Methods and models for the design and study of dynamic agent organizations
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1 INTRODUCTION

1.1 BACKGROUND

The aim of this thesis is to create models and methods for the design and evaluation of dynamic agent organizations. Multi-Agent System (MAS) organizations can exist in many shapes and sizes. As organizations become larger, different forms of coordination are required to handle the scale of the organization (Durfee, 2001). For example, the TAEMS coordination framework (Lesser, 2002; Lesser, Decker, Wagner, Carver, Garvey, Neiman, and Xuan, 2004) is suited to coordinate relatively complex tasks in small organizations while larger organizations require other approaches, e.g. Scerri, Farinelli, Okamoto, and Tambe (2005), but these are not suited for complex tasks. We also identify a number of structural aspects of organizations, adopted from Dignum (2004), the communication structure (the language used to communicate and its semantics), the normative structure (the expectations and boundaries of agent behavior in the organization), the social structure (agent roles and relations between roles) and the interaction structure (how should agents interact). For example for tree structured organizations some approaches (e.g. So and Durfee (1996)) are suited while in the case of a team of agents (a group of agents sharing a common goal), approaches like the communicative multi-agent team decision problem (COM-MTDP) model (Pynadath and Tambe, 2002) can be used to find optimal decision making policies.

An approach to integrate different types of organization and coordination into a single framework is the 5C (5 Capabilities) model (van Aart, 2004) which identifies five different dimensions of what an agent should be capable of. The 5C model contains the capabilities for agents to communicate with each other. Furthermore the 5C model enables agents to reason about their goals, to plan how these goals can be achieved and to execute tasks. Finally, the 5C model enables agents to reason about their environment and other agents. The 5C model has been applied to design different types of organizations (van Aart, Wielinga, and Schreiber, 2004) however these are all static organization forms (Mintzberg, 1993) which might not be suited to operate in dynamic environments.

Some task-environments may require agents to be able to adapt their organization in response to changes in the task-environment (Carley, 1997). Following Dignum, Dignum, and Sonenberg (2004) we can distinguish between two types of organizational adaptation. The first is the adaptation of behavior and the second the adaptation of structure.
Adaptation of behavior can be achieved for example by changing the coordination mechanism that is used in an organization. In Excelente-Toledo and Jennings (2004) agents can switch between coordination mechanisms during task execution, taking into account a setup-time of the new organization and its expected success and reward. In Martin and Barber (2006), agents change coordination mechanisms by selecting the appropriate level of autonomy needed to perform a certain task. In a similar fashion, van der Vecht, Dignum, Meyer, and Neef (2008) enables agents to switch between explicit coordination and emergent coordination. Other work in this area by Rosenfeld, Kaminka, Kraus, and Shehory (2008) is more focused on determining the costs of coordination mechanisms to determine which coordination mechanism to choose.

In research on adapting structural elements in an organization, hierarchical organization structures are often used. In So and Durfee (1996) the branching factor in the hierarchy is changed to match the granularity of the task that is currently being executed by the organization. Carley (1997) introduces a number of modifications for hierarchical organizations such as adding and removing agents from the organization, changing the hierarchical relations between agents, and reallocation of resources and information from one agent to another agent. Similar forms of adaptation have been used by Horling, Benyo, and Lesser (2001) and (Kamboj and Decker, 2007b) who change relations between agents in the organization and add/remove agents respectively.

These approaches all provide specific types of organization and focus on the algorithms that make these types of reorganization possible. What is lacking in this research is a more generic view, similar to van Aart (2004), of the capabilities that are needed by the agents to reorganize the organization. The ability to reorganize demands specific capabilities of agents such as the ability to reason about the goals of the organization, the performance of the organization and the task-environment in which they operate. Furthermore, when reorganization requires agents to be able to perform multiple types of tasks, enact multiple roles or coordinate work using multiple coordination mechanisms, an agent architecture is needed that provides this flexibility.

Whether an organization is well designed depends on the task-environment of the organization, i.e. the task(s) the organization should perform and the environment in which the organization is embedded. The organization design model (So and Durfee, 1998) shows, at an abstract level, the relation between the organizational design of a MAS, its task-environment and the performance of the MAS organization. Sims, Corkill, and Lesser (2008) describes an automated approach to organization design and uses a model consisting of a set of domain specific input parameters and performance indicators. In Dignum (2013), Kripke semantics are used to describe environments and changes in the environment. What is lacking in both approaches is a vocabulary to describe the task-environment with sufficient detail that it can be used to construct a performance model based on explicit qualitative relations.
1.2 APPROACH

1.2.1 Research Questions

The central question of this thesis is how to develop methods and models for the design and evaluation of (dynamic) MAS organizations. This leads to the following research questions that will be addressed in this thesis:

1. What are the methods and models to design agents that operate in static organizations?
   These models should include the knowledge needed by agents to reason about the structure of the organization and their role in the organization. Agents should also be able to reason about tasks that are performed by the organization and how tasks are divided between agents. The methods should provide a MAS designer of a static organization with a number of design choices on how to design the organizational structure.

2. What are the methods and models to design agents that operate in dynamic organizations?
   These models should include the knowledge needed for agents to reason about organizational change, what different types of organizational change exist and how these changes are triggered. The methods should provide a MAS designer with a number of design choices on how to design an adaptive organization.

3. What are the methods and models to evaluate the performance of MAS organizations?
   These models should provide a MAS designer with insight in the factors that determine organizational performance. The methods should guide the design of MAS simulation environments and MAS experiments to study the performance of MAS organizations.

1.2.2 Thesis Structure

One of the aims of our research questions is to identify the knowledge that is needed by agents to operate in dynamic organizations. In this thesis we describe these knowledge level models (Newell, 1982) using elements of the CommonKADS methodology (Schreiber, Akkermans, Anjewierden, de Hoog, Shadbolt, van de Velde, and Wielinga, 2000). In these knowledge models we distinguish between declarative and procedural knowledge.

This thesis is structured in three parts, where each part is related to one of the research questions. In Chapters 2 and 3 we provide the basic model ingredients for designing MAS organizations and we use these to design two static organizations for a smart grid scenario, a centralized and a decentralized organization. We then extend the design of the decentralized organization
and implement this organization. In a case study we use this organization to coordinate power consumption of households on the low-voltage power grid. This is a static and stable environment for agents to communicate and cooperate and it provides a relatively simple task for the agents to coordinate. This allows us to design a static organization where we can identify the different organizational concepts and the types of decisions that agents make to coordinate the distribution of energy.

Chapters 4, 5 and 6 form the second and largest part of this thesis. In this part we focus on models and methods for designing dynamic MAS organizations. In Chapter 4 we present the AgentCoRe framework for agent coordination and reorganization. This framework contains the model ingredients to enable agents to decompose tasks, assign tasks, change the organization structure and decide on which coordination mechanism to use.

In Chapters 4 and 5 we design organizations that are able to perform search and rescue in the RoboCupRescue simulation environment (Kitano, Tadokoro, Noda, Matsubara, Takahashi, Shinjou, and Shimada, 1999). This search and rescue task requires agents to decompose the search and rescue task into smaller subtasks and divide these subtasks among the different agents. When we design a MAS organization for this environment, we need agents that have the procedural knowledge for making decisions about task decomposition and task assignment. Furthermore, RoboCupRescue allows us to create settings that require agents to change the structure of their organization. This allows us to identify the decision making process that agents need for this type of organizational change.

In Chapter 6 we focus on the selection of coordination mechanisms which is the second decision module related to reorganization in the AgentCoRe framework. We describe the different types of decisions that are made and evaluate our approach in an abstract task simulation environment. Compared to previous chapters this simulation environment that is less domain specific. The decision making process for the dynamic selection of coordination mechanisms is empirically validated in the abstract task environment and also validated by using it as a framework to compare other approaches known in the literature. Furthermore we compare our decision making framework with three existing approaches to the selection of coordination mechanisms and show that our framework is sufficiently generic to cover each of these approaches.

Chapter 7 forms the third and final part of this thesis. In this chapter we present a methodology for designing simulation environments to evaluate the performance of MAS organizations. We apply the methodology to the design of a search and rescue simulation environment. In a series of experiments we show how the performance of a MAS organization is evaluated.

The basis for the methodology used in this chapter is a model that provides us with a vocabulary to describe task-environment and organization factors that influence MAS performance. This model is based on the organization de-
sign model by So and Durfee (1996). We validate our model and methodology by designing a simulation environment for the search and rescue domain.

Using this simulation environment we can now design experiments to identify relations between factors in the MAS organization and the task-environment and how they influence the performance of the organization. For this purpose we will design a MAS organization for the search and rescue simulation environment. In a number of experiments we investigate the effect of varying a number of parameters in the task-environment and/or the MAS organization on the performance of that organization. We use the output of these experiments to create a simple model that describes the relation between the MAS organization, task-environment and organization performance. In a number of follow up experiments, this model is gradually expanded to cover more aspects of the MAS organization and its task-environment.

We conclude this thesis in Chapter 8 by revisiting the three research questions and by discussing the applicability of the methods and models described in this thesis. Finally we present directions for future work.

1.3 MAIN CONTRIBUTIONS

The contributions of this thesis can be divided into empirical results, models and methods.

1.3.1 Empirical results

In our study on **MAS organizations for smart grids** we have demonstrated the effectiveness of a decentralized approach to coordinate power production and consumption in improving voltage quality on the low voltage distribution grid. We avoid peak loads on the transformer and at the same time we reduce voltage drops at the end of the feeders. This study confirms the results obtained by theoretically optimal solutions while using a more practical approach which does not depend on accurate long term (i.e. 12 to 24 hours) forecasting. In our study, the forecasting window is reduced to 5 minutes. Related work in the field shows that this need for forecasting can be further reduced using an event-based approach to market based coordination.

In our study on **a dynamic MAS organization in the RoboCupRescue simulation environment** we compare two static organizations with a dynamic organization. Our results show that a hierarchical MAS organization is able to deal with unexpected differences in workload and limited communication capacity by adapting its hierarchical structure. Existing work on balancing workload between agents has always considered computational agents (Franklin and Graesser, 1996) that can be spawned or cloned in parts of the organization where the workload is high. Our work shows that hierarchical structures can
also be successfully modified for MAS organizations consisting of robotic agents (Franklin and Graesser, 1996) that cannot be spanned or cloned.

In our study on the dynamic selection of coordination mechanisms, we show that by switching between centralized and decentralized coordination, a MAS organization is able to respond to failures in the communication infrastructure. These two results are again in line with existing work on adapting the behavior of MAS organizations by the dynamic selection of coordination mechanisms. Our results show that this type of organizational adaption can be successfully used to deal with changes in the communication infrastructure.

1.3.2 Models

The AgentCoRe framework is a knowledge level framework that describes the knowledge that is needed for agents to operate in dynamic MAS organizations. The framework describes the knowledge for four main decisions that agents need to be able to make: the decomposition of tasks into subtasks, the assignment of tasks to agents, the adaptation of the organization structure and the selection of coordination mechanisms. For each of these decisions, the AgentCoRe framework provides a number of declarative and procedural knowledge elements as well as inference structures that show how these knowledge elements are used to make that decision.

The Extended Organization Design model is a model that describes the task-environment of agents. It also describes certain organizational factors including the capabilities of individual agents. The EOD model also shows how task-environment factors and organizational factors influence performance of agents.

1.3.3 Methods

For the design of MAS organizations we identify three organizational design patterns. The first design pattern is to make a clear separation between positions and roles in an organization. Positions are held by agents performing certain tasks. By introducing roles, the agent can be decoupled from a set of tasks. Using this design pattern, a position in the organization is described by one or more roles that can be enacted by agents. The second design pattern is to make an explicit distinction between operational and management activities in an organization. This design pattern allows operational knowledge to be more easily re-used in different organizations. This pattern also provides insight to the MAS designer as to whether complexity is in the operational activities of an organization or in the management of those operational activities. The third organizational design pattern is to provide agents with a limited organizational awareness.
For the design of MAS simulation environments we provide a three step approach. The aim of this method is to construct a simulation environment that provides the MAS experimenter with insight in and control on the simulation environment. Throughout this method, the extended organization design model is used to provide the necessary vocabulary to describe possible task-environment and organization factors and MAS performance. The first step of this method is to select the task-environment and organizational factors that the MAS experimenter wants to manipulate. The second step is to operationalize the selected factors to concepts in a specific domain (e.g. search and rescue). The third step is to implement the operationalized factors in a simulator.

For the study on the performance of MAS organizations we provide an iterative approach to the design of experiments. The extended organization design model is used to guide the choice for which parameters to vary. Application of this model leads to a conceptual performance model, showing how different task-environment factors influence certain aspects of MAS performance.