Methods and models for the design and study of dynamic agent organizations
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The aim of this thesis is to develop models and methods for the design and evaluation of dynamic MAS organizations. Our main instruments have been the design and implementation of prototypes and using these prototypes for experimentation. The goal in the development of models and methods for (dynamic) MAS organizations is to identify and describe the knowledge needed by agents to operate in a dynamic organization. Specifically we focus on the separation of domain knowledge and generic knowledge. This generic knowledge will allow types of decision making about organizations to be re-used for different application domains where adaptive organizations can be an advantage. Ultimately, the goal of enabling agents to adapt their organization, and understanding the impact of these changes on performance, is to achieve a certain level of robustness to unforeseen changes in the task-environment of the agents. In this thesis we have also identified a number of organizational design patterns that can be used to guide the design of static and dynamic organizations.

8.1 revisiting the research questions

8.1.1 What are the methods and models to design agents that operate in static organizations?

In Chapters 2 and 3 we explore the design of MAS organizations for smart grids. We design static organizations using different organization structures and different control mechanisms. In Chapter 2 we introduce the basic ingredients to model these organization structures. Based on authority relations we design a hierarchical organization using centralized coordination. Based on equal working relations we design an organization using a market based coordination mechanism.

In the design of these two organizations we distinguish between operational and management tasks to decouple two fundamentally different activities in an organization. This organizational design pattern allows operational knowledge of agents to be re-used in multiple organizations. This clear separation between operational and management activities also helps to make certain design decisions more explicit. An example of a design tradeoff that becomes more explicit is the following. A complex operational task that is split into fine grained simple operational tasks might require more complex management tasks to handle this complexity. When these operational tasks become less fine
grained the complexity shifts from the management tasks to the operational tasks.

In Chapter 4 we introduce the use of organizational roles in the design of MAS organizations. This allows us to decouple the organization design from individual agents. Instead we describe the organization in terms of certain behavior (i.e. the type of tasks that need to be executed) that is needed in a certain position in the organization. Similar to the tasks, we also distinguish between operational roles and management roles. Operational roles involve activities related to the operational aspects of the organization, usually performing tasks or actions that are aimed at changing the environment of the agent (e.g. searching for victims) while management roles are roles that focus on organization activities such as coordinating work and re-organization. The role based approach creates flexibility in the organization to more easily transfer tasks between agents based on their roles and to reallocate agents from one role to the other while keeping the organization structure intact.

Another design feature that the organizations in Chapters 2, 3 and 4 have in common is that the agents have a limited organizational awareness, i.e. they only need to know about and interact with a limited set of agents in order to perform their tasks. The application of this organizational design pattern results in a loosely coupled organization. For example, in the tree shaped structure of the market based coordination mechanism, agents only need to know the agents from whom they receive bids, and the agent to whom they send their (aggregated) bids. This loose coupling provides a degree of flexibility that can be used to also design more dynamic MAS organizations.

In Chapter 4 we also introduce two management decisions that agents need to be able to make in an organizational context. These two decisions are part of the AgentCoRe framework. The first decision is the decomposition of tasks into subtasks. This allows organizations to split large and complex tasks into smaller tasks until they are small enough for individual agents to be executed. The output of this decision is a so-called task structure which shows how tasks are decomposed into subtasks and what the dependencies are between tasks. The second decision is the assignment of tasks to agents. This allows organizations to actually couple the most suitable agents to specific tasks. The assignment can be based on the capabilities of agents or other constraints such as the workload of agents. The output of this decision is an assignment structure which describes which tasks are assigned to which agents. Both management decisions are described using inference structures to allow for re-use of these templates for solving problems in multiple domains.

8.1.2 What are the methods and models to design agents that operate in dynamic organizations?

By distinguishing between operational and management activities, by using roles to decouple task assignments from agents, and by limiting the scope of
awareness and interaction of agents, we embed flexibility in organizations. This enables us to design dynamic organizations that use this flexibility to adapt the organization when needed.

Before we actually design dynamic organizations we first identify two main decisions that agents need to be able to make in dynamic organization in Chapter 4. These are the adaptation of the structure of the organization and the dynamic selection of coordination mechanisms. Again, these decisions are described in terms of inference structures.

The first decision has been used in Chapter 5 to enable agents to change the structure of a hierarchical organization by reallocating agents to different places in the hierarchical structure. The key design principle is that decision making authority for a task is transferred to the agent with the best knowledge for that task. Instead of sending large amounts of information between agents we transfer decision making authority to the agents that have the best knowledge for making these decisions. Another design principle is that regardless of how the organization structure is adapted, the adaptation should adhere to existing organizational constraints. An example of such a constraint, as described in Chapter 5, is that the process of making a modification to the organizational structure should also follow existing authority and communication relations.

In Chapter 6 we use the decision for selecting a coordination mechanism to design a dynamic organization where agents are able to switch between two coordination mechanisms. In this case, the agents use a centralized coordination mechanism when the communication infrastructure is working properly. When the communication infrastructure breaks, the agents will switch to a decentralized form of coordination and continue to work with agents with whom they can still communicate.

8.1.3 What are the methods and models to evaluate the performance of MAS organizations?

Next to describing the knowledge of agents in organizations, this thesis also aims at describing the task-environment of agents and their organization. In Chapter 7 we present the Extended Organization Design model. This model provides a generic vocabulary to describe MAS organizations and their task-environment. It also provides a set of domain independent performance metrics. The advantage of a domain independent vocabulary is that it can be used as a basis to design the task-environment of a MAS for studying the performance of MAS organizations. Instead of designing a MAS simulation environment and then trying to generalize its features once experiments have been performed, the model in Chapter 7 can be used to guide the design of a simulation environment. For this we have created a methodology for selecting a generic organizational or task-environment factor, operationalizing the factor and implementing the factor. This approach has been tested in the design of a search and rescue simulation environment.
In Chapter 7 we have taken an experimental and incremental approach to creating a performance model of a MAS organization. This performance model describes the relation between MAS organizational features and task-environment features and how they influence the performance of the organization. In our approach we start with a relatively simple experimental setup by varying only one or two parameters. Based on the outcome of the initial experiments, we then gradually add more parameters to create a more complex performance model for the organization.

8.2 Discussion

8.2.1 On the Organizational Design Space

As illustrated in the work by Sims et al. (2008) on automated organization design, the organizational design space is large and the problem of finding the right organization for a certain task is complex. In this thesis we have designed and implemented a number of organizations using different structures and coordination mechanisms. In most cases we have chosen a tree-structured organization, except for Chapters 6 and 7 where we also have organizations based on dynamic team formation. Coordination mechanisms vary from market based coordination to centralized coordination with fine grained tasks to mutual adjustment in Chapters 3, 5 and 7 respectively.

Although the organizations in this thesis are different in each chapter, they do not cover the complete range in the organizational design space. For example, we only consider MAS that have explicit coordination mechanisms and leave emergent coordination out of scope. The AgentCoRe framework has only been applied in this thesis to organizations with explicitly defined coordination mechanisms. The framework is less suited to design organizations using emergent coordination because emergent coordination requires the agents to have less or no knowledge at all of their organization. Furthermore we only consider relatively simple tree structured organizations and leave out more complex structures where agents can have more and different relations that also require a larger organizational awareness. In order to manage these more complex organizations, more advanced task decomposition and task assignment algorithms such as TAEMS (Lesser et al., 2004) are needed. However this does not limit the applicability of the AgentCoRe framework because the framework describes these algorithms at a conceptual level and as such it allows for more advanced algorithms to be used.

Similar to organization design, the design space of reorganization is also large. Dignum et al. (2004) distinguishes between structural adaptation and behavioral adaptation of organizations. Furthermore, reorganization can be collaborative/consensus driven or directive/master driven. In this thesis we study both the adaptation of organizational structures in Chapter 5 and the adaptation of organizational behavior in Chapter 6. In both chapters however
we only consider a directive approach to reorganization. The AgentCoRe inference structure for adapting the organization structure does not provide a placeholder for a collaborative process that initiates organizational change. In order to use the AgentCoRe framework to design a collaborative adaptation of the organization structure, the inference mechanism would require a modification to include a collaborative decision on whether and how to change the organization. For adapting organization behavior, the AgentCoRe inference structure does provide a placeholder for a collaborative change process. Therefore we do not foresee any impediments to use the AgentCoRe framework to design collaborative adaptation of organization behavior.

### 8.2.2 On the Evaluation of MAS Performance

When evaluating the performance of a MAS organization, a MAS experimenter is faced with two decisions. The first is which simulation environment to select for the evaluation. This decision includes the analysis of existing simulation environments as well as the consideration to build a custom simulation environment. The second decision for a MAS experimenter is to design the experiments that will be conducted using the simulation environment. In this thesis we have conducted a number of experiments to investigate the performance of MAS organizations. For these experiments we have used a number of different simulation environments: a low-voltage distribution grid simulator based on Ciric et al. (2003), the RoboCupRescue simulation environment (Kitano et al., 1999), an abstract task environment (Ghijsen et al., 2008a) and another search and rescue simulation environment (Ghijsen et al., 2012).

In Chapter 7 we present a design methodology for designing a MAS simulation environment. Although this methodology has not been applied to analyze existing simulation environments, we believe the Extended Organization Design model is sufficiently generic to also describe a simulation environment such as RoboCupRescue. The methodology could then be used to trace how certain generic factors of the task environment have been operationalized and implemented. This should provide the experimenter with sufficient insight on the degree of control and the available parameters to control to decide on whether to select a certain simulation environment or not.

In this thesis we have applied our methodology for designing MAS simulation environments only once. Because of this the vocabulary provided by the EOD model has only been validated in this single case. Therefore, it is likely that the EOD model will undergo some changes when it is applied to design other types of simulation environments. Because the EOD builds upon existing work by So and Durfee (1998), it is unlikely that the global structure of the EOD requires major modifications in order to be applied to other domains than Search and Rescue.

A general problem, that also exists in the experiments in this thesis, is that a considerable amount of parameters can be varied in most simulation
environments. This can result in a large parameter space when trying to investigate the effect of these parameters on MAS organization performance. In Chapter 7 we discuss an iterative approach to conducting experiments to investigate MAS performance. Although this approach does not prescribe which parameters to vary and how to vary this parameters, it does provide a structured approach for a MAS experimenter to get more control over the large parameter space.

8.2.3 On the Influence of Communication on Organization Design

In this thesis we have used a number of different simulation environments and each of these simulation environments provided different abstraction levels of the environment, ranging from very accurate (low-voltage grid) to as abstract as possible (Abstract Task Environment).

Throughout this thesis we have designed different organizations for each of the simulation environments and the design of these organization has been heavily influenced by the simulated communication infrastructure that was available for the agents to exchange messages. The communication infrastructure allows agents to communicate with each other. It determines if communication is possible, with whom can be communicated and how much can be communicated. For example, the RoboCupRescue Simulator allows agents of the same type (e.g. ambulance, fire brigade or police) to communicate to its “center” agent which acts as a relay station. This center agent can then broadcast messages to all other agents of the same type. Furthermore, agents of different types can communicate directly when they are within hearing distance of each other. The size of messages that can be sent is also restricted by the communication infrastructure.

The design of the RoboCupRescue communication infrastructure restricts the possible organization forms that can operate in the simulator. The communication infrastructure favors shallow hierarchical organizations, where all communication is done via the center agents. Structural cooperation between agents is difficult to design because communication either has to travel via the centers of the different types or is done at an ad-hoc basis when agents are within hearing distance.

The abstract task-environment introduced in Chapter 6, provides a communication infrastructure that allows only one agent per time step to communicate. This requires organizations to actively coordinate the access to the communication infrastructure. In principle this favors a centralized organization where one agent decides for every time-step who is allowed to communicate. By introducing dynamics in the communication infrastructure we disrupt the centralized organization in a later stage of communication. This causes a less optimal decentralized coordination and communication scheme to outperform the more optimal centralized organization. This shows the large influence of the communication infrastructure on the design of MAS organizations and
how robust these MAS organizations are to changes in the communication infrastructure.

The low-voltage distribution grid simulator does not impose any restrictions on agent communication. Theoretically, all agents could communicate as much information as they need with all other agents. This has allowed us to focus on the coordination problem at hand, how to coordinate the distribution of a scarce resource while at the same time preventing each agent to provide detailed information about its current and future energy use. The latter restriction on communication is not imposed by the communication infrastructure but instead by a need to protect the privacy of energy consumers and because prediction of future energy consumption is not practically feasible.

Finally, in Chapter 7 we have designed a communication infrastructure while trying to minimize influences on organization design. It has resulted in a complex communication infrastructure that requires agents to adapt their messages to fit with a given bandwidth, to consider communication failure because (parts of) the communication network are temporarily down or because the network is flooded by broadcast messages and agents become overloaded. Although this infrastructure allows a lot of freedom in organization design it also requires agents to have complex capabilities to exploit the freedom offered by this simulation environment.

\section*{8.3 Future research}

For future research we propose two lines of research. The first is to continue to apply and refine the AgentCoRe decision making framework. The second line of research is on a systematic empirical comparison of different MAS organizations and modeling the performance of MAS organizations.

In this thesis we have used the AgentCoRe framework to guide the design of a number of different dynamic MAS organizations. In this way we have attempted to validate the completeness of the AgentCoRe framework. Each of the four decision making modules in the AgentCoRe framework contains a number of different reasoning processes. In order to validate the scope of AgentCoRe, we have focussed in this thesis on applying the whole spectrum of reasoning processes. Due to the complexity of the decision making modules and their reasoning processes we have sometimes been forced to use simple operationalizations of the reasoning processes while more complex solutions are also available. The AgentCoRe framework provides the opportunity for a number of more in-depth studies in the design of dynamic MAS organizations.

The first opportunity for further research is the dynamic selection of coordination mechanisms. In chapter 6 we have validated this framework against a number of existing approaches and shown that the different reasoning processes of the inference mechanism are, explicitly but sometime also implicitly, present in these different approaches. What our analysis shows is that even these existing approaches focus on only a few reasoning processes of the
inference mechanism. For example, the approach by Martin and Barber (2006) focuses on cost calculation and the process of switching to another form of coordination. Rosenfeld et al. (2008) also focuses on cost calculation but also tries to include multiple selection criteria. Further research in this area should be aimed at combining the available approaches and result in an even more advanced MAS organization that is able to switch between different coordination mechanisms.

The reorganize inference structure in the AgentCoRe framework offers the second opportunity for further research. In this thesis we have only explored a limited number of triggers for organization change and also focused on specific types of changes in the organization. Further research should focus on exploring different triggers and attempt to generalize these triggers such that they are applicable in multiple domains. Furthermore, this research should identify appropriate generic responses for each of these triggers. The organizational model by Dignum (2004) provides an extensive overview of all possible organizational concepts that are subject to reorganization. The result would be a catalogue of triggers for organizational change and appropriate responses.

The simulation environment presented in Chapter 7 offers the opportunity to evaluate and compare the performance of different MAS organizations. This simulation environment facilitates an elaborate empirical study on the performance of different MAS organizations. For each MAS organization, the task-environment parameters can be systematically varied to create a performance model for that organization. These models can then be used as input for the dynamic selection of coordination mechanisms. Furthermore, these models can then be used as a basis for a more analytical comparison of the different organizations and to increase the general understanding of the performance of MAS organizations.

Based on these directions for further research, we conclude that this thesis shows that knowledge level models and methods can form a solid basis for the design and evaluation of static and dynamic MAS organizations.