Organizational Architectures for Large-Scale Multi-Agent Systems' Development: An Initial Ontology

Markus Schatten

Artificial Intelligence Laboratory,
Faculty of Organization and Informatics,
University of Zagreb, Pavlinska 2, 42000 Varaždin
markus.schatten@foi.hr

Abstract. An initial conceptualization of organizational design techniques for large-scale multi-agent systems (LSMAS) based on the paradigm of organizational architecture is introduced. Seven perspectives (organizational structure, processes, culture, strategy, individual agents, organizational agents and inter-organizational context) are analyzed and defined. By using a graph theoretic approach and recursive definitions the ontological framework allows for modeling all perspectives on an arbitrary level of detail and complexity from the global system to low level individuals. The provided conceptualization is the foundation of a to be established ontology on organizational design methods for designing, developing and maintaining LSMAS.

Keywords: ontology, large scale multi agent systems, organizational design, organizational architecture.

1 Introduction

Due to their complexity and high-level of concurrency large-scale multi-agent systems (LSMAS) have to be modeled using a higher level of abstraction to be comprehensible at a global level [1]. (Human) organization theory provides us with the necessary methodology to approach complex systems and through the process of organizational design allows us to develop, analyze and optimize different perspectives of organization: structure, processes, culture, strategy, individual behavior and dynamics [2].

Due to the less formal approach to this field of research[1] in order to be usable in LSMAS development, we find it necessary to establish an ontology of organizational design methods that will allow for modeling complex systems having a formal semantic. The ultimate goal is for the ontology to act as a meta-model

[1] Descriptions from organization theory often include metaphors and vague descriptions which cannot directly be formalized mathematically. Also there are various schools of organization theory which often differ significantly in their conceptualizations.

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for a to be established LSMAS development framework that would allow for organizational design of such systems on a high level of abstraction.

The idea of applying organizational design methods to multi-agent systems (MAS) is not new, and there has been a substantial amount of research in this area.[2] We have chosen to limit our approach to a specific worldview in organization theory, namely the paradigm of organizational architecture, which is put forward by [6–10]. From this perspective an organization consists of its organizational structure, organizational culture, its business processes, strategy and individual agents (human or artificial) which together form a complete mutually interconnected system.

Due to the highly unstructured domain to be formalized we used a three step approach in formalizing the needed knowledge about organizational architecture. Firstly we have developed a wiki about organizational design methods[3] in order to provide a (as much as possible) state-of-the-art literature review on organizational architecture in a collaborative environment. Afterwards this wiki was annotated with semantic descriptors to yield a semantic wiki [11–13] in order to make a first step towards formalizing the domain. The last and final step is to use the experience gathered during the semantic wiki development in order to establish a formal ontology of organizational design methods which are applicable to LSMAS. The first part of this step is presented in this article.

The rest of the paper is organized as follows: in section 2 we shall introduce the paradigm of organizational architecture as the main theoretical foundation for the to be established ontology. In section 3 we establish a number of formal concept definitions and their interrelations that capture the most important aspects of our approach. In 4 we draw our conclusions and provide guidelines for future research.

2 Organizational Architecture as a LSMAS Framework

Organizational architecture represents a well established paradigm for describing (human) organizations [6–10, 14]. We will adopt the interpretation of [2] that organizational architecture is a complex organizational system which can be modeled from different perspectives: organizational structure, organizational culture, business processes, strategy and individual agents (human or artificial) which are mutually intertwined. Additionally we will add two important aspects of organizations which are not clearly captured by these perspectives: (1) organizational dynamics and (2) contextual and inter-organizational aspects. We are now able to provide an informal definition of these perspectives:

Organizational structure defines the decision and information flows of an organization.

[2] Due to space constraints, we are unable to provide a comprehensive literature review, but the interested reader is advised to consult [3–5] for an extensive review.

[3] Available at `http://ai.foi.hr/oovasis/wiki`, in Croatian.

Organizational culture defines important intangible aspects of an organization including knowledge, norms, reward systems, language and similar.
Strategy defines the long term objectives of an organization, action plans for their realization as well as tools on how to measure success.
Processes define the activities and procedures of an organization.
Individual agents define the most important asset of any organization - the individuals actually performing the work.
Organizational dynamics define organizational changes including reorganization of any of the above mentioned components.
Context and inter-organizational aspects define organizational behavior towards its environment including strategic alliances, joint ventures, mergers, splits, spinouts and similar.

In the following we will focus on the organizational perspectives leaving individual agent modeling to future research.

3 Conceptualization

In the following we will give a number of more formal definitions that shall outline the main concepts of the to be established ontology of organizational design methods. These definitions are in a way a continuation of the work in [15–17]. While establishing these definitions we were guided by a set of simple but subtle objectives: (1) we want to keep the number of (basic) concepts at a minimum in order to avoid redundancy, but not at the cost of limited expressivity; (2) we will tend to use conceptualizations that are compatible with well established agent development approaches in order to allow for their introduction in the to be developed modeling language; (3) we will tend to establish well founded relations between the perspectives of organizational architecture (as outlined in section 2) to allow compatibility between different forms of organizing regardless of perspective; (4) we will have established organizational design and engineering methods in mind when providing the definitions in order to allow the establishment of not only a best-practices knowledge base, but also a familiar framework for modeling and design, (5) we shall have the interorganizational perspective in mind when defining concepts so not to limit definitions to the design of only one organization, but a multitude of them, as well as the design of their mutual interplay; (6) concepts should be atomic in order to allow for (inter-)organizational dynamics including exchange of perspectives and reorganization.

Herein we will take a graph theoretic approach to defining the various concepts in the perspectives whereby as an inspiration we shall use the fractal organization principle [18][4] which allows us to define organizational concepts recursively. Let us first consider the organizational structure perspective.

Definition 1. *An organizational unit is defined as follows:*

[4] Please bare in mind that this is a (human) organizational principle, not necessarily a mathematical structure.

- *Any agent is an organizational unit.*
- *If $OU = (O, R, C)$ is a labeled graph in which O is the set of organizational units (nodes), R is a labeled set of roles (relations, arcs) and C is a criteria of organizing then OU is an organizational unit.*

This definition has an important implication: it allows us to deal with agents, groups and teams of agents, organizations of agents, networks of organizations of agents (or organizations of organizations) as well as virtual organizations of agents (as overlay structures in the sense of [19]) in the same way. This in particular means that organizational units may form a lattice structure in which each unit can belong to several super-units and/or be composed of several subunits. The criteria of organizing could for example be an objective, function, goal, mission, unit name, higher-order role etc. Note that the fixed point in this definition is the individual agent, the implications of which are twofold: (1) it allows us to connect the perspective of structure with the perspective of individuals (directly), and (2) it allows us to model structure as a network of organizational units, which is defined over the relation of a criteria of organizing. This further implies connections to all other perspectives which might be the particular criteria. Due to the recursive nature of the definition, in a complex organizational hierarchy we are actually dealing with layered hypergraphs (in which edges actually represent graphs). In this way a zooming facility can be implemented that would allow a developer to comprehend the organizational structure on an arbitrary level of detail. Thus, an organizational unit, in a way, represents an aggregation of the underlaying complexity similarly to holonic, swarm-like, aggregate, multi-level and other conceptualizations. Note here also, that the definition of an organizational unit is detached from the definition of an organization, and thus allows us to model interorganizational structure in which organizational units might represent different organizations which might have mutual relations (for example competitor, strategic partner, spinout etc.).

The processes perspective can be modeled in a very similar manner.

Definition 2. *An organizational process is defined as follows:*

- *Any atomic activity performed by some individual agent is an organizational process.*
- *If $OP = (P, R, C)$ is a labeled directed graph in which P is a set of organizational processes, R is a labeled set of ordered relations between processes and C is criteria of organizing, then OP is an organizational process.*

The given definition allows for modeling organizations as networks of processes which can be defined in a number of ways. For example, the criteria for organizing might be that one process uses inputs from another or that two processes are using the same resources, or even that two processes are performed by the same organizational unit or that they are crucial for the same organizational goal. Again this definition is recursive, and inherits the same properties as the definition of organizational units above - possible zooming facilities and detachment of actual organization (thus it is possible to model interorganizational

processes). Another possibility here that emerged is to model the same process from various perspectives (e.g. criteria of organizing). Note that the fixed point in this definition is an atomic activity or service performed by some individual agent. This means that we have one possible connection to the individuals perspective as well as to all other perspectives if different criteria are selected.

We will closely bound the strategic perspective to the paradigm of the balanced scorecard [20], but adapt it by again using the fractal principle.

Definition 3. *An organizational strategy is defined as follows:*

- *Any measurable objective that can be achieved by an atomic activity is a strategy.*
- *If $OS = (S, R, C)$ is a labeled directed graph in which S is a set of strategies , R is a set of relations between the strategies and C is a criteria of connections, then OS is an organizational strategy.*

Such a definition provides us with the possibility to model agent organizations as networks of objectives which might be defined in a number of ways depending on the criteria of connections. Such criteria might be influence (the outcome of one strategy influences another, e.g. a mathematical function), responsibility (two strategies are under the responsibility of the same organizational unit), achieveability (two strategies can be achieved by the same organizational process), etc. Note that we deliberately excluded two very important aspects of strategy: action plans and decisions. Both plans and decisions are part of the dynamics perspective, since they represent active changes in this or other perspectives. Due to the recursive definition we are again able to model strategy on a number of different levels of detail, and, due to the detachment of a particular organization, we are able to model interorganizational strategy (for strategic partnerships for example). The fixed point in this case is an atomic objective that can be achieved by an atomic activity which allows the connection of this perspective to the process perspective.

Organizational culture in human organizations is a complex cybernetic system that deals with various intangible aspects of organizational behavior including but not limited to language, symbols, rituals, customs, methods of problem solving, knowledge, learning etc. Due to this complex nature, formalizing culture (for agent organization and even more for human organizations) is a quite hard and non-trivial open research question. In [17] we used cultural artifacts (for example knowledge in some agent's knowledge base, written norms of behavior, language protocols, learning processes etc.) as the fixed point of definition, allowing us to model organizational culture as networks of cultural artifacts. The problem with this definition is that it remained quite vague and didn't quite fit into the rest of the proposed framework since it overlapped with the other perspectives (for example procedures and protocols might be modeled as processes).

In order to provide a more applicable conceptualization of the organizational culture perspective we decided to introduce give a more detailed view by defining only one special concept which is of greatest importance - knowledge artifacts, while other (possibly valuable) concepts have been excluded for the time being.

These excluded concepts might be included in the final version of the ontology if they show to be valuable enough and applicable to a wide range of LSMAS applications. We will model knowledge in terms of organizational memory [21] again in a recursive manner.

Definition 4. *Organizational knowledge artifacts are defined as follows:*

- *Any knowledge artifact*[5] *that is accessible to agents is an organizational knowledge artifact.*
- *If* $OK = (K, R, C)$ *is a labeled graph in which* K *is a set of organizational knowledge artifacts,* R *is a set of relations between these artifacts and* C *is an organization criteria, then* OK *is an organizational knowledge artifact.*

Thus, agent organizations can be seen as a network of knowledge artifacts which are accessible by particular agents. Special cases of knowledge artifacts are norms which establish the rules of interaction between agents and values which influence decision making and selection of objectives.

The individual agent perspective does not need much additional explanation since the design and implementation of agents is a well researched field. Still we do need to point out the implications of the aforementioned perspectives on agents. Since agents have to be aware of their organizational context depending on the organizational model the various perspectives will introduce context knowledge into the particular knowledge-bases of agents. Also since agents have to behave in accordance to the model, it will introduce agent behaviors and protocols which agents will have to adhere to.

In the organizational dynamics perspective there are three important concepts: (1) time, (2) event and (3) change. In [16, 17] we have introduced active graph grammars (AGGs) to model changes in the organizational structure of agent organizations. AGGs are an active database theory inspired formalism that allow reactive behavior in graph structures. Since all of the above concepts (organizational units, processes, strategy and knowledge artifacts) are defined in terms of graphs, AGGs (or any similar formalism that allows for event detection and graph transformation) can be used to introduce changes in any of the perspectives. In this way reorganization can occur on any level. AGGs (or similar formalisms) will allow us to implement a best practices knowledge base of organizational design techniques which will be individuals in the to be established ontology.

Some drawbacks of AGGs is that they are defined to be local to agents and that they allow only for reactive behavior. The first problem could be approached by defining AGGs as shared knowledge artifacts to which all agents comply to a certain criteria (are part of an organizational unit for example) have access to. The drawback regarding reactive behavior might be solved using a BDI approach to agents in which the plans are consecutive executions of active graph rewriting rules.

[5] By knowledge artifact we understand a wide range of explicit knowledge in which we assume that it is queriable by the agent, including but not limited to data and knowledge bases, neural networks and machine learning architectures, various information services etc.

This last remark brings us to another important aspect of organizational dynamics and that is the continuous performance of the LSMAS that is being modeled. All previous perspectives only dealt with the static (structural) aspects of organizational architecture. These static aspects set the stage of performance: for example a defined strategy is a referent point in decision making and execution of action. This situation is fairly compatible with the usual BDI approach: beliefs are knowledge artifacts, desires are strategies and intentions are plans for executing processes. While this is a well known procedure for individual agents, the recursive definition of perspectives (especially organizational units and strategy) introduce some additional complexity: here a multitude of agents or even multitude of agent organizations have to reach consensus about a collective process to be performed. Beliefs, reasoning techniques and possible actions of agents might differ considerably, thus there is need for distributed consensus making techniques like abstract argumentation. Still extending the BDI approach to agent organizations is an open research question.

In the end the contextual and inter-organizational perspective has already been partially addressed in the other perspectives, mostly regarding inter-organizational aspects. To model the environment of agent organizations we will use the usual approach to introduce a special individual agent to which all other agents have access.

4 Conclusions and Future Work

In this work-in-progress paper we gave an initial conceptualization for a to be established organizational design methods ontology based on the paradigm of organizational architecture. We defined seven important perspectives that shall allow us different views of a complex system: organizational structure, processes, strategy, culture, individual agents, organizational dynamics and inter-organizational context. By using recursive definitions of most important concepts (organizational units, processes, strategy, knowledge) we established a framework that shall allow us to view parts of agent organizations on an arbitrary level of detail. Since each of these definitions has a criteria of organizing we allowed for modeling different views of the same underlying instances.

Our future work is oriented towards the implementation of this ontology in OWL with the goal of establishing a meta-model for a graphical modeling language of LSMAS. This language should then be implemented in a modeling tool together with a best-practices knowledge base of organizational design techniques.

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