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Understanding Organizational Congruence: Formal model and simulation framework

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Abstract

Despite a large number of studies, the effect of organizational structure on the performance and the individual cognition of its members is still not well understood. Our research aims at developing tools and formalisms to model organizations and evaluate their performance under different circumstances. Organizational effectiveness depends on many factors, including excellence, effective planning and capability to understand and match context requirements. Different organizational structures are clearly better matched to certain problems and context requirements than others, but methods to determine which structure better fits the requirements and goals of a group are non-existent. We propose a combination of agent-based formal models and agent-base simulation that supports the analysis of the congruence of different organizational structures to different problems and requirements.

1. INTRODUCTION

Researchers agree that organizations allow and support an individual (be it a person, a computer system, or an institution) to recognize its role, and the roles of others, in accomplishing collective goals. Organizational Theory research recognizes that organizations are instruments of purpose, that is they are seen as coordinated by intentions and goals [12]. In similar fashion, MAS researchers realize that the specification of an organization for a MAS helps coordinating the agents' autonomous behavior [10]. In this sense, an organization can be defined as a set of entities regulated by mechanisms of social order and created by more or less autonomous actors to achieve common goals [4].

Contingency theory suggests that a match among (business) strategy, organizational structure, and the characteristics of the environment is necessary for high performance. Organizations that exhibit such a match are said to be congruent with their environment and strategy. Our research aims at testing congruence theories by developing formal models that enable the specification and comparison of different organizational structures, their performance properties and congruence. Such models will serve as basis for the development of simulations to experiment in a laboratory setting scenarios that exploit the differences between structures in different domains.

Following our extensive research in agent organizations, in this paper we are interested in understanding the decision processes that enable designed, purposeful organizations[1] to evaluate their fit to the environment and determine the changes that result in better performance given those environmental conditions. That is, we assume that organizations try to locate the structure that best fits their environment and will make changes in their design accordingly [2]. In the real world, organizational change strategies take different forms, such as hiring new personnel, training, downsizing, or reassign tasks and/or personnel. Obviously, what the organization considers to be the optimal design depends on what it perceives as important (e.g., minimizing salaries, maximizing production, or maximizing decision accuracy) [2]. Essentially, the organization is seen as trying to minimize or maximize some cost function that specifies its performance.

In theory, and assuming a stable environment, the optimal organizational design can be found that satisfies a given cost function. Following this line, it is conceivable to accept that, in theory, an optimal organizational design can be found for each environment type. In case of environmental changes, organization adaptation is then achieved by identifying the optimal design for the new situation and modify the existing organization to meet that design. Obviously, in practice many factors will contribute to make such a 'clean cut' solution impossible: it is not usually possible to identify all the environment parameters and their consequences for the organization, there is not sufficient knowledge about such optimal designs, in highly dynamic environments is not feasible to assume a different organizational design every time the environment conditions change, etc. Nevertheless, even if incomplete and theoretical in nature, knowledge of which environment features should be monitored in order to identify triggers for reorganization, and knowledge about types of organizational design that are better suited for a particular situation, can be used as guidelines for real organizations faced with reorganization decisions. Literature in organizational decision making shows that organizations must continually monitor their environment and make strategic decisions to keep the firm strengths aligned with new opportunities and threats in the environment [1]. Often, firms that change their strategy in face of changes in the environment

[1] Our focus is thus not on emergent organizations.

outperform those that maintain the same organization strategy and design. Providing decision-makers with knowledge and tools that enable them to effectively identify, assess and respond to environment changes is therefore of utmost importance for the survival of the organization. Our research follows two parallel but interrelated paths. On the one hand, we are using simulations to identify environment characteristics and the response of different organizational designs to those characteristics. These results can be used to inform strategic decisions concerning reorganization [6]. Empirical observations of human organizations form the basis for the design of these simulations. On the other hand, we have developed formal models that enable the specification of abstract organization models and the verification of formal properties such as flexibility or robustness [9] in dynamic environments [7]. Results of the simulation project will lead to the adaptation and refinement of the formal models. Conversely, we will use the verification results of the formal models to determine and test different measures for the simulation of the behavior of natural groups. The project aims at a comparison the evolution of behavior in both the simulation and the formal models to draw conclusions about the validity of agent-based simulations as predictors of group behavior. The long term objective is to use the knowledge that is generated by this evaluation process, to develop theories of organization that can be used as a basis for organizational design and analysis.

2. FORMAL MODELS FOR CHANGE

Organizations and their environments are not static. Agents can migrate, organizational objectives can change, or operational behavior can evolve. That is, as circumstances change, organizational structures must also be able to change, disappear or grow. Models for MAS must therefore not only cater for adaptive agents [11] but also be able to describe dynamically adapting organizations to changes in the environment. In fact, organizations are active entities, capable not only of adapting to the environment but also of changing that environment, which leads to the question of how and why change decisions are made in organizations [8]. It is therefore important to understand how different organizations can be designed considering different populations of agents, performing different tasks in changing environments, to meet various performance goals [16]. Given that there are different views, aims and approaches to modelling and analyze organizations, as described above, the difficulty of comparing, analyzing and choosing a given approach becomes clear. Even if our aim is not to solve this problem, in this research we aim at identify initial steps towards the specification of a formal 'minimal' model for the study of organizational performance which can be used to this effect.

The motivations for developing an abstract organizational model are twofold. In the one hand, the need for a formal, provable system that in an abstract way enables to represent organizations, their environment, objectives and agents in a way that enables their partial contributions to the performance of the organization in a changing environment. On the other hand, such a model must be realistic enough to incorporate the more 'pragmatic' considerations faced by real organizations. Most existing formal models lack this realism, either by ignoring temporal issues, by taking a very restrictive view on the controllability of agents, or by assuming complete control and knowledge within the systems (cf. [17], [15], [14]). Another important realism requirement, is the notion that agent activity has a cost, that is, choosing one or the other course of action is not only dependent on agent capabilities but the costs of the action must compare positively to its benefits. To sum up, formal models for organizations that are able to deal with realistic situations, must meet the following requirements:

1. represent notions of ability and activity of agents, without requiring knowledge about the specific actions available to a specific agent (open environments);
2. represent ability and activity of a group of agents;
3. deal with temporal issues, especially the fact that activity takes time;
4. accept limitedness of agent capability;
5. represent the notion of responsibility for the achievement of a given state of affairs;
6. represent organizational (global) goals and its dependency on agents' activities (organizational structure);
7. relate activity and organizational structure;
8. represent organizational dynamics (evolution of organization over time, changes on agent population);
9. deal with resource limitations and the dependency of activity on resources (e.g. costs);
10. deal with normative issues (representation of boundaries for action and the violation thereof).

We classify the independent variables that determine performance into three broad classes. The first are the *structural factors*, which are the components and features of the organization (such as roles, dependencies, constraints, norms and regulations). The second are *task environmental factors*, which are the components and features of the task (such as size, time constraints, uncertainty). The third class of factors are *agent factors*, which are the characteristics of the individual agents concerning task capability, intelligence (including decision making and reasoning capabilities), social awareness, etc. These three classes of factors jointly determine the performance of the organization. To sum up, models aimed at understanding or specifying organizational performance or behavior must be able to represent the *environment*, that is, this is the space in which the organization exist. This space is not completely controllable by the agents and therefore results of agent activity are not always guaranteed; the *agents*, which are entities with the capability to act, that is to control the state of some element in the environment. Agents are defined by their capabilities; and the *organization*, a more or less structured set of agents, together with some global objective(s).

3. REORGANIZATION MODEL

Reorganization of the structure of an organization is a crucial issue in multi-agent systems that operate in an open, dynamic environment. Currently, most coordination mechanisms are imposed upon the system at design time, and their modification implies the redesign of the system. However, autonomous agents must be able to evaluate and decide the most appropriate organization given the environment conditions. That is, there is a need for dynamic reorganization of coordination structures. In [5], we explored different issues on dynamic reorganization of agent societies and have identified the following reorganization situations:

Behavioral Change In this case the organizational structure stays the same but the agents currently enacting roles, decide (collectively or individually) to use different protocols for the same abstract interaction described in the structure. This type of reorganizations includes changes in agent population, adoption of different plans to achieve organizational goals, and changes on interaction patterns.

Structural Change In this case a decision is made concerning the modification of one or more structural elements.

1. *Organizational Self Design*: that is, dynamic variation in emergent societies, resulting from changes in the interaction between agents.
2. *Structural Adaptation*: In this case, designed societies are adapted to environment changes by adding, deleting or modifying its structural elements (e.g. roles, dependencies, norms, ontologies, communication primitives).

Based on this classification, the work presented in this paper concerns structural adaptation, that is, designed changes on organization structure. In [7], we described a formal logical framework for organization specification based on temporal deontic logic, that is increasingly extended to include the requirements listed in section 2 above. That is, we started with a simple model that only implements some of the requirements and extend it successively to incorporate more complex requirements. At the moment, we are working on the further extension of the model to include the notions of role and norms. In the remainder of this section we will introduce this model. Note that for reasons of readability and space we omit here the formal semantics of the model, sufficing with a informal description of its components. We refer the interested reader to [7] for a full description of the formal semantics.

3.1. Agents and organizations

We assume the environment to be represented as a partially ordered set of worlds, each representing a state of affairs holding at a given moment. Changes in a state correspond to transition to a next world. Choice is represented by more than one possible future for each world. Each world includes the agents, relations, resources and conditions existing in that world. Agents are active entities that can make change happen. We assume a set of atomic facts, Φ, the basic components of the domain. All other facts can be constructed as a composition of atomic facts. However, at any moment, unexpected change can also occur, which is not result of the action of any of the agents in that world.

The notions of agent capability and action have been widely discussed in MAS. The intuition is that an agent possesses capabilities that make action possible. That is, in order to talk about agent activity, or, that agent a possesses the ability to make proposition φ hold in some next state in a path from the current world, we need to establish the control of the agent over the (truth) value of φ. For each agent a we partition the set of atomic facts Φ in any world w of M in two classes: the set of atomic facts that agent a can control, C_a, and the set of atomic facts that a cannot control, $\overline{C_a}$. Control over a more complex fact (i.e. not atomic fact), φ, is possible when there is some way for agent a to change the value of φ through its control of some of the atomic facts that compose φ. Furthermore, the formalism is so that no agent can control the obvious (tautologies), and if an agent controls a fact φ it also controls its negation. In the following, we will overload the operator C_a, respectively $\overline{C_a}$, and use $C_a\varphi$, respectively $\overline{C_a}\varphi$ to represent the fact that proposition φ is controllable by a, respectively uncontrollable by a. For example, if we consider a world where the basic facts are *sand-door* and *paint-door*, an agent a that has only the capability to perform *sand-door*, that is, C_a*(sand-door)*, will not be able to control the composite fact *(sand-door **and** paint-door)*.

The notion of controllability expresses the fact that an agent a has the capability to bring φ about. It does not mean that the agent will indeed ever do it. Obviously, agents must be able to *act* on the world and as such bring states of affairs to happen. The result of a successful action is that the resulting facts will hold in all possible next worlds. We represent action by $E_a\varphi$, meaning that agent a sees to it that fact φ holds in all next worlds.

Moreover, it is realistic to assume that agents are limited on their capabilities, that is, on what parameters of the world they can control. This implies that in MAS certain states of affairs can only be reached if two or more agents cooperate to bring that state to be. One of the main ideas behind organizations is the notion that the combined action of two or more agents can result in an effect that none of the involved agents could bring about by themselves. We define control and action of a group of agents based on the combined atomic capabilities of the agent in the group. For the example above, if the group contains two agents a and b, such that a can control *sand-door* and b can control *paint-door*, none of the agents can achieve the combination, but working as a group it is indeed possible to realize both. This is represented by $C_{\{a,b\}}$*(sand-door **and** paint-door)*.

We see organizations as instruments of purpose, that is, organizations have goals that should be realized. The objectives of an organization are achieved through agent action. In order to make this possible, an organization must employ the relevant agents, so that it can 'enforce' the possibility of making its desires happen. Furthermore, one of the main reasons for creating organizations is efficiency, that is, to provide the means for coordination that enable the achievement of global goals in an efficient manner. However, even if the agents in the organization have group control over all organizational objectives, they have no means to coordinate their activities in order to efficiently achieve those objectives. In most cases, the objectives of the organization are only known to a few of the agents in the organization, who may have no control over those objectives. It is therefore necessary to organize agents in the organization in a way that enables objectives to be passed to those agents that can effectively realize them. Dependency between agents a and b is represented by $a \leq b$ meaning that agent a is able to delegate the realization of some state of affairs to agent b.

We therefore define an organization as a partially ordered set of agents (where the ordering indicates the dependency relations between agents), a set of objectives (states of affairs to achieve) and a set of assets (states of affairs holding at a given moment). Moreover, agents can be made responsible for some of the objectives of the organization, which means that either the agent attempts the realization of that objective, or it will delegate the objective to another agent with whom it has a dependency relation. We represent responsibility by $R_a\varphi$. Furthermore, in a organization, order relations between agents indicate how agents can interact so that responsibilities can be delegated between agents. That is, given an organization $O = ((\{a,b\}, a \leq_O b), D_O, S^w_O)$ and a proposition φ, such that $R_a\varphi$, the order relation between a and b guarantees that if a decides to pass its responsibility for φ to b, that is, $E_aR_b\varphi$, then b will became responsible for it, $R_b\varphi$ and will need to see to it that eventually φ is the case. We refer to [7] for a formal proof.

This is a simplified definition of organizations, that enables some theoretical properties. However, it already incorporates some realistic notions such as bounded capabilities of agents, coordination and control. As an example, consider the organization $O = ((A, \leq_O), D, S^0)$, where:
A is the set of agents $\{a,b,c,d\}$,
$\leq_O$ are dependencies between the agents:
$(a \leq_O b,\ a \leq_O c \leq_O d))$,
D is the objective of the organization:
$D = ($*sand-door* $\wedge$ *paint-door*$)\vee$ *tile-floor*,
S^0 is the initial state:
$\{R_aD, C_b$*sand-door*, C_d*paint-door*, $C_{\{b,c\}}$*tile-floor*$\}$

Note that the initial organizational state S^0 indicates the capabilities of the agents in A and that agent a is responsible for the achievement of the organizational goal[2]. This example also shows that organizations are dependent on the capabilities of their agents to achieve their objectives. In this case, without agent b, the organization can never achieve its goals. A possible strategy for this organization to realize the organizational objectives is:

s_1:	E_aR_b*sand-door* $\wedge E_aR_c$*paint-door*
...	...
s_i:	R_b*sand-door* $\wedge E_cR_d$*paint-door*
s_{i+i}:	R_b*sand-door* $\wedge R_d$*paint-door*
...	...
s_N:	*sand-door* $\wedge$ *paint-door*

3.2. Evaluating organization structure

Changes in the environment lead to alterations on the effectiveness of the organization and therefore in a need to reorganize, or at least, the need to consider the consequences of the change to the organization's effectiveness and possibly efficiency. On the other hand, organizations are active entities, capable not only of adapting to the environment but also of changing that environment. This means that organizations are in state of, to a certain degree, altering environment conditions to meet their aims and requirements, which leads to the question of how and why reorganization decisions should be reached.

Rational organizations will constantly try to identify the optimal organizational design to meet the current characteristics of their environment, and will choose a change strategy that they believe will improve their current situation. In terms of our model, in an ideal successful organization, the set of desires D_O will be a subset of the organizational state S_O, which is under the control of the agent in the organization.

[2] We are ignoring here the difference between roles (represented the capabilities intended/required by the organization) and agents (the actual entities that can enact roles). The concept of agent in the above organization O should be seen as that of a *role-enacting agent* [4].

Reorganization activities aim therefore at aligning these sets, either by attempting to change the current state, or by altering the set of desires. This process is depicted in figure 1. In summary, reorganization consists of two activities. Firstly, the formal representation and evaluation of current organizational state and its 'distance' to desired state, and, secondly, the formalization of reorganization strategies, that is, the purposeful change of organizational constituents (structure, agent population, objectives) in order to make a path to desired state possible and efficient.

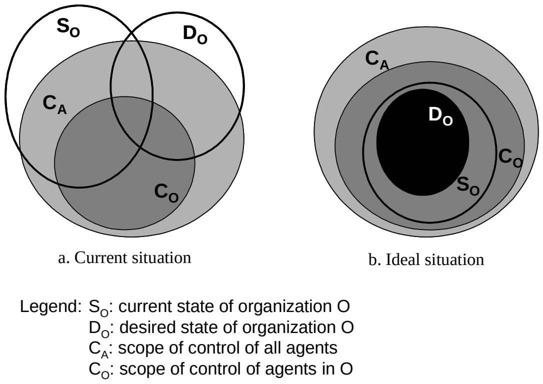

Figure 1. States and control.

There is no one best way to organize or structure the organization, but not all structures are equally effective, that is, organizational structure is one determinant of organizational performance. Performance of the organization can then be seen as the measure to which its objectives are achieved at a certain moment. Because environments evolve, performance will vary.

Intuitively, performance is a value function on the environment (current world), agents and organizational capability, and on the task (desired state of affairs). Formally, we define a function *perform*, such that $perform(w, G_{\leq}, \varphi)$ returns the value of the performance in world w of structured group $G_{\leq}$ for φ, indicating how well G can realize φ. We assume that for each agent and each world, the performance for each atomic proposition p is fixed.

The *perform* function can be seen as the cost associated with a transition in the world W. Several properties can be specified to describe how to determine the value of *perform* for complex propositions. For example, $perform(w, G_{\leq}, p)$ + $perform(w, G_{\leq}, q) \leq$
$perform(w, G_{\leq}, p \wedge q)$, represents the fact that the cost of performing a sequence of activities can be higher than the sum of the costs associated with each activity, for that agent [3] (i.e. agents can get 'tired'). Some authors have used finite state machines to describe organization transitions [13]. An important difference between our work and such approaches is the temporal dimension of our model, that is, an organization can never move to a previous state even if conceptually equivalent, all states are different in time.

3.3. Changing organization design

Because organizations aim at making certain states of affairs to be the case, and only agents can bring affairs to be, it is important for organization $O = ((A, \leq_O), D, S^0)$ to make sure it 'hires' and organizes an adequate set of agents $(A_O, \leq_O)$ such that the combined action of those agents has the potentiality to bring about the desired state of affairs D_O. The dependency relation $\leq_O$ between the agents must allow for the desired states to be achieved, that is, dependencies must be sufficient for responsibilities to be passed to the appropriate agents, that is, the agents that have the necessary capabilities. If that is not the case, the organization should take the steps needed to decide and implement reorganization, such that the resulting organization O' is indeed able to realize its objectives $D_{O'}$. In practice, reorganization activities can be classified in three groups:

- **Staffing**: Changes on the set of agents: adding new agents, or deleting agents from the set. Corresponding to personnel activities in human organizations (hiring, firing and training). Staffing operators are $staff^+(O, a)$ and $staff^-(O, a)$, resulting in the addition, resp. deletion of agent a from the organization.

- **Structuring** Changes on the ordering structure of the organization. Corresponding to infrastructural changes in human organizations: e.g. changes in composition of departments or positions. Structuring operators are $struct^+(O, (a \leq b))$ and $struct^-(O, (a \leq b))$, resulting in the addition, resp. deletion of delegation link $a \leq b$ from the organization.

- **Strategy** Changes on the objectives of the organization: adding or deleting desired states. Corresponding to strategic (or second-order) changes in human organizations: on the mission, vision, or charter of the organization. Strategy operators are $strateg^+(O, d)$ and $strateg^-(O, d)$, resulting in the addition, resp. deletion of objective d from the set of organizational objectives.

The classification above is very generic, but it allows for the representation of all different types of modifications that can be performed on the formal definition of organization we use. Furthermore, most realistic adaptation possibilities can be represented in this classification. For instance, a change of role allocation is represented by the deletion of one agent and the addition of a new one, with the new capabilities (cf. footnote for our current, simplified, notion of role enacting agent). The organizational model represents organizational strategy as objectives, abstracting from e.g. the notion of plan. These objectives represent desired states of the world (which in turn can represent anything) and should not be confused with the idea of organizational vision or goals as used in business contexts.

A reorganization strategy should take into account the current performance and determine which characteristics of the organization should be modified in order to achieve a better performance. The general idea behind reorganization strategies, is that one should be able to evaluate the utility of the current state of affairs (that is, what happens if nothing changes), and the utility of future states of affairs that can be obtained by performing reorganization actions. The choice is then to choose the future with the highest utility. By applying the $perform$ function defined above, one is able to describe the cost of reorganization. This can be used to decide about when to reorganize. A possible strategy to decide whether to realize reorganization operation σ is if $perform(w,O,\sigma) + perform(w',O',D_O) \leq perform(w,O,D_O)$, where O' is the organization in w' resulting from the realization of σ on organization O in w. Informally, this strategy says that if the cost of reorganization plus the cost of achieving D_O by the reorganized organization is less than the cost of achieving D_O without reorganizing, then reorganization should be chosen.

As an example, consider a painters organization such that: $O = ((\{a,b,c,d\},(a \leq_O b,\ a \leq_O c))),D,S^0)$, where $D =$ (*sand-door* $\wedge$ *paint-door*), and $S^O = \{R_aD$, C_b*sand-door*, C_d*paint-door*$\}$. It can easily be seen that even though the agents in the organization possess the capabilities to realize the organizational objective, they cannot coordinate efficiently to get it done. Namely, there is no dependency relation to agent d that possesses a necessary capability to get the job done. A possible reorganization is represented by: $struct^+(O,(a \leq d))$. Moreover, by giving agent a the capability to realize this structuring operation, $C_a struct^+(O,(a \leq d))$ autonomic reorganization can be achieved, in the sense that an agent can itself change the organization design.

4. SIMULATIONS FOR ORGANIZATIONS

The model described in the previous section is used to specifiy different organization structures, agents' capabilities and environmental conditions. As already mentioned, in theory, given a certain environment and a set of agents with some characteristics, it should be possible to identify, which organizational form will perform the best according to different performance indicators. Ultimate aim of this research is to develop simulations in order to test this hypothesis. However, to collect quantitative data from the simulation one should overcome two obstacles. The first obstacle is to decide as to how an organization can be implemented into a working system since organizational concepts are open to interpretation. Second problem is to operationalize the development of the simulations such that the different organizational designs can be clearly specified and identified, and that the time and effort from design to implementation is minimalized.

We are developing an ontology of organizational designs that eventually, through appropriate semi-automated transformations, leads to an executable simulation of the organization. In a second stage, the output of the simulations is used to test our hypothesis. The framework we are developing consists of three steps. In the first step an ontology of organizational designs is developed, using RDF/RDFS. The second step involves marshalling ontology's instances corresponding to particular organization into JAVA class files that are used to generate the agents and environment objects to be used by the Repast engine to run the simulation. In the last stage the quantitative results generated by the simulation are analyzed. Concerning the agent architectures, we are using two different approaches. In the first, Repast agent are used which provide the facilities to deploy simulations with a large number of agents, but their cognitive capabilities are limited. On the second approach, we use the 3APL language for design of BDI agents to model the individual agents that interact in a Repast environment. In this way, we are able to analyze the cognitive processes of the agents, but current state of the implementation does not allow for the deployment of large number of agents. In the final version of this paper, we will provide more details concerning these two approaches.

The contribution of this work is threefold. Firstly, a model driven approach generates common ground and as such enables otherwise independent researchers to communicate with each other on a more formal basis, and the comparison and repeatability of experiments in a structured way. Secondly, it enables the non-experts to define and simulate an organization of agents without knowing theories in the agent research, RDF/RDFS, or even JAVA language. They may work at the conceptual level and generate the corresponding simulation results. And finally, these results will help (non)experts to determine the optimal organization model for specific environment. It is also important to note that this model can be extended intuitively via extending the conceptual level and fusing these changes into preceding steps.

5. CONCLUSIONS

Dynamic reorganization of agent systems is needed in order to enable systems to enforce or adapt to changes in the environment. This issue has been discussed by many researchers and several domain-oriented solutions have been proposed. However, such solutions often lack a formal basis. This prohibited the development of theories about reorganization and it prevented comparison or adaptation to other domains or situations. In this paper we presented a first attempt at a formal model for organizational concepts and the reorganization process, based on modal temporal logic. We have applied the proposed model to existing domain-specific systems proposed in recent literature. The current model is based on the notions of controllability, *stit*, attempt and responsibility. In the future, we will extend the model to include deontic concepts and their relation to the operational concepts presented in this paper. We are currently engaged in the full axiomatization of the logic presented here as well as an implementation for simulating the reorganization process. This simulation framework provides, on the one hand, a structured efficient way to deploy many different organizational and environment designs, by resourcing to the use of ontologies describing organization structures, environment characteristics and agent capabilities, and providing semi-automatic means to generate simulations from the ontology instances. On the other hand, the simulation looks both at systems of many agents, and at the cognitive characteristics of agents.

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