

To combine both game-theory and dependence-based approaches, Grossi and Turrini [2010] inherit game theoretic solution concepts of Nash equilibrium, referred to as best response equilibrium *(BR-equilibrium)* and dominant strategies which they call *DS-equilibrium*. Using game theory they redefine the basic notion of dependence theory, where agent i depends on another agent j for the achievement of a goal g. This is defined in terms of j selecting a strategy in the game that favors i for realizing g. If j's chosen strategy is the best it can do for i, then the dependency is in the best response sense. If the chosen strategy maximizes i's well-being, then the dependency is in the sense of a dominant strategy. This results in a definition of a dependence structure composed of agents with *BR* and *DS* strategies. This structure is further used to define dependence cycles [Sichman and Conte 2002] in a game theoretical sense, where agents form a chain of dependencies to support an agent indirectly depending on another. In a 3-person game with agents i, j and k, pairwise dependencies between i and j as well as between j and k, result in an indirect dependency between i and k. Grossi and Turrini [2010] use this notion to redefine reciprocal dependence.

Using their combined definitions of dependence theory and game theory, Grossi and Turrini [2010] provide their definition of an agreement as the result of agents coordinating via the exchange of BR or DS strategies for a chosen goal. They contend that these agreements give rise to the formation of coalitions and use them to define coalitional games based on cooperative game theory and *dependence games* which extend coalitional games to include their notion of agreements. Finally, to address the stability of agreements the authors explore the game theory notion of core within dependence games.

Grossi and Turrini [2010] describe an application of their definition of the basic notion of dependence theory to the two-person Prisoner's dilemma game. Their definition of dependence cycles is demonstrated in a three-person version of the game. Both versions of the game are used in an example to demonstrate their definition of agreements as well as their determination of the core within coalitional and dependence games.

Grossi and Turrini [2010] claim their examples demonstrate their use of dependence structures to predict agent behavior with regard to agreements towards coalition formation.

Grossi and Turrini [2010] claim to have demonstrated that dependence concepts such as dependence cycles can be defined in the game theoretic sense. They also claim to have shown that dependence theory can be used within game theoretic notions such as the core to predict agent behavior in a multi-agent system.

2.5.2 *Summary.*

Year	Author	Title of Paper	Major Contribution
2010	Grossi and Turrini	Dependence theory via game theory.	Redefines social dependence in terms of game theory for coalition formation.

Table V. Major Contribution in Combining Social Dependence and Game Theory

3. CONCLUDING COMMENTS

Sichman et al. [1994] appear to be the first to define a social reasoning mechanism based on the concepts of social dependence. They developed a model where agents store information about each other and use it to calculate their dependencies on each other. The authors stated that their model was domain-independent and allowed for the formation of coalitions in dynamic environments. They noted however, that the model did not consider the utility of dependencies such as the attachment of importance to goals or cost to actions. Additionally, the model only supported coalition formation between pairs of agents.

Alonso [1998] is the first to address the consideration of cost and benefit in social dependence-based coalition formation. The author incorporated utility-based rationality into the process using AND/OR trees. David et al. [1999] addressed the same issue by extending Sichman's [1994] external description structure to include utility concepts. In David et al. [2001] the authors furthered the study by comparing utility-based rationality against rationality based on social dependence . They claim to have noticed different levels of complexity in the search space depending the form of rationality applied first by the agents. To quantify dependencies, Hsieh et al. [2004] attached additional variables to actions, resources, plans and goals. Their fuzzy inference model allowed agents to evaluate their degree of dependencies on each other taking into consideration both qualitative and quantitative aspects. Grossi and Turrini's Grossi and Turrini [2010] study attempts to integrate game theory into social dependence-based coalition formation . They contend that the model allows social dependence to benefit from the mathematical foundations of game theory facilitating the quantification of dependencies.

Sichman [1995], Sichman [1998], Brainov and Sandholm [1999] and Boella et al. [2004] address concerns that arise from dynamic coalition formation. These involve the consequences of agents having the ability to enter and leave the environment at will or change their plans. In Sichman [1995] and Sichman [1998] agents can detect inconsistencies in what they believe about each other and revise the information maintained. Brainov and Sandholm [1999] explores these aspects by elaborating on the stability of agent plans. In Boella et al. [2004], dynamic coalitions are treated as attacks.

Research papers dealing explicitly with formalizing the coalition formation process include Alonso [1998] and Panzarasa et al. [2002] where multi-modal logic was used. Boella et al. [2004] addresses the formalization of the emergence of groups.

Carabelea et al. [2005] redefined Sichman et al.'s [1994] to explicitly include concepts of social power.

Sichman [1998], Alonso [1998], Conte et al. [1998] and Conte and Pedone [1998] present models for coalition formation between pairs of agents. In these models partnerships are formed between agents that directly depend upon each other. Sichman [1998] appears to be the pioneer for social dependence-based coalition formation models. Alonso [1998] addressed agents choosing partners based on preferences, Conte et al. [1998] explored predicting the emergence of groups and Conte and Pedone [1998] dealt with the formation of coalitions between agents with different goals and different decision-making strategies.

The research papers Brainov and Sandholm [1999], David et al. [1999], Morgado and Gaspar [2000], Boella et al. [2004], Monteiro and Sichman [2006], Sauro [2006], An et al. [2007] and Boella et al. [2009] address coalition formation among indirectly related agents. These models allow agents to infer indirect dependencies and thus increase the number of possible coalitions that can be formed. This notion began with a decision-theoretic approach provided by Brainov and Sandholm [1999] allowing an agent to depend on a group of agents and a group of agents to depend on an agent. A complementary approach was used by Boella et al. [2004], where the aspect that agents could help or obstruct each other was formalized by determining feasible states. David et al. [1999] and David et al. [2001] experimented with multiple-partner coalitions by introducing the combination of dependence strength and dependence situations. Morgado and Gasper's [2000] model supported the inference of indirect relationships by agents resulting in the formation of nested coalitions. Monteiro and Sichman [2006] extended the model of coalition formation between pairs of agents by Conte and Pedone [1998] to support multiple-partner coalitions. Sauro [2006] and Boella et al. [2009] explored coalition formation via chains of exchanges and An et al. [2007] explicitly addressed coalition formation based on transitive dependencies.

4. ANNOTATIONS

4.1 Alonso 1998

Citation: Alonso, E. 1998. How individuals negotiate societies. In *Proceedings of the 3rd International Conference on Multi Agent Systems*. ICMAS '98. 18–25.

Problem. Autonomous and heterogeneous agents may cooperate towards achieving their individual goals. In deciding who to cooperate with, agents are often driven by their dependencies and the utility of the association, that is, what they would gain relative to what it would cost them. Existing studies have not tackled agents' ability to cooperate when they have different goals but common intermediary interests. The entire cooperative process needs to be formalized for better understanding.

Previous Work. The author refers to previous work by Jennings [1992], Sichman et al. [1994] and Wooldridge and Jennings [1996].

Shortcomings of Previous Work. The author criticizes Jennings' [1992] model for its restriction to cooperation between agents with common goals based on their needs. Sichman et al.'s [1994] model is criticized for accommodating cooperation between agents with different goals only when it is required. Another noted shortfall is the absence of a formalization for weak dependencies defined as the situation when an agent prefers to cooperate with another to achieve a goal even though it is capable of achieving it alone. The approach is also criticized for its exploration of why interaction occurs between agents without specifying how it does and the presumption that social reasoning can be based on unilateral relationships. In the model by Wooldridge and Jennings [1996], agents with common goals choose partners depending on their needs and/or preferences. However, the model is criticized for its lack of a representation tool for the concept of cooperation based on preferences.

New Idea/Algorithm/Architecture. Alonso [1998] presents a formal model for agents cooperating towards achieving their goals using Castelfranchi et al.'s [1992] social dependence concepts combined with utility-based rationality. In the model AND/OR trees are built for each agent's specific goals and sub-goals or plans down to the level of actions while utilities for actions are computed with respect to the cost and benefit of their intended plan. The cooperative process begins when agents recognize who they can cooperate with, achieved via the evaluation of their dependencies on each other. Alonso [1998] formally defines two ways that an agent might recognize the need to cooperate with another towards achieving a goal. In the first case the dependency is the result of the presence of a sub-goal that an agent is unable to achieve while another can. In the second, termed a weak dependency, an agent can achieve all its sub-goals but prefers accomplishing its goal via cooperation rather than autonomously. The first case represents a mutual dependency while the second represents a reciprocal one where the preferred agent can be seen as having power over the one that prefers it. The model allows agents to cooperate even in the absence of common goals, as sub-goals for heterogeneous agents might hierarchically lead to different goals. Unilateral relationships where an agent might initiate cooperation with another in the absence of a mutual benefit are not supported.

Alonso [1998] introduces the concept of a *pure deal* that represents a sequence of actions to define how agents negotiate cooperation. Agents enter into deals with each other by accepting to execute the respective actions. Utilities assist in ensuring that cooperation is fair and the negotiation process is driven by the dependence situations. Mutually dependent agents simply exchange the necessary actions, reciprocal dependency leads to deals based on maximizing utility for both agents and if an agent has power over another then the deal will be driven by the utility of the dominant agent. Agents are assumed to be honest with regard to the actions they can execute and expected to honor deals that they commit to. In the strategy adopted for negotiation, agents seek to make the most profitable deal which may lead to the proposal and acceptance of a counteroffer. Once an agreement is reached cooperating agents can be regarded as belonging to a group, working together towards the accomplishment of goals or partial goals.

Experiments Conducted. Alonso [1998] does not describe any experiments conducted.

Results. Alonso [1998] does not present any results.

Conclusions. Alonso [1998] claims that his model covers all the steps of the coordination process and is uncomplicated. He states that the model allows coordination in the absence of common goals and formally defines weak relationships thus increasing the cooperative space. Finally he claims that his use of dependence relations clarifies the negotiation stage, which defines the agents' ability to calculate fair deals.

Citations By Others. [Morgado and Gaspar 2000; David et al. 2001; Sauro 2006]

4.2 An et al. 2007

Citation: An, B., Shen, Z., Miao, C., and Cheng, D. 2007. Algorithms for transitive dependence-based coalition formation. *IEEE Transactions on Industrial Informatics 3,* 3, 234–245.

Problem. In order for an agent to realize its goal it may need the assistance of a second agent. It is possible that the second agent can only provide this assistance with the help of a third agent. An et al. [2007] address how agents can reason about the dependencies of agents that they depend on when forming coalitions. This is important because an agent can only realize its goal if these secondary dependencies are taken into consideration.

Previous Work. The authors cite previous work by An et al. [2005].

Shortcomings of Previous Work. An et al. [2007] criticize their previous work An et al. [2005] for only supporting the generation of suboptimal coalitions.

New Idea/Algorithm/Architecture. An et al. [2007] introduce the notion of transitive dependence into social reasoning based on agent dependencies [Sichman et al. 1994; Morgado and Gaspar 2000]. In An et al.'s [2007] framework, every agent has goals, plans and actions. Actions combine to make up a plan and plans make up a goal. Agents may work together to achieve some or all of their goals. They introduce the notion of *action dependency* which exists between two actions for an agent if the agent will only perform one action on the condition that the other action be performed in return. The agent may also require that a set of actions be performed in return. In such a case, when all the actions in that set are required the dependency becomes an *and-action dependency*. In the event that only one of the actions in the set are required the dependency is deemed an *or-action dependency*. Action dependency relations are used to describe transitive dependencies between agents.

In An et al.'s [2007] framework, a coalition represents a group of agents that can perform all actions requested by a particular agent for the achievement of a specific goal. If all transitive dependencies are satisfied then the coalition is deemed feasible. The authors provide two algorithms that can be used by agents to form optimal coalitions, that is, partnerships involving the best partners for the least cost. Given an agent's goal, a set of plans to achieve the goal, abilities of agents in the environment and all action dependence relations, the algorithms return a coalition composed of a group of agents and their respective actions to perform for the achievement of the goal. The first algorithm looks for the optimal coalition for a goal among agents where there is no and-action dependence and the second searches for a coalition in an environment with and-action dependencies. The second algorithm is allowed to complete prior to finding the optimal coalition, thus being an anytime algorithm. With regard to cost of actions, every agent that can perform an action has a minimum offer it would accept in order to perform it. Alternatively, every agent that needs an action has a maximum offer that it can propose for it. Both algorithms employ a four step process to form the coalition. First, for each agent that is requested to perform an action in a plan, the algorithms determine the lowest cost for the action taking into account all action dependencies. Next, for each action in a plan, all agents that can perform it are compared and the lowest cost and the associated agent from the first step is selected. The third step involves the summation of the cost of all required actions in each plan. Finally, the plan with the least cost is chosen and all agents involved form a coalition. In the first step of both algorithms, An et al. [2007] use a directed *dependence graph* to characterize the calculation of the cost to an agent to perform an action taking into account all action dependencies.

Experiments Conducted . An et al. [2007] state that they built a simulation composed of agents to test their algorithms for generating coalitions in an environment without and-action dependencies and one with and-action dependencies. Variables of the environment included the number of agents, the number of actions an agent could perform representing its ability, the number of plans for a goal, probability of action dependency, probability of and-action dependence and or-action dependence. The performance of the algorithms were measured in terms of the average processing time and standardized utility which explored how close the generated coalition was, to the optimal coalition. The authors claim that the algorithms were run with several variations of the variables.

Results. An et al. [2007] conducted experiments in an environment without and-action dependence. They state that as the number of agents increased, the processing time increased faster and faster. They claim to have observed that varying the probability of or-action dependencies had very little effect on processing time for the same number of agents. Processing time also increased with an increase in the number of agents for environment with and-action dependencies. However the rise was almost linear. In this environment, an increase in the probability of and-action dependencies resulted in steady increase in processing time. An et al. [2007] claim in their final observation that the longer the with and-action dependence algorithm was executed, the closer it got to generating the optimal coalition.

Conclusions. An et al. [2007] state that they have provided algorithms for generating optimal coalitions for the achievement of a particular goal. They claim that their algorithm for generating coalitions in environments without and-dependence relations is of polynomial complexity. Although their with and-action dependence algorithm is of a higher complexity and the problem is shown to be NP-complete, the authors claim that the algorithm is efficient. They state that their algorithms are applicable in a variety of domains including supply chain management, automotive and service oriented computing, workflow and multi-agent manufacturing systems.

Citations By Others. There are no specific references to this paper by other researchers in this survey.

4.3 Boella et al. 2004

Citation: Boella, G., Sauro, L., and Torre, L. v. d. 2004. Power and dependence relations in groups of agents. In *Proceedings of the IEEE/WIC/ACM International Conference on Intelligent Agent Technology*. IAT '04. IEEE Computer Society, Washington, DC, USA, 246–252.

Problem. When self-interested agents coordinate their efforts for the achievement of their individual goals in multi-agent systems, groups emerge. Boella et al. [2004] address the formalization of the emergence of groups as a result of power and dependence relationships. This is important as it helps find inconsistencies in the underlying definitions of the coalition formation process.

Previous Work. The authors refer to previous work by Brainov and Sandholm [1999] and Sichman and Conte [2002].

Shortcomings of Previous Work. The authors criticize the decision-theoretic approach used in Brainov and Sandholm [1999] to examine social relations, for inferring group behaviors and their effect on how goals are achieved, making it difficult to calculate their benefits. Conte and Sichman's [2002] study is criticized for not considering concurrency management problems such as goal obstruction.

New Idea/Algorithm/Architecture. Boella et al. [2004] present a model of a multi-agent system, that represents the environment in terms of important attributes and values. An assignment of values to all attributes in a given system, results in one possible state of the environment. Agents are represented in terms of the actions they can perform. As a result, feasible states can be formalized using rules that examine preconditions of actions and their effects. These effects include the fact that carrying out an action may obstruct another. Attribute values are deemed compatible when no conflicts arise from actions that are carried out in their state. Boella et al. [2004] define feasible rules and feasible set of rules to accommodate concurrency management in situations where the effect of an an agent action is the activation of multiple rules that may not be compatible with each other. Boella et al. [2004] formalize Castelfranchi's [2003] notion of power and Castelfranchi et al.'s [1992] concepts of dependence using their model. They use tagged graphs based on Sichman and Conte's [2002] concept of dependence graphs, to model agent dependencies. Cooperation is regarded in terms of the agent's goal objective and the actions needed to be performed to meet it. The authors extend their formalized model to include agent intentions and group intentions. Finally, cooperation among groups of agents is formalized.

Experiments Conducted. Boella et al. [2004] do not describe any experiments conducted.

Results. Boella et al. [2004] do not present any results.

Conclusions. Boella et al. [2004] claim their study provides a formalization of agents ability to help or obstruct each other for the achievement of their goals. They also state that their model differentiates between an agent's ability to help another and its intention to do so. Another claim made is that their model facilitates the calculation of the utility or benefits obtained from the behavior of a group. They state that their model addresses concurrency management which has been left out in some prior research done.

Citations By Others. [Boella et al. 2005; 2009]

4.4 Boella *et al.* 2008

Citation: Boella, G., van der Torre, L., and Villata, S. 2008. Attack relations among dynamic coalitions. In *Proceedings 20th Belgian-Netherlands Conference on Artificial Intelligence*, A. Nijholt, M. Pantic, M. Poel, and H. Hondorp, Eds. BNAIC '08. 25–32.

Problem. Boella et al. [2008] address the problem of creating a model to support reasoning about how coalitions evolve due to agents gaining or losing abilities, or agents entering or leaving the environment. Another problem addressed by Boella et al. [2008], is reasoning about how coalitions attack each other. This notion refers to the identification of conflicting coalitions, such as when an agent belongs to multiple coalitions or when different coalitions are trying to achieve the same goal. This is important because it can affect how coalitions are formed.

Previous Work. The authors refer to previous work by Amgoud [2005].

Shortcomings of Previous Work. The authors state that Amgoud's [2005] task-based model for coalition formation assumes that agents do not belong to more than one coalition at a time and is limited in the number of attacks covered.

New Idea/Algorithm/Architecture. Boella et al. [2008] generalize Amgoud's [2005] task-based argumentation model for coalition formation by providing a framework based on Sichman and Conte's [2002] dependence network theory. Using argumentation in coalition formation involves reasoning by generating arguments and using them to form coalitions. In Boella et al.'s [2008] model, attacks between coalitions occur when the coalitions have a common goal or when dependencies are added or removed. To support this dynamic property of coalitions, the authors utilize Caire et al.'s [2008] notion of dynamic dependence networks, an extension of Sichman and Conte's [2002] work, which supports the change of dependencies between agents over time due to agent actions. Boella et al. [2008] establish two kinds of dynamic dependencies which they refer to as *positive* dynamic dependency and *negative* dynamic dependency. A positive dynamic dependency refers to the addition of a dependency due to another group of agents gaining an ability while a negative dependency occurs when a dependency is removed by a group of agents as a results of an agent abandoning a goal or losing an ability. Corresponding to Amgoud's [2005] model where attack relations occur because coalitions share a common task, Boella et al. [2008] formalize when coalitions attack each other because they have a common goal. They formalize a second kind of attack where a coalition attacks another by adding or removing a dependency.

Experiments Conducted. Boella et al. [2008] use examples to illustrate reasoning about coalition attacks. They present examples demonstrating attacks via addition or removal of dependencies.

Results. Boella et al. [2008] claim their examples demonstrate a wide of range of attacks among coalitions.

Conclusions. Boella et al. [2008] state that their model is a generalization of a previous model that uses argumentation to form coalitions [Amgoud 2005]. They claim that their model covers more attack relations and can be used to study not only coalition formation but coalition evolution as well.

Citations By Others. There are no specific references to this paper by other researchers in this survey.

4.5 Boella et al. 2009

Citation: Boella, G., Sauro, L., and van der Torre, L. 2009. Algorithms for finding coalitions exploiting a new reciprocity condition. *Logic Journal of IGPL 17,* 3, 273–297.

Problem. In coalition formation, self-interested agents agree to help each other to achieve their respective goals either in the form of cooperation in the case of a shared goal, or exchange when the goals differ. Boella et al. [2009] address the problem that arises from the fact that all possible chains of exchanges between goal-directed agents are not attainable concurrently and how coalitions can be formed taking this into account. This is important because knowing which exchanges are not realizable at the same time simplifies the coalition formation process.

Previous Work. The authors refer to previous work by Boella et al. [2005], Sauro [2005], Boella et al. [2006] and Sauro [2006].

Shortcomings of Previous Work. The authors state that the work in Boella et al. [2005] did not consider the costs and benefits involved in coalition formation based on exchange. Sauro's [2005] game-theoretic approach is criticized for requiring a comparison between a coalition and all others to verify that it satisfies the criteria for forming a coalition. They do not provide any criticism for the study by Boella et al. [2006], but state that their work elaborates the introduced algorithms and demonstrates examples. The authors do not criticize Sauro's [2006] study which considers both cooperation and exchange but note that it differs from theirs which is restricted to exchanges.

New Idea/Algorithm/Architecture. Inspired by Castelfranchi's [2003] concept of social exchanges, Boella et al. [2009] use Conte and Sichman's [2002] notion of dependence graphs to represent possible coalitions among goal-directed agents. Addressing coalition formation only in the form of collaboration via exchanges, a coalition is a subgraph of a dependence graph that has vertices representing agents and AND-edges, labeled with a goal. The AND-edges relate a goal to an agent that wants to achieve the goal and a set of agents willing to assist it. Each coalition requires that each agent must make some contribution towards the goal and the coalition cannot be based on private needs that do not demand collaboration. Coalitions are further confined to agents that give in order to receive, the *do-ut-des* property [Boella et al. 2005], and groups that are indecomposable, the *i-dud* property. Complementary to the power-based approach used in Sauro [2006], Boella et al.'s [2009] i-dud property supports only coalitions formed between agents with different goals. Paths in the graph are used to denote networks of exchanges and the i-dud property which disallows the decomposition of a coalition into smaller coalitions that can be formed on their own, is formalized. Conte and Sichman's [2002] condition that agents collaborate only when they are not self-sufficient is relaxed to allow agents to delegate even actions they are capable of when it makes sense cost-wise. Algorithms are provided to find coalitions and all possible sub coalitions that satisfy the property. The computational complexity of the algorithms are discussed.

Experiments Conducted. Boella et al. [2009] state that they used a game providing a test-bed for exchange of resources between agents to test how their approach restricts the set of permissible coalitions and demonstrate their use of AND-graphs to represent coalitions explicitly. Their chips and boxes game supported four agents, each with two chips and two boxes that could vary between three colors. The goal of an agent was to fill each of its boxes with a chip that had the same color as its box, thus requiring the agents to exchange chips. The authors state that the problem was represented with AND-graphs and the algorithms were applied to find possible coalitions that satisfied both the do-ut-des and i-dud properties.

Results. Boella et al. [2009] state that when applied to their version of a chips and boxes game, their algorithms found all coalitions and sub coalitions that satisfied the do-ut-des and i-dud properties.

Conclusions. Boella et al. [2009] state that their algorithm is tractable because verifying that a coalition satisfies their defined criteria only involves the coalition and its sub coalitions rather than all coalitions in the system.

Citations By Others. There are no specific references to this paper by other researchers in this survey.

4.6 Brainov and Sandholm 1999

Citation: Brainov, S. and Sandholm, T. 1999. Power, dependence and stability in multiagent plans. In *Proceedings of the 16th National Conference on Artificial intelligence and the 11th Innovative Applications of Artificial Intelligence Conference*. AAAI '99/IAAI '99. American Association for Artificial Intelligence, Menlo Park, CA, USA, 11–16.

Problem. In coalition formation where self-interested agents collaborate for the achievement of their individual goals, social dependence based methods so far have been based on bilateral dependence relations between agents. Brainov and Sandholm [1999] address the formalization of dependence between an agent and a group or a group and an agent. This is important because an agent is just as likely to depend on a group of agents for the achievement of its goal, as it is likely to depend on just a single agent. The authors also address the consequences of an agent making changes to its plans and its effects on other agents that it is collaborating with.

Previous Work. The authors refer to previous work by Sichman et al. [1994].

Shortcomings of Previous Work. The authors criticize Sichman et al.'s [1994] for its limitation to dependence, that is, dependence between two agents.

New Idea/Algorithm/Architecture. Brainov and Sandholm [1999] introduce the notion of group dependence, a generalization of Sichman et al.'s [1994] previously defined notion of social dependence between pairs of agents. Group dependence accounts for an agent depending on a group of agents as well as a group of agents depending on an agent. In the context of joint plans, they use transitive dependence to characterize reciprocal dependence, the case when a group of agents depend on another group of agents either via a direct dependency or indirectly via a transitive dependency. In their formalization of a group of agents depending on an agent for a plan, they formalize a group of agents' dependence on an agent for a plan in two scenarios. The first scenario addresses when every agent in the group is required to have the plan in its plan list and the second assumes that all agents in the group do not necessarily have the plan in their plan list but must give their permission to whichever agent among them is fulfilling the plan. In formalizing an agent's dependence on a group of agents for a plan they show that only in acting together can the group of agents help or hurt the agent that depends on them.

To address the stability of agents' plans, or the consequences to agent dependencies within joint plans when an agent changes its plan Brainov and Sandholm [1999] differentiate between *individually stable* and *coalitionally stable* plans. Individual stability disallows an agent, on its own, from deviating from the plan and coalitional stability forces at least one agent to oppose to the deviation of a subgroup of agents in the joint plan.

Experiments Conducted. Brainov and Sandholm [1999] do not describe any conducted experiments.

Results. Brainov and Sandholm [1999] do not provide any results.

Conclusions. Brainov and Sandholm [1999] claim that their model formalizes the notion of group dependence among autonomous agents, where an agent can depend on a group of agents or a group of agents can depend on an agent. They claim that their approach where an agent's ability to influence others is related to specific joint plans is better than game theory approaches which relate an agent's power to a general ability to exert influence, because it covers all forms of interaction between agents.

Citations By Others. [Boella et al. 2004; Boella et al. 2004; Sauro 2005]

4.7 Carabelea et al. 2005

Citation: Carabelea, C., Boissier, O., and Castelfranchi, C. 2005. Using social power to enable agents to reason about being part of a group. In *Engineering Societies in the Agents World V*, M.-P. Gleizes, A. Omicini, and F. Zambonelli, Eds. Lecture Notes in Computer Science, vol. 3451. Springer Berlin / Heidelberg, 898–898.

Problem. Autonomous and heterogeneous agents may collaborate towards achieving their goals. These agents may need to reason about the ramifications of belonging to a group which can affect their decision-making process of joining one. An agent needs to understand the rules imposed on how it behaves in order to make adequate decisions about who to cooperate with. Existing studies also do not distinguish between dependencies based on having the ability to do something and the permission to do it.

Previous Work. The authors refer to previous work by Sichman et al. [1994].

Shortcomings of Previous Work. The authors state that the work by Sichman et al. [1994] does not consider when agents collaborate as a result of a prohibition to execute a plan or action towards a goal or the lack of access to a needed resource.

New Idea/Algorithm/Architecture. Carabelea et al. [2005] use Sichman et al.'s [1994] social dependence concepts and their approach where information about agents is described in terms of goals, actions, resources and plans, as well as Castelfranchi's [2003] power theory, to formalize how agents reason about joining groups. Carabelea et al. [2005] distinguish between *individual powers* and *social powers* with the former represented by an agents' own goals, actions, resources and plans while the latter is represented by powers obtained via dependence relationships. Within individual powers agents can have *executional*, *deontic* or *full* powers. In achieving an objective, executional power specifies when an agent knows how, deontic power indicates when an agent is permitted to and full powers specify when an agent has both executional and deontic powers, is aware of them and intends to use them. In multi-agent systems individual powers lead to social powers as agents may depend on the powers of others to achieve their objectives. If an agent is aware of its dependence on another for a goal then the other agent is deemed to have *influencing power* over it. To this effect agents can gain new powers through access to the powers of others.

Carabelea et al. [2005] define additional powers that agents can have when they belong to a group. These powers are obtained via standard obligatory behavior or authority specified by roles. Agent relationships within groups are defined in terms of power, dependencies, authority relationships, roles and norms. Agents use these relationships to determine what they would gain or lose in reasoning about joining groups. While certain relationships may restrict an agents' powers others might enhance it. Furthermore if necessary, a group can also calculate the benefits or costs of allowing an agent to join it.

Experiments Conducted. Carabelea et al. [2005] state that they have begun implementation of a system called *MOISE+* that can be used to study agent reasoning about belonging to groups.

Results. Carabelea et al. [2005] do not present any results.

Conclusions. Carabelea et al. [2005] state that their model can be used in the design of a multi-agent system towards predicting how agents will behave in a group. They state that agents in such a system can then reason about the ramifications of being part of group and thus decide on whether to join it. It is also claimed that the model makes it possible for agents to be aware of their limitations with respect to power.

Citations By Others. There are no specific references to this paper by other researchers in this survey.

4.8 Conte et al. 1998

Citation: Conte, R., Castelfranchi, C., and Veneziano, V. 1998. The computer simulation of partnership formation. *Computational & Mathematical Organization Theory 4*, 293–315.

Problem. Autonomous and disparate agents may form coalitions to achieve goals that they cannot or do not wish to accomplish on their own. There is a need to explore how agent relationships influence the emergence of these coalitions and how such emergence can be predicted. This is necessary to better understand coalition formation.

Previous Work. The authors refer to previous work by Willer [1992] based on power-dependence theory and the study by Axelrod [1995] where a game-theory approach is used.

Shortcomings of Previous Work. In the power-dependence based exchange network theory presented by Willer [1992], exchange partnerships emerge from the dependencies between agents. This approach is criticized for not supporting the prediction of agent behavior. The authors criticize Axelrod's [1995] game theory approach for using quantitative rather than qualitative measures in relating agents and relying on hostile relationships to explain how coalitions emerge. Both cited studies are criticized for allowing the system designer to control agent dependencies. According to the authors, dependencies among agents should be brought about by the agents' features.

New Idea/Algorithm/Architecture. Conte et al. [1998] use the *MICROdep* system [Veneziano et al. 1996], an extension of *DEPNET* [Sichman et al. 1994] to demonstrate the emergence of coalitions in a society of heterogeneous agents. While

DEPNET generates dependence networks from agents' individual properties which include agents' goals, actions, resources and plans, *MICROdep* is a simulation that figures out partnerships from the networks. Dependence relations between agents specify the extent of an agent's autonomy with regard to its plans for a specific goal. An agent may depend on every agent in a set of agents *(AND_ dependence)* or on any agent in a set of agents *(OR_ dependence)* to accomplish a goal. Additionally a set of agents may depend on one agent *(CO-dependence)* for the achievement of the same goal. The authors utilize these dependencies to formally define the concept of *negotiation power* that intersects an agent's chances to ask for help with its ability to provide help.

Once *MICROdep* figures out the dependence networks and negotiation powers of the agents, it generates a list of favored partners for each agent and then globally formulates the partnerships. The list of favored partners is generated either with a goal-oriented or a gain-oriented criteria. Regarding a provision of help as a cost and the reception of help as a benefit, goal-oriented agents rank agents in their preference list primarily by benefits and secondarily by costs while gain-oriented agents perform the opposite. In forming partnerships, *MICROdep* requires potential partners to represent each other in their preference lists. Partnerships are extracted by repeatedly selecting pairs of agents with the highest *partnership value (p.v.)* and the lowest *difference between values (d.a.v)* from the preference matrix for all agents. The *p.v.* is computed via the summation of values in respective agents' preference lists while the *d.a.v.* represents the absolute value of the difference in the values.

Experiments Conducted. Conte et al. [1998] state that they performed experiments using *MICROdep* simulations to determine the ability of negotiation power to predict coalition formation and evaluate the difference between goal-oriented and gain-oriented methods for partner selection. They claim to have run simulations with agencies of varying sizes.

Results. Conte et al. [1998] claim that the results demonstrated an analogy between the negotiation power of an agent and how often it appeared in the preference lists of other agents. They state that the analogy was stronger when agents utilized the gain-oriented criteria in generating the preference list, than when the goal-oriented approach was applied. Additionally, Conte et al. [1998] claim that correlations were also observed between an agent's negotiation power and partnership formation as well as partnership value. They state that the results were dependent on agency size, allowing for more predictability as the number of agents increased, with negotiation power being the most predictable aspect. They also claim to have observed that partnership values obtained via the goal-oriented approach were more predictable than those derived with the gain-oriented criteria.

Conclusions. Conte et al. [1998] state that their model demonstrates the emergence of coalitions from dependence relations within an agency and how the formation of these partnerships can be predicted. They state that their model illustrates a method for heterogeneous agents to make rational decisions that differs from models that are utility-based. The authors claim in their model agent dependencies emerge from a description of the agency instead of being controlled by the system designer. They also claim that their model lays the foundation for studying multi-agent partnerships as opposed to partnerships between pairs of agents.

Citations By Others. [Conte and Sichman 2002; Sichman and Conte 2002; Monteiro and Sichman 2006]

4.9 Conte and Pedone 1998

Citation: CONTE, R. AND PEDONE, R. 1998. Finding the best partner: The PART-NET system. In *Proceedings of the 1st International Workshop on Multi-Agent Systems and Agent-Based Simulation.* Springer-Verlag, London, UK, 156–168.

Problem. Partnerships may be formed between pairs of autonomous agents with different goals and different decision-making strategies. An outstanding problem is understanding how such agents rationally choose partners and how their behavior can be predicted.

Previous Work. The authors refer to previous work regarding rationality in agencies by Conte and Sichman [1995], Conte and Castelfranchi [1996] and Conte and Paolucci [1997].

Shortcomings of Previous Work. The authors state that in Conte and Sichman [1995] rationality is determined by agent goals, in Conte and Castelfranchi [1996] it is dependent on different social actions conducted between agents and in Conte and Paolucci [1997] it is context-dependent. They state that their approach is different in that it considers both differing agent goals and decision-making strategies. They do not specifically identify any shortcomings of the previous work cited.

New Idea/Algorithm/Architecture. Conte and Pedone [1998] introduce the *PART-NET* system, that uses Sichman et al.'s [1994] notion of reciprocal dependence in the formation of partnerships among disparate agents. Regarded as an exchange, reciprocal dependence refers to a pair of agents depending on each other for the achievement of two different goals. *PART-NET* generates agent structures composed of goals, actions, dependence relationships and a chosen decision-making scheme. Conte and Pedone [1998] identify three different decision-making schemes:

—*substantialist* or *hedonist*: agent decisions are based on the importance of goals.
—*instrumentalist* or *utilitarian*: agents make decisions with the objective of maximizing the difference between receiving help and offering help towards achieving goals.
—*miser*: agent decisions aim to minimize the cost of actions.

Each agent depending on its chosen scheme, selects and orders agents that it is reciprocally dependent upon. The highest ranked agent for the hedonist will help it achieve its most important goal regardless of cost, the best partner for the utilitarian will help it achieve its most important goal that will cost the partner the least and the top ranked agent for the miser will request it's help towards the goal that bears the least cost to it. While misers and utilitarians will give up their most important goals in certain situations, hedonists will not. After generating agent structures, the *PART-NET* simulation forms partnerships by iteratively trimming the matrix of plausible partnerships. When one agent is matched against multiple partners, the agent chooses the match that rewards it the most and cancels the rest. At each simulation step the agent structures are regenerated with costs and benefits recalculated. The simulation ends when no more matches can be made.

Experiments Conducted. Conte and Pedone [1998] state that the *PART-NET* simulation was run to form partnerships and compare the varying influences of the three decision-making strategies both in homogeneous and heterogeneous environments. Homogeneous agencies represented the implementation of a single strategy while in heterogeneous environments there was a mix of strategies.

Results. Conte and Pedone [1998] claim that utilitarians were shown to be more flexible than hedonists who needed more goals and/or agents to obtain higher benefits. In heterogeneous environments, where a mix of decision-making strategies was implemented, although utilitarians initially benefited the most followed by hedonists and lastly misers, hedonists would outperform the others over time. In a homogeneous agency where all agents employed a single decision-making strategy however, hedonists had the highest benefits right from the start. Overall, the authors state that heterogeneous environments produced agents with higher benefits than homogeneous ones. They also claim that their results demonstrated that hedonists are more frequently requested as partners than misers and utilitarians.

Conclusions. Conte and Pedone [1998] claim that their concept demonstrates partnership formation based on different decision-making schemes. They also state that agent structures generated by the *PART-NET* system facilitate qualitative comparisons between disparate agents that form partnerships in an agency.

Citations By Others. [David et al. 2001; Conte and Sichman 2002; Monteiro and Sichman 2005; 2006]

4.10 David et al. 1999

Citation: David, N., Sichman, J. S. a., and Coelho, H. 1999. Extending social reasoning to cope with multiple partner coalitions. In *Proceedings of the 9th European Workshop on Modelling Autonomous Agents in a Multi-Agent World: MultiAgent System Engineering*. MAAMAW '99. Springer-Verlag, London, UK, 175–187.

Problem. Research so far dealing with autonomous agents effectively selecting partners for the achievement of their goals have either used a quantitative approach or a qualitative one, but not both. The quantitative approach which is utility-based, as in game theory, studies ways to maximize the agent's expected utility while in the complementary-based qualitative approach, such as dependence and social power, agents select partners based on social or psychological relations. Both perspectives are important in partner selection because in the real world effective partner selection would require considering both one's utility as well as preferences and social relations. David et al. [1999] address the problem of combining a qualitative and a quantitative approach to coalition formation. Another problem addressed by David et al. [1999] is multiple partner coalitions because prior research has only considered coalition formation between pairs of agents.

Previous Work. The authors refer to previous work by Zlotkin and Rosenschein [1994], Sichman et al. [1994] and Sichman and Demazeau [1995b].

Shortcomings of Previous Work. The authors criticize the work by Zlotkin and Rosenschein [1994] for its limitation to a quantitative approach to coalition formation. Sichman et al. [1994] and Sichman and Demazeau [1995b] are criticized for their limitation to a qualitative approach to coalition formation and for not addressing multiple partner coalitions, assuming coalition formation only between pairs of agents.

New Idea/Algorithm/Architecture. David et al. [1999] present a model that extends Sichman et al.'s [1994] social reasoning mechanism which permits an agent (*subject*) to represent some properties of others *(objects)* in the environment and use it to reason about their susceptibility to assist it in achieving a goal. The *external description* data structure used by each *subject* agent to store information about *object* agents is extended to include a weight property and a cost property. The weight property represents the significance given to each goal by the object agent. The cost property denotes the cost given by the object agent to each of its actions. The cost of a plan is the sum of all costs associated with all the plan's actions depending on the costs given by the agent's involved, and is calculated dynamically since it depends on the feasibility of the plan. David et al. [1999] introduce *inverse dependencies* which define dependence from the view of the object agents using dependencies on actions. In their model complementary-based partner selection is based on *offered goals*, *offered plans* and *offered actions* which refer to inverse dependencies based on goals, plans and actions respectively. Utility-based partner selection utilizes information stored in the cost property and the weight property. A function *action-strength* is provided that gives a strength value to an offered action, depending on the number of plans and goals the action contributes to and the significance of those goals. Action-strength values are combined to determine an object agent's dependence strength with a *dep-strength* function.

According to David et al. [1999], the multiple-partner coalition problem involves finding the best possible partner for each of an object agent's action-dependency, taking into account the fact that each possible partner may depend on others. To identify agents likely to accept a proposal for coalition formation, with the additional objective of reducing communication flow between agents, they introduce a function called *highest dep-sit* that finds the subset of agents with the highest dependence situations for an object agent's goal and plan. The partner to propose to is chosen based on the highest dependence situation and dependence strength and the lowest action-dependency cost that carries out the highest number of action-dependencies.

Experiments Conducted. David et al. [1999] state that they conducted an experiment involving coalition formation for software reuse to test their model. A company's projects represented goals, different configurations represented plans and packages denoted actions. Projects were assigned a significance value and packages were given costs. Companies could form coalitions with others to carry out projects.

Results. David et al. [1999] claim that their results demonstrated different types of dependencies and strengths playing a role in how partners were selected. They claim to have observed that choosing a goal with respect to a proposal is more qualitative-based while action choice is related to dependence based on cost, implying that it is important to access possible proposals before attempting partner selection for coalition formation.

Conclusions. David et al. [1999] state that their approach combines qualitative and quantitative notions in the choice of partners for coalition formation, thus making partner selection more effective. They also state that their model supports multiple partner coalitions where dependencies are represented by considering pairs of agents and agents depending on them.

Citations By Others. [Ito and Sichman 2000; Morgado and Gaspar 2000; An et al. 2005]

4.11 David et al. 2001

Citation: David, N., Sichman, J., and Coelho, H. 2001. Agent-based social simulation with coalitions in social reasoning. In *Multi-Agent-Based Simulation*, S. Moss and P. Davidsson, Eds. Lecture Notes in Computer Science, vol. 1979. Springer Berlin / Heidelberg, 93–112.

Problem. In order to predict the decisions made by agents in a multi-agent system it is essential to represent and analyze the cognition of the agents. These analyses and representations facilitate the exploration of how agents make rational choices with respect to their goals, selection of partners and generation of adequate proposals for the formation of not only coalitions between pairs of agents but also multiple partner coalitions.

Previous Work. The authors refer to previous work by Conte and Pedone [1998].

Shortcomings of Previous Work. The authors do not specify any shortcomings of the work by [Conte and Pedone 1998] but state that both approaches are based on some common aspects. They state that while Conte and Pedone [1998] provide some analysis of rational choice at individual and group level, they focus on the individual level.

New Idea/Algorithm/Architecture. To evaluate rationality in the decision making process of agents in a multi-agent system, David et al. [2001] use concepts of social dependence relations and dependence situations [Sichman 1998]. They distinguish between *motivation-oriented* rationality where agents make decisions based on how they socially interact with each other often via cooperation or exchange and *utility-based* rationality where agents' decisions are driven by the desire to maximize benefits and reduce costs. Dependence relations are refined to include *inverse dependencies*, which provide a view of dependencies from the dependent agent. The authors describe how offered goals, offered actions and offered plans are derived by an agent identifying an action he can offer another agent towards that agent's plan for a particular goal. In generating proposals and choosing partners, they combine utility-oriented and motivation-oriented rationality and identify that agents using utility-based criteria are driven by their choice of actions regardless of goals while those using motivation-based criteria decide according to their goals. They emphasize the importance of both forms of rationality in a multi-agent system. Multiple partner coalitions are handled by agents choosing partners depending on action-dependencies. Dependence situations are used to analyze motivation-driven choices and a domain-dependent concept called *dependence strength* that takes costs and benefits for actions as well as agent preferences into account for the analysis of utility-driven choices is introduced. In combining agent preferences with costs and benefits the utility-based criteria uses utility and motivation concepts.

Experiments Conducted. David et al. [2001] state that they used a social simulation to test their approach. In the paper, they present an example of rational decision making by agents in an airline transportation carrier system. They describe goals as preferred or available carriers, actions as origin/destination pairs of locations and plans as routes composed of several stops.

Results. David et al. [2001] claim their experiments demonstrated rational agent choices with regard to goals, proposals and partner selection utilizing motivation-based and utility-based criteria both in successful and unsuccessful coalition formation. They claim to have noticed power influence of varying degrees for the same dependence situation and observed different levels of complexity in the search space depending on the order of utility-based and motivation-based criteria.

Conclusions. David et al. [2001] claim that their approach shows how rationality driven by both motivation and utility can be used to analyze social dependency patterns that emerge in multi-agent systems.

Citations By Others. There are no specific references to this paper by other researchers in this survey.

4.12 Grossi and Turrini 2010

Citation: Grossi, D. and Turrini, P. 2010. Dependence theory via game theory. In *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems.* AAMAS '10, vol. 1. International Foundation for Autonomous Agents and Multiagent Systems, Richland, SC, 1147–1154.

Problem. Research so far in coalition formation have usually used the game theory approach and the dependence theory alternatively. However, combining these two approaches can provide dependence theory with the mathematical foundation that has been well established in game theory, and give the game theory approach the ability to analyze agent cooperation given their dependencies. The objective of Grossi and Turrini [2010] is to provide a formal model of both approaches combined. They contend that the aspect of dependence theory that explores use of dependencies to predict agent behavior lacks formal foundations.

Previous Work. The authors refer to previous work where dependence theory and game theory were combined for coalition formation by Bonzon et al. [2009] and Sauro et al. [2009] which they state extends a study that started with Boella et al. [2006].

Shortcomings of Previous Work. The authors state that the studies by Bonzon et al. [2009] and Sauro et al. [2009] relate different dependence relations within Boolean games to solution concepts from game theory. They state that these studies are limited to Boolean games and focus on the use of dependence theory to analyze the games. Grossi and Turrini [2010], however, use game theory to formalize certain aspects of dependence theory leading to coalition formation.

New Idea/Algorithm/Architecture. To combine both game theory and dependence-based approaches, Grossi and Turrini [2010] inherit game theoretic solution concepts of Nash equilibrium, referred to as best response equilibrium *(BR-equilibrium)* and dominant strategies which they call *DS-equilibrium.* Using game theory they redefine the basic notion of dependence theory, where agent i depends on another agent j for the achievement of a goal g. This is defined in terms of j selecting a strategy in the game that favors i for realizing g. If j's chosen strategy is the best it can do for i, then the dependency is in the best response sense. If the chosen strategy maximizes i's well-being, then the dependency is in the sense of a dominant strategy. This results in a definition of a dependence structure composed of agents with *BR* and *DS* strategies. This structure is further used to define dependence cycles [Sichman and Conte 2002] in a game theoretical sense, where agents form a chain of dependencies to support an agent indirectly depending on another. In a 3-person game with agents i, j and k, pairwise dependencies between i and j as well as between j and k, result in an indirect dependency between i and k. Grossi and Turrini [2010] use this notion to redefine reciprocal dependence.

Using their combined definitions of dependence theory and game theory, Grossi and Turrini [2010] provide their definition of an agreement as the result of agents coordinating via the exchange of BR or DS strategies for a chosen goal. They contend that these agreements give rise to the formation of coalitions and use them to define coalitional games based on cooperative game theory and *dependence games* which extend coalitional games to include their notion of agreements. Finally, to address the stability of agreements the authors explore the game theory notion of core within dependence games.

Experiments Conducted. Grossi and Turrini [2010] describe an application of their definition of the basic notion of dependence theory to the two-person Prisoner's dilemma game. Their definition of dependence cycles is demonstrated in a three-person version of the game. Both versions of the game are used in an example to demonstrate their definition of agreements as well as their determination of the core within coalitional and dependence games.

Results. Grossi and Turrini [2010] claim their examples demonstrate their use of dependence structures to predict agent behavior with regard to agreements towards coalition formation.

Conclusions. Grossi and Turrini [2010] claim to have demonstrated that dependence concepts such as dependence cycles can be defined in the game theoretic sense. They also claim to have shown that dependence theory can be used within game theoretic notions such as the core to predict agent behavior in a multi-agent system.

Citations By Others. There are no specific references to this paper by other researchers in this survey.

4.13 Hsieh et al. 2004

Citation: Hsieh, L., Liu, A., Yu, S.-E., and Hsu, H. C. 2004. A method in social reasoning mechanism for intelligent agents using fuzzy inference. In *Proceedings of the International Computer Symposium.* ICS '04. Taipei, Taiwan, 405–410.

Problem. When determining agent dependencies, current social reasoning methods are exact rather than approximate. For example, an agent depends on another if it lacks a needed resource that the other can provide. Hsieh et al. [2004] address the drawback that existing social reasoning methods do not support defining a degree of dependency. Another addressed issue is the fact that dependence by itself is qualitative and does not consider the costs involved in partnership formation. These issues limit how an agent organizes its relationships, selects partners and responds to partnership proposals from other agents.

Previous Work. The authors refer to previous work by Sichman et al. [1994] and Sichman [1998].

Shortcomings of Previous Work. The authors identify several shortfalls in the social reasoning mechanism presented by Sichman et al. [1994] and Sichman [1998]. First, they state that the model ignores goals deemed unachievable. Next, the model only supports partnerships between agents when the benefits are immediate, missing out on situations when a benefit may exist at a later time. The model is criticized for allowing an agent to assist another without a reward, which might contradict with an agent's ability to be autonomous. Finally, the authors state that in the model, dependence is considered in qualitative rather than quantitative terms.

New Idea/Algorithm/Architecture. Hsieh et al. [2004] integrate fuzzy inference into Sichman et al.'s [1994] social reasoning mechanism. Hsieh et al.'s [2004] model supports the evaluation of agent dependencies, an agent's selection of goals to pursue and plans to carry them out, its selection of needed partners and how it responds to help requests from others, all estimated using a fuzzy inference system.

To estimate an agent's dependency on another for a missing action or resource, Hsieh et al. [2004] introduce three variables: *importance*, *urgency*, and *accessibility.* They introduce a formula that uses these variables to estimate how badly the action or resource is needed or the degree of dependency an agent has for it. A resource that is rare would have a low accessibility value which in turn would increase the degree of dependency. If an agent has only one plan for achieving a goal then needed actions or resources become more urgent especially if the agent considers the goal important. Using the formula, an agent is able to calculate its level of dependence with respect to a specific agent.

The criteria for goal and plan selection for pursuit includes variables for the importance of the goal, the feasibility of the plan, as well as the urgency and cost of missing actions and resources. The fuzzy inference system uses these variables to generate a *priority* value. Basically, the agent selects the goal-plan pair with the highest priority value. Goal-plan pairs that are urgent, important, feasible and have a low cost are more likely to be chosen.

In partnership selection the agent identifies other agents possessing its missing actions and resources based on the goal-plan selected for execution, and sends a request for assistance. Ultimately, the agent wishes to choose the best partner to send a proposal to. To accomplish this, Hsieh et al. [2004] variables were introduced to consider the cost of missing items, prior history of assistance between agents, the level of dependency between agents, whether needed items are in use by the agent being proposed to and how willing the agent is to help depending on how selfish or generous it is. When fed into the fuzzy inference system, these criteria are used to generate a *possibility* value. A proposal would be made to the agent with the highest possibility value.

When responding to proposals for help from other agents, the agent rejects the proposal if it no longer has the needed action or resource, or it has no information about the other agent. Criteria similar to partnership selection is fed into the fuzzy inference system and the value returned is compared to a given threshold to determine acceptance or rejection by the agent.

Experiments Conducted. Hsieh et al. [2004] state that they built a simulation system that used their social reasoning model to control robots. The system was used to conduct three experiments in societies composed of five agents each. The first experiment compared a society made up of selfish agents, one composed of generous agents and a third made up of normal agents. The summation of the importance and urgency variables was used to determine better performance. The second experiment assumed that the agents trusted each other more by increasing the default value of the variable representing agents prior history of assistance. The final experiment evaluated a society with one generous agent and four normal agents compared to a society of five normal agents.

Results. Hsieh et al. [2004] state that the first experiment showed generous agents obtaining the highest performance, followed by normal agents with selfish agents performing the worst. The second experiment demonstrated increase in performance relative to the increase in trust. Finally, the last experiment demonstrated an 8% decrease in the performance of the generous agent operating among normal ones, while the performance of the normal agents increased slightly by 0.4%.

Conclusions. Hsieh et al. [2004] claim their model enhances the previous social reasoning models [Sichman et al. 1994; Sichman 1998], because integrating fuzzy inference rules allows agents to create a better balance between achieving a goal and its urgency or importance. They also state their model considers additional variables in the reasoning process thus improving the social relationships between agents.

Citations By Others. There are no specific references to this paper by other researchers in this survey.

4.14 Monteiro and Sichman 2006

Citation: Monteiro, J. d. L. d. R. and Sichman, J. S. a. 2006. PartNET++: Simulating multiple agent partnerships using dependence graphs. In *Multi-Agent-Based Simulation VI*, J. Sichman and L. Antunes, Eds. Lecture Notes in Computer Science, vol. 3891. Springer Berlin / Heidelberg, 14–23.

Problem. Multiple-partner partnerships may be formed among autonomous agents with different goals and different decision-making strategies. An existing problem is understanding how such agents rationally choose partners and how their behavior can be predicted. This is important because partner selection is more complex when multiple agents as opposed to a single agent can jointly assist an agent to achieve its goal, particularly when these agents employ different strategies when making decisions.

Previous Work. The authors refer to previous work by Conte and Pedone [1998]
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Shortcomings of Previous Work. The authors state that their work extends the study by Conte and Pedone [1998] from the formation of partnerships between pairs of agents to partnership formation between multiple agents.

New Idea/Algorithm/Architecture. Monteiro and Sichman [2006] present the *PartNET++* system that extends Conte and Pedone's [1998] *PART-NET* system from generating exchange partnerships between pairs of agents to multiple agents. To accomplish this they introduce the notion of *plans* into the system that makes it possible to achieve a goal via the execution of a sequence of actions as opposed to only one action. An agent may then form a partnership with multiple agents where different agents are responsible for performing the actions. To facilitate partnership formation among multiple agents in *PartNET++*, Monteiro and Sichman [2006] represent agent dependencies using social dependence graphs [Conte and Sichman 2002]. In dependence graphs, nodes represent agents, goals, plans or actions and edges can have a positive weight that represents the importance of a goal or a negative weight that represents the cost of an action. An agent has a goal that contains a plan made up of a sequence of actions. Monteiro and Sichman [2006] introduce *social stratification* (STR) and *social intolerance* (INT). STR specifies the maximum number of agents in the agency that can act as mediators in partnerships where agents may indirectly benefit each other. In such cases an agent may not be able to execute an action to benefit a second agent it needs, but can assist a third that in turn helps the second. INT refers to the allowed number of intolerant agents, that is agents that will only act as mediators when assured that all actions towards at least one of their plans will be executed in exchange.

Part of the algorithm used for *PartNET++* is based on Sichman's [1998] *DEPINT* system. Each agent randomly chooses partners towards the accomplishment of one of its goals depending on its strategy [Conte and Pedone 1998] and settings for STR and INT.

Experiments Conducted. Monteiro and Sichman [2006] state that various experiments were conducted to verify that the results obtained from the *PART-NET* system would be repeated for multiple partners. Agencies were generated with varying sizes and each was run 100 times to compute averages and standard deviations. Goal importance and action costs were randomly generated. However, in all experiments conducted INT was set to 1.

Results. Monteiro and Sichman [2006] claim that they were able to duplicate all the results from the *PART-NET* system in the new system except for one.

They could not replicate *PART-NET*'s determination that agents in heterogeneous environments obtained better benefits on average than agents in homogeneous ones.

Conclusions. Monteiro and Sichman [2006] claim that their simulation explains the formation of multiple-partner partnerships among agents and provides a test bed for other social theories.

Citations By Others. There are no specific references to this paper by other researchers in this survey.

4.15 Morgado and Gasper 2000

Citation: MORGADO, L. AND GASPAR, G. 2000. A social reasoning mechanism based on a new approach for coalition formation. In *Proceedings of the 2nd International Symposium "From Agent Theory to Agent Implementation"*. Vienna, Austria, No page numbers available.

Problem. Autonomous and heterogeneous agents may desire or need the assistance of other agents for the achievement of their individual goals. In order to take advantage of each others' abilities, agents need the capability to reason about each other. In the absence of such a mechanism, an agent would not know who to approach for help. Existing studies do not account for agents reasoning about others beyond those they are directly related to. There are aspects of existing models that can be improved such as how agents choose partners, how agents reason about each other and how to reduce the amount of communication that has to occur between agents. These improvements are expected to facilitate the formation of groups towards solving complex problems.

Previous Work. The authors refer to previous work by Sichman [1995], Alonso [1998], David [1998] and David et al. [1999].

Shortcomings of Previous Work. The authors state that Sichman's [1995] model is not easily applicable to real problems that are often complex. The model is criticized for its requirement that the details of all plans be available and for not supporting agents reasoning about others beyond those they directly depend on thus limiting the number of possible coalitions. Another noted shortfall is the fact that the model provides no recourse for situations where the assignment of an activity fails after related activities have been successfully assigned. The approaches used by Sichman [1995] and Alonso [1998] are criticized for being limited to coalitions formed between pairs of agents. David's [1998] model supports agents belonging to multiple groups. However, the authors state that the model's requirement that agents know the capabilities of all agents in all groups they belong to, increases required communication between agents. Finally, the authors identify three aspects that can be improved with all cited studies namely the process to select partners, dealing with agents having incomplete information about each other and reducing agent communication.

New Idea/Algorithm/Architecture. Morgado and Gaspar [2000] present a dependence-based social reasoning model for coalition formation where a goal may be achieved via a chain of nested coalitions. The authors note that when reasoning about others in a society an agent can use either a *global perspective* or a *local perspective*. An agent reasoning globally is aware of the actions of all agents that can participate in a coalition and can therefore reason about all possible dependencies it needs in the society. An agent that adopts a local perspective can only reason about agents that it directly depends upon and may not be aware of indirect relationships that may result in coalition formation. In Morgado and Gasper's [2000] model agents use a local perspective in reasoning but infer indirect relationships resulting in the formation of multiple connected and nested coalitions.

To support agents maintaining information about each other Morgado and Gaspar [2000] redefine Sichman et al.'s [1994] *external description* structure to include goals, plans and capacities and clarify that their model has a different notion of goals and plans. Capacities encompass actions an agent can perform and resources within its control, but not in relation to the agent's goals as in Sichman et al. [1994]. According to Morgado and Gaspar [2000], this distinction is to account for the fact that in their model agents do not necessarily know all all the necessary actions for a goal, since required actions may be achieved via indirect relationships. If an agent has a capacity for an activity then it can either achieve it on its own, or via the formulation of a plan that involves assigning it to other agents. Another deviation from Sichman et al. [1994] involves the explicit adoption of goals. When an agent agrees to execute an activity on another agent's behalf it adds the respective goal to its own goals resulting perhaps in a revision of its own plans. Finally, plans represent agent capacities for achieving goals involving activities that may depend on other activities. In using the represented knowledge to reason about others Morgado and Gaspar [2000] inherit Sichman et al.'s [1994] concept of *dependence situations.* Once goals, plans and dependence situations are identified possible coalitions can be formed and later on refined to valid coalitions, that ensure the assignment of all necessary activities and do not include activities assigned to more than one agent.

Experiments Conducted. Morgado and Gaspar [2000] state that their model was implemented in a system named *CADS.* The system added time and order constraints to the model by restricting the time required for the completion of a plan and enforcing an order for activities. The authors claim that the system was used to generate a simulation of groups of agents forming coalitions towards the development of various projects.

Results. Morgado and Gaspar [2000] claim that their experiments resulted in the impulsive formation of nested coalitions without agents in the external coalitions needing to reason about all agents in the nested one.

Conclusions. Morgado and Gaspar [2000] state that their social reasoning model, that results in the formation of coalitions with agents indirectly dependent on each other, reduces computational complexity without sacrificing the number of coalitions formed. They claim that communication between agents is reduced because agents only need to reason about those they are directly related to, but can still benefit from activities provided by agents they are indirectly related to. They also state that their model represents coalitions in such a way that both the analysis and negotiation stages can be combined.

Citations By Others. [An et al. 2007]

4.16 Panzarasa et al. 2002

Citation: Panzarasa, P., Jennings, N. R., and Norman, T. J. 2002. Formalizing collaborative decision-making and practical reasoning in multi-agent systems. *Journal of Logic and Computation 12,* 1 (Feb.), 55–117.

Problem. In order to facilitate understanding how autonomous and heterogeneous agents cooperate towards achieving their individual goals in a social environment the entire decision-making process of the agents needs to be formalized from their mental aspects to their interactions with each other.

Previous Work. The authors refer to previous work by Wooldridge and Jennings [1999].

Shortcomings of Previous Work. The authors state that their work provides a way for agents to influence the behavior and mental aspects of other agents with regard to collaboration which is a limitation of the work by Wooldridge and Jennings [1999].

New Idea/Algorithm/Architecture. Using multi-modal logic, Panzarasa et al.'s [2002] model combines the mental aspects of autonomous agents represented by their beliefs, desires, goals and intentions with social aspects represented by their interactions with each other to formalize how agents decide to cooperate. Agent interactions are defined with respect to their relationships with each other viewed in terms of roles or how roles relate to each other. Prior to the start of the collaborative process agents need to identify potential partners for the accomplishment of a goal. According to the authors agents socially dependent on each other [Sichman 1995], have the capacity to recognize a potential for collaboration. The authors formalize the recognition stage by identifying that social dependence can be brought about by an agent's inability to achieve an objective on its own, an agent desiring to collaborate even when it does not have to, an agent compelled to collaborate due to its role or an agent simply forced into collaboration by other agents. The authors assume that once an agent identifies potential partners it will need to influence them towards the formation of a new group using any form of interaction. To handle situations where agents with the same objectives might be in competition with each other and therefore not desire to collaborate, the authors formalize the notions of *joint intentions* and *joint commitments.* The term *social practical reasoning* is introduced to formalize agents reasoning on their own about how the group goes about achieving the committed objective once the group is formed. Finally the negotiation process whereby agents in a group agree on the appropriate way to achieve the goal is conducted by agents making their intentions known and influencing each other towards adopting their reasoned course of action.

Experiments Conducted. Panzarasa et al. [2002] do not describe any conducted experiments.

Results. Panzarasa et al. [2002] do not present any results.

Conclusions. Panzarasa et al. [2002] state that their formal model covers all aspects of the collaborative process from agents identifying potential partners for collaboration to jointly deciding to form a group. They state that contrary to existing models their work accounts for agents with conflicting mindsets and agents influencing the mindsets of others.

Citations By Others. There are no specific references to this paper by other researchers in this survey.

4.17 Sauro 2006

Citation: Sauro, L. 2006. Qualitative criteria of admissibility for enforced agreements. *Computational & Mathematical Organization Theory 12*, 147–168.

Problem. In coalition formation, self-interested agents agree to help each other achieve their respective goals either in the form of cooperation in the case of a shared goal, or exchange when the goals differ. When dealing with exchanges, prior models have been limited to exchanges between two agents ignoring other possibilities where agents might help each other. Sauro [2006] addresses agents reasoning about each other in situations where the exchange involves more than two agents. This reasoning considers both the agents recognition of potential partners as well as the associated costs and benefits. In Sauro [2006], conditions under which these complex exchanges can occur are formalized. In the model, there is no general preference for cooperation over exchange as agents can decide on either form of agreement as they deem suitable. A coalition is formed simply when all involved agents commit to it and can consist of both forms of agreements.

Previous Work . The author identifies previous work by Sichman et al. [1994], Wooldridge and Jennings [1994], Alonso [1998], Sichman and Demazeau [2001] and Castelfranchi [2003].

Shortcomings of Previous Work. The author criticizes Wooldridge and Jennings' [1994] for only supporting coalition formation among agents with common goals. He states that the models in Sichman et al. [1994] and Castelfranchi [2003] only support exchanges between pairs of agents. The author states that in his model cooperation and exchange are equally likely as a choice for the agents. This differs from Sichman and Demazeau's [2001] approach where agents prefer cooperation over exchange which is criticized for providing an environment where agents may be forced into a form of agreement by other agents.

New Idea/Algorithm/Architecture. In Sauro's [2006] model agents help each other either via cooperation or social exchange [Castelfranchi 2003], without any demands from other agents. Once a coalition is formed, the participating agents are deemed committed and required to abide by the conditions of the agreement. Sauro [2006] defines a multi-agent system in terms of a *power structure* which does not focus on individual agent characteristics, but rather describes the environment in terms of which agents can work together for the achievement of one or more goals without internal conflicts. *Power frames* are introduced to describe possible coalitions that can be formed. To address the fact that all power frames do not lead to valid coalitions, Sauro [2006] introduces formalizations of two properties that must hold for an agreement to occur. The *do-ut-des* property specifies that an agent will only give something if it is assured the benefit of getting something else in exchange. To support indirect exchanges, which are exchanges involving more than two agents, the do-ut-des property uses Conte and Sichman's [2002] notion of dependence graphs. An example of an indirect exchange involves three agents collaborating where the first depends on the second, the second depends on the third and the third depends on the first. The *composition* or *indecomposable do-ut-des* property extends the do-ut-des property by considering a balance between coalition benefits and the associated coalition costs. This results in the formation of small coalitions wherever possible.

Experiments Conducted. Sauro [2006] does not describe any conducted experiments.

Results. Sauro [2006] does not present any results.

Conclusions. Sauro [2006] states that his model extends Castelfranchi's [2003] social dependence theory by supporting coalitions formed from chains of exchanges. He claims that his model supports cooperation and social exchange with equal plausibility. His defined conditions under which valid coalitions can be formed differ from existing solution criteria offered by game theory approaches in two ways. First, since his agents are goal-directed possible coalitions are compared by examining their achievable goals and associated risks without deep analysis of the coalitions themselves. Second, his approach allows the evaluation of whether a coalition can be formed without comparing it to others.

Citations By Others. [Boella et al. 2009]

4.18 Sichman et al. 1994

Citation: Sichman, J. S., Conte, R., Demazeau, Y., and Castelfranchi, C. 1994. A social reasoning mechanism based on dependence networks. In *Proceedings of the 11th European Conference on Artificial Intelligence*. ECAI '94. John Wiley and Sons, 188–192.

This paper is a reduced version of Sichman's [1995] doctoral thesis.

Problem. Autonomous and heterogeneous agents in dynamic environments may desire or need the assistance of other agents for the achievement of their individual goals. In order to take advantage of each others abilities and to adapt to a changing environment, agents need the capability to reason about each other. In the absence of such a mechanism, an agent would not know who to approach for help or how to adjust its existing relationships when agents enter or leave an environment.

Previous Work . The authors refer to previous work by Yu and Mylopoulos [1993].

Shortcomings of Previous Work. The authors criticize the study by Yu and Mylopoulos [1993] for being domain dependent.

New Idea/Algorithm/Architecture. Sichman et al. [1994] utilize Castelfranchi's [1990] notion of social power within multi-agent systems and Castelfranchi et al.'s [1992] social dependence concepts, to define a social reasoning mechanism involving *dependence relations* and *dependence situations*. The model is based on dynamic coalition formation, where agents depend on each other for the accomplishment of goals in an environment where they may enter and leave at will. An agent maintains information about other agents in the agency in data structures called *external descriptions*, which it uses to figure out agents that it depends on and agents that depend on it, and how to cooperate or exchange help with such agents. An *external description* structure contains an agent's goals, the actions it can perform, resources it controls and the plans it uses in the achievement of its goals. These plans may involve the use of resources and actions that are controlled and carried out respectively by other agents, in which case, the agent depends on others to execute the plan.

Sichman et al. [1994] describe the notion of *dependence situations* that relates two agents and a goal. They identify three possible types of dependence situations, namely *mutual dependence*, *reciprocal dependence* and *unilateral dependence*. Mutual dependence refers to agents depending on each other for the same goal (cooperation), while with reciprocal dependence, they depend on each other for different goals (exchange). Both dependence situations can be either *locally believed* or *mutually believed* distinguishing between an agent that uses only its own plans to reason about others, and one that uses both its own plans and that of others for the reasoning process. The third case, *unilateral dependence*, refers to a one-way dependence between agents, where the first agent depends on the second to achieve a goal without the second agent depending on the first for the achievement of any of its goals. Ultimately, these dependence situations assist agents in selecting partners that are more likely to accept a proposal for coalition formation.

Experiments Conducted. Sichman et al. [1994] state that their model was used to implement a simulator called *DEPNET*.

Results. Sichman et al. [1994] claim that *DEPNET* figures out dependence relationships and dependence situations between agents, building a network of dependencies for an agent.

Conclusions. Sichman et al. [1994] state that their model reduces communication between agents because agents do not need to contact each other every time an action or resource is needed. Additionally agents are able to reason about who they depend on and also who depends on them.

Citations By Others. [Conte and Sichman 1995; Sichman and Demazeau 1995a; D'Inverno and Luck 1996; Sichman 1996; Conte et al. 1998; Conte and Pedone 1998; Brainov and Sandholm 1999; David et al. 1999; 2001; Conte and Sichman 2002; Sichman and Conte 2002; Boella et al. 2004; Hsieh et al. 2004; An et al. 2005; An et al. 2005a; An et al. 2005; Carabelea et al. 2005; Sauro 2005; 2006; An et al. 2007]

4.19 Sichman 1995

Citation: Sichman, J. S. 1995. Du raisonnement social chez les agents: Une approche fondée sur la théorie de la dépendance. Ph.D. thesis, INP Grenoble, Laboratoire LEIBNIZ.

Problem. Autonomous and heterogeneous agents in dynamic environments may desire or need the assistance of other agents for the achievement of their individual goals. In order to take advantage of each others abilities and adapt to a changing environment agents need the capability to reason about each other. This is the problem addressed in Sichman's [1995] doctoral thesis. Reduced versions of the thesis are annotated in Sections 4.18 and 4.20. The thesis was written in French, however there is a translated version of the abstract available in English.

Previous Work. Sections 4.18 and 4.20 note previous work cited by Sichman [1995].

Shortcomings of Previous Work. Sections 4.18 and 4.20 describe shortcomings of the previous work identified by Sichman [1995].

New Idea/Algorithm/Architecture. Sichman [1995] defines a social reasoning mechanism that facilitates an agent reasoning about another agent by computing its dependencies on the agent, or specifically how the agent helps or prevents it from achieving its goals. He refers to these dependencies as *dependence relations* and *dependence situations*. The approach is based on dynamic coalition formation in an environment where agents may enter and leave at will. In his model, information maintained by agents about others is used as a criteria for choosing partners with which to cooperate or exchange help. An agent is also able to evaluate viable plans and achievable goals at the time of execution. The model also accounts for incompatibilities between agent's beliefs about each others abilities.

Experiments Conducted. Sichman [1995] states that his method was used to implement a simulator called *DEPNET* and a multi-agent system called *DEPINT* demonstrating two different ways that it can be used.

Results. Sichman [1995] claims that *DEPNET* figures out dependence relationships and dependence situations between agents, building a network of dependencies for an agent, and that *DEPINT* utilizes agent dependencies for coalition formation.

Conclusions. Sichman [1995] states that his approach makes it feasible to figure out the social power of agents in an agency and analyze and predict different patterns of interactions between them. He also states that it can be used to design dynamic environments where agents enter and leave the society at any time.

Citations By Others. [Sichman and Demazeau 1995b; 1996; Castelfranchi 1997; Sichman 1998; Ito and Sichman 2000; Morgado and Gaspar 2000; Sichman and Demazeau 2001; Panzarasa et al. 2002; Castelfranchi 2003; Monteiro and Sichman 2006; De Marchi et al. 2009; De Marchi and Moraes 2009].

4.20 Sichman 1998

Citation: Sichman, J. S. 1998. DEPINT: Dependence-based coalition formation in an open multi-agent scenario. *Journal of Artificial Societies and Social Simulation 1,* 2, [Online] http://jasss.soc.surrey.ac.uk/1/2/3.html.

This paper presents the design and implementation of a system that depicts the social reasoning mechanism introduced in Sichman [1995].

Problem. Autonomous and heterogeneous agents in dynamic environments may be incapable or simply not wish to achieve their individual goals solely. To this effect agents may form coalitions towards providing assistance to each other. In the formation of these coalitions several problems arise. In order to adapt to the implications of agents entering or leaving the agency at will, agents should be able to determine at any given time their realizable goals so that they do not pursue goals that cannot be accomplished. Agents need the ability to detect inconsistencies in what they believe each other capable of because it cannot be assumed that the knowledge agents possess about each other is always complete and correct. Agents need the capacity to determine the other agents that are likely to join them in pursuing their goals since agents are not expected to be charitable.

Previous Work. The authors refers to previous work in group formation for problem solving by Smith [1980] and Wooldridge and Jennings [1994]. He also refers to studies conducted by Yu and Mylopoulos [1993] and Carle et al. [1994] regarding the representation of agent dependencies.

Shortcomings of Previous Work. The author claims there is less global communication required among agents in his model compared to Smith's [1980] contract net model and criticizes the studies conducted by Smith [1980] and Wooldridge and Jennings [1994] for their confinement to a formal level. He states that unlike the studies by Yu and Mylopoulos [1993] and Carle et al. [1994] that utilize objective views, his model represents agent dependencies subjectively by taking the agents' perspectives into account.

New Idea/Algorithm/Architecture. In this paper, Sichman [1998] presents his design and implementation of the *DEPINT* system that demonstrates coalition formation of agents in a dynamic environment utilizing his social reasoning mechanism [Sichman 1995]. He adopts concepts from Sichman et al. [1994], including the *external description* data structure and *dependence situations.* He introduces *goal situations* used to relate an agent to a specific goal with regard to the agent's plans. Agents utilize both situations to choose partners for coalition formation by inferring the three possible types of dependence situations, namely *mutual dependence*, *reciprocal dependence* and *unilateral dependence*. The situations are also used to identify incompatibility between agents' external descriptions and allow for revision of agent's beliefs about each others abilities at run time. In the model, the author differentiates between what an agent knows and what it believes, by stating that an agent knows its own plans and actions but believes that of others.

Coalitions in the *DEPINT* system can only be formed between two partners and agent behaviors are either *passive* or *active.* When active, the agent uses its reasoning to select a goal, plan and partner if it determines it cannot achieve the goal on its own, and proposes a coalition to another agent. When passive, the user of the system simulates the process and the agent can only accept or reject received proposals. In both cases, belief revision occurs whenever inconsistency is detected.

Experiments Conducted. Sichman [1998] states that he built the *DEPINT* system in a multi-agent system software development environment that supports active agents that communicate with each other.

Results. Sichman [1998] claims that the *DEPINT* system illustrated the dynamic formation of coalitions based on dependencies between agents, the ability of agents to adapt to others entering and leaving the society at will and revise inconsistent information in beliefs they have about each other. He presents examples of successful and unsuccessful coalition formation, as well as belief revision.

Conclusions. Sichman [1998] states that the *DEPINT* system is the first system to use social dependence for coalition formation in a dynamic multi-agent system and also the first to represent how agents depend on each other subjectively. He states that his model supports agent adaptation in dynamic environments, agent ability to determine viable plans and achievable goals and detect inconsistencies between agent representations of each other. He claims that compared to other models, there is little global communication in his system as an agent need only broadcast a message to all the others in the agency once upon entering the agency. All further communication is between an agent and a specific agent it identifies to send a coalition proposal to.

Citations By Others. [Ito and Sichman 2000; David et al. 2001; Sichman and Demazeau 2001; Conte and Sichman 2002; Hsieh et al. 2004; An et al. 2005b; An et al. 2005; An et al. 2007; Boella et al. 2008; Grossi and Turrini 2010].

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