

Structural Evaluation of Agent Organizations

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ABSTRACT

A multi-agent system can be analyzed and specified as an organization consisting of roles and their relations. The performance of an organization depends on many factors among which the topology of its organizational structure, i.e., the set of relations holding between its roles. This short paper provides the sketch of quantitative methods for addressing the issue of the analysis, evaluation, and comparison of organizational structures. To this aim, quantitative concepts from graph theory are applied which deliver numerical analyzes of organizational structures. Here, an illustrative number of these concepts is sketched and their connection to properties that are commonly indicated as critical for organizations (robustness, flexibility and efficiency) is shown.

Categories and Subject Descriptors

F.2.11 [Distributed Artificial Intelligence]: Multiagent Systems—*Multiagent Organizations*; F.2.11 [Distributed Artificial Intelligence]: Coherence and Coordination

General Terms

Theory.

Keywords

Social structure, multi-agent organizations, graph theory.

1. INTRODUCTION

The notion of organization plays an important role in multi-agent systems, which is also reflected in many agent-oriented software methodologies (cf. GAIA, TROPOS). The performance of different organizations depends on organizations' characteristics such as robustness, flexibility, and efficiency. For example, hierarchies are known not to perform well in rapidly changing environments because of their poor flexibility. The paper is based on the intuition that a connection can be drawn between some of these characteristics and graph-theoretical properties of the structure of organizations. For example, flexibility depends on how strongly the roles in

the organization are connected with one another. We claim that an investigation of this connection is important for the development of appropriate methods for comparing and evaluating different types of organizations and their performances.

We believe that, in order to tackle the evaluation problem, “the space of organizational options must be mapped, and their relative benefits and costs understood” [5], and to provide such a “map” a rigorous analysis of organizational structure plays a crucial role. The perspective chosen consists thus in addressing the evaluation issue from a structural perspective, that is to say, analyzing the organizational structure of MAS and providing a way to rigorously describe the pros and cons of them which lie in their structures.

More concretely, it is known for instance that *flexibility* is an advantage of network types of organizations and a disadvantage of hierarchical ones in rapidly changing environments. The notion of flexibility, though complex and multi-faceted, can be definitely given an interpretation on the basis of merely structural aspects. Intuitively, the more abundant are the connections between the roles in the organization, the more flexible is the organization. The point is to relate the notion of flexibility to precise properties of the organizational structure. Given an organization, can it be said to be flexible? And to what degree? Is it more flexible than another one as far as structure is concerned? How can a designer foster flexibility in a MAS just working on its structure? These types of questions constitute, in a nutshell, the target of the present work.

2. ORGANIZATIONAL STRUCTURE

In [3] a view on organizational structure has been proposed, inspired by foundational work on the theory of organizations (see for instance [7]), which is based on the claim that organizations do not exhibit only one structural dimension, but rather a multiplicity of interrelated dimensions, the dimensions of *power*, *coordination* and *control*.

According to this view, an organizational structure consists actually of (at least) three different structures. A natural way of modeling this notion of organizational structure is via directed graphs, which we represent here as systems of relations.

DEFINITION 1. (Organizational structure)

An organizational structure *OS* is a tuple:

$$\langle Roles, R_{Pow}, R_{Coord}, R_{Contr} \rangle$$

where *Roles* is the finite set of roles, and $R_{Pow}, R_{Coord}, R_{Contr}$ are three irreflexive binary relations on *Roles* characterizing the *Power*, respectively, the *Coordination* and the *Control* structures.

For every R_k s.t. $k \in \{Pow, Coord, Contr\}$, we denote with $Roles_k$ the subset of *Roles* such that, if $(x, y) \in R_k$ then $x, y \in$

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$Roles_k$. In other words, sets $Roles_k$ denote the set of roles involved in the structural dimension k . Each digraph $\langle Roles_k, R_k \rangle$ in OS will be also referred to as the *structural dimension k of OS* .

Besides the representation of organizational structure as systems of three different relations, the aforementioned [3] proposes also a formal analysis of the effects that each of these relations has on the activities of the agents playing roles in the organization. Briefly, the *power structure* defines the task delegation patterns possible within the organization. The *coordination structure* concerns the flow of knowledge within the organization, and the *control structure* has finally to do with the task recovery functions of the organization. In other words, the existence of a power link between role a and role b implies that every delegation of tasks from agent a (agent enacting role a) to agent b (agent enacting role b) ends up in the creation of an obligation directed to agent b . If a and b are connected via a coordination link, then every information act from a to b ends up in creating the corresponding knowledge in agent b . Finally, a control link between a and b implies that agent a has to monitor the activities of agent b , possibly taking over the tasks of agent b which have not been accomplished.

3. MEASURING STRUCTURE

This section presents three examples of equations measuring specific graph-theoretical aspects of organizational structures: connectedness, economy and univocity.

Connectedness of an OS concerns how strongly roles are linked with one another within one of the structural dimensions k , or in other words, how much is the given structure split in fragments.

$$\text{Connect}_k(OS) = 1 - \frac{|\text{DISCON}_k|}{|Roles_k| * (|Roles_k| - 1)} \quad (1)$$

where $|R_k| > 0$ and DISCON_k is the set of ordered pairs (x, y) of $Roles_k$ s.t. there is neither a R_k -semipath¹ from x to y nor from y to x , i.e., the set of disconnected ordered pairs of the structural dimension $\langle Roles_k, R_k \rangle$. The condition $|R_k| > 0$ states that the structural dimension k does indeed exist. If the structure does not exist it cannot be measured. In practice, formula 1 measures how much that dimension is ‘not disconnected’. With respect to connectedness, an important notion is that of cutpoint or, in an organizational reading, *liason role* [4], i.e., a role whose removal decreases the connectedness of the structure.

The *economy* of a given OS expresses a kind of balance between keeping the structure connected and of minimizing the number of links:

$$\text{Economy}_k(OS) = 1 - \frac{|R_k| - (|Roles_k| - 1)}{|Roles_k| * (|Roles_k| - 1) - (|Roles_k| - 1)} \quad (2)$$

where $|R_k| > 0$. The equation is based on the intuition according to which the most ‘economical’ digraph of n points consists of $n-1$ links, i.e., the minimum number of links which is still sufficient to keep the digraph connected. Indeed, the nominator of the fraction, consists of the number of links in the structural dimension k which are in excess or in defect w.r.t. the optimum of $n-1$ links. The denominator denotes instead the absolute number of links in excess in k . If $|R_k| = n-1$ then the value of $\text{Economy}_k(OS)$ is optimal, i.e., equal to 1. The equation measures, therefore, how much k is ‘not expensive’ in terms of links, given that “links are not without cost in a social systems” [6]. Notice that $\text{Economy}_k(OS) = 1$ does

¹A R_k -semipath (of length n) is a sequence $\langle x_1, \dots, x_{n+1} \rangle$ of distinct elements of $Roles$ s.t. $\forall x_i \ 1 \leq i \leq n, (x_i, x_{i+1}) \in R_k$ or $(x_{i+1}, x_i) \in R_k$.

not imply $\text{Connect}_k(OS) = 1$, it does only imply that there are enough links in R_k for it to be possibly connected. If the existence of symmetric links in R_k is assumed, then $n-1$ links are clearly not enough any more for guaranteeing connectedness. On the other hand, notice also that $\text{Economy}_k(OS)$ can assume a value greater than 1. That indicates a sort of ‘over-efficiency’ of k . In this case, it is easy to see that, if $\text{Economy}_k(OS) > 1$ then $\text{Connect}_k(OS) < 1$. In other words, if the economy measure of OS is lower than the optimal value 1, then OS has more links than the ones necessary for OS to be connected. If the economy measure is instead higher than the optimal value 1, than there are in OS too few links for it to be connected.

The property of *univocity* expresses the tendency of an OS to display the absence of redundant links ending up in the same role. In other words, how many of those connections are such that no role has more than one incident link of the same structural dimension.

$$\text{Univocity}_k(OS) = \frac{|\text{IN}_k|}{|Roles_k|} \quad (3)$$

where $|R_k| > 0$ and IN_k denotes the set of roles x in $Roles_k$ which either have indegree equal to 1 in k or which are a source² of k or of some subgraphs of k . Intuitively, equation 3 measures how much a dimension k is univocal or “non ambiguous”. The most univocal structures are assumed to be either the ones in which every point, except the source, has one and only one incident link (like in trees), or the ones in which exactly all points have only one incident link (like in cycles). Univocity has to do with the level of conflict and redundancies of a given structure.

4. LINKING STRUCTURAL MEASURES TO ORGANIZATIONAL PROPERTIES

In this section we show how graph-theoretical properties of organizational structures can be used as a ground for establishing to what extent an organization exhibits key properties such as robustness, flexibility and efficiency.

Robustness. “Robustness is simply a measure of how stable the yield is in the face of anticipated risks. [...] *Adding robustness thus adds complexity*” [9].

A key “system characteristic” which should be preserved by any organization is the continuity of the task delegation chain. Failure of an agent enacting a role in this structure halts the delegation process only if the role it enacts is a *liason role*, i.e. a role the removal of which would result in a disconnected structure. So, the more alternative paths exist in the power graph the more robust is the organization: in a nutshell, low value for Univocity_{Pow} ³. Moreover, the coordination structure determines how well information can disseminate over the organization. For robustness it is important that information about failures can spread to the roles that can take responsible action. Also this structure can serve as a back up for a failure of the power structure. So, one can easily claim that the more connected (Connect_{Coord}) and less economical (Economy_{Coord}) the coordination structure is, the more robust the organization is.

To sum up, relevant structural measures for robustness are:

Economy_{Contr}	0	Univocity_{Pow}	0	Connect_{Coord}	1
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The 1 and 0 symbol indicate the value which is considered to maximize robustness with respect to that measure. For instance, the

²A *source* in $Roles$ is an element s s.t. $\forall d \in Roles$ with $d \neq s$ there exists a R_k -path from s to d .

³See also [2] for similar investigations on this issue.

maximum enhancement of robustness obtainable via modification of the connectedness measure is yielded by value 1.

Flexibility. “Flexible organizations are a looser co-operative association than classic hierarchical organizations. [...] Flexible organizations are continually in flux and are able to adapt in a flexible way to changing circumstances” [8].

As suggested by the above quote, an articulated power structure hinders flexibility constraining the distribution of tasks to predisposed patterns. In contrast, network organizations and teams, where no power structure exists, are commonly indicated as the paradigmatic example of flexible organizations. This suggests, for enhancing flexibility at the structural level, a low degrees of $Connect_{Pow}$. In absence of a power structure a coordination structure becomes essential because the knowledge concerning which agent might be capable to handle the new task needs to flow within the whole organization. The more roles are connected in this structure the more likely the right agent can be found to perform a new task. Connectedness together with a low level of economy ($Connect_{Coord}$ and $Economy_{Coord}$) are thus directly linked also to the enhancement of the flexibility of an organization.

To recapitulate, these are the relevant measures for flexibility:

$Connect_{Pow}$	0	$Connect_{Coord}$	1	$Economy_{Coord}$	0
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Again, 1 and 0 indicate the measures’ values which are considered to maximize flexibility.

Efficiency. According to [1], efficiency mostly refers to the amount of resources used by the organization to perform its tasks. All links in the different organizational structures incur a certain cost to be maintained. So, the less links there are, the more efficient is the organization. Notice, on the other hand, that the maximum efficiency would require a power structure with one unique source from which the delegation of subtasks propagates. So, a fragmented power structure is intuitively *over-efficient* since links would miss through which the delegation activity can take place. Because of this a hierarchical, tree-like, power structure covering all the roles seems to be the most efficient. In fact, the existence of a power structure means efficient distribution of tasks, and a tree is the most efficient structure to cover all roles. Such a structure exhibits value 1 for $Economy_{Pow}$. As to coordination and control, the economy measure ($Economy_{Coord}$ and $Economy_{Contr}$) should also be required to be optimal in order to minimize the amount of links. These are thus the measures we consider to be related to efficiency:

$Economy_{Pow}$	1	$Economy_{Contr}$	1	$Economy_{Coord}$	1
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Again, 1 and 0 indicate the measures’ values which are considered to maximize efficiency.

Needless to say, more different types of measures, which we can not expose here for space reasons, would provide a deeper analysis of the structural properties we touched upon.

5. TUNING STRUCTURAL MEASURES TO ORGANIZATIONAL PROPERTIES

At this stage the obvious question is whether organizations can be designed which maximize the adherence to all three properties at the same time. From a structural point of view and as intuition suggests, it is easy to show that this is not possible. Consider, for instance, the coordination structure. In fact, efficiency increases when $Economy_{Coord}$ approximates 1. Maximum robustness and flexibility both require $Economy_{Coord}$ equal to 0, while maximum

efficiency requires $Economy_{Coord}$ equal to 1:

	Robust	Flexible	Efficient
$Economy_{Coord}(OS)$	0	0	1

Intuitively, both robustness and flexibility increase the number of structural links and thus the costs of the organizational overhead, while efficiency reduces these overhead costs. Similar problems exist, for instance, for the power structure. The robustness criterion requires as many redundancies as possible, and therefore low levels of univocity, while flexibility demands the structure to be as small as possible and therefore with very low degrees of completeness. A number of similar incompatibilities can be detected and mathematically investigated.

Since it is not possible to maximize the adherence to all properties at the same time, the point becomes then to find suitable compromise solutions. An extensive analysis of the interdependencies between the various structural measures could provide useful insights on this type of issues.

6. CONCLUSIONS

The work addressed the issue of the influence of organizational structures on the performance of organizations, aiming at providing a rigorous method for analyzing, comparing and evaluating different types of structures. We proceeded as follows. First, making use of graph theory, we provided a number of meaningful measures for quantifying the adherence of organizational structures to specific structural features. Second, these measures have been used to ground a numerical analysis of the key organizational properties of robustness, efficiency and flexibility. Third, it has been shown that such an analysis pose the ground for an exact investigation of the extent to which those properties can conflict with each other, providing interesting information for a more aware design of organizational structures.

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