Semantical Concepts for a Formal Structural Dynamics of Situated Multiagent Systems

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Abstract. This paper introduces semantical concepts to support a formal structural dynamics of situated multiagent systems. Multiagent systems are seen from the perspective of the Population-Organization model, a minimal semantical model where the performance of organizational roles by agents, and the realization of organizational links by social exchanges between agents, are the key mechanisms for the implementation of an organization structure by a population structure. The structural dynamics of a multiagent system may then be modelled as a set of transformations on the system's overall population-organization structure. We illustrate the proposed approach to structural dynamics by introducing a small set of operational rules for an exchange value-based dynamics of organizational links. The paper sets the stage for further work on structural dynamics where other structural elements, besides organizational links, may be taken into account.

1 Introduction

PopOrg, a minimal population-organization based model, was introduced in [1] in order to support the study of the structural dynamics of multiagent systems (MAS). Both time-invariant and time-variant versions of the model were introduced, but no specific mechanism was presented to account for any possible structural dynamism.

In this paper, we improve the above mentioned work by refining that model with the notion that social interactions are exchanges performed between agents. Also, we present an exchange value-based mechanism able to account for some aspects of the structural dynamics of multiagent systems. As an illustration of the possibilities allowed by the model, we combine the two ideas to define a simple set of operational rules for an elementary exchange value-based dynamics of organizational links.

The work sets the stage for further studies on the structural dynamics of multiagent systems by establishing the basis of a mechanism where further aspects of the structural dynamics of such systems may be considered, besides the dynamics of links.

We remark that the paper is based on a distinction between the notions of intensional and extensional descriptions of systems: intensional descriptions deal with subjective aspects pertaining to the internal functioning of the agents that operate in a system (like norms, values, etc.), while extensional descriptions deal with objective aspects pertaining to the external functioning of those agents (like actions performed, objects exchanged, etc.).

The main concerns of the paper are, thus, an extensional description of the structural dynamics of multiagent systems organizations, and a possible way to articulate such extensional dynamics with the intensional aspect of the exchange values involved in the interactions between the agents that participate in the organizations.

On the other hand, we note that the process model that underlies the structural dynamics of the population-organizational model [1] is similar to the general signal-based denotational model that underlies some declarative languages devised to specify real-time reactive systems [2]. This encourages the view that the PopOrg model may suitably be construed as an adequate model for multiagent systems situated in environments presenting real-time constraints.

In fact, it is only natural to expect that it is precisely in the case of situated multiagent systems that the issues of structural dynamics arise crucially (both because of the pressures for the adaptation of the system to the variations in the environment and because of the values that agents may assign to the concrete resources made available to them by the environment – see Sect. 5, on related works).

The paper is organized as follows. In Sec. 2, we revisit the PopOrg model, refining its notion of interaction through a general notion of social exchange. In Sec. 3, we summarize the particular exchange values approach to social interactions [3] that we adopt, reviewing its notion of exchange value and its model of social exchange.

Section 4 illustrates the general purpose of the paper by joining the revisited PopOrg model with the adopted system of social exchanges, allowing for a simple mechanism able to support a preliminary model of exchange value-based dynamics of organizational links.

Section 5 summarizes related work. Section 6 brings the Conclusion and explores further aspects of the proposal.

A technical remark: we use the following coordinate-wise notation, when dealing with vectors (n-tuples) of sets (assuming $expr_0 \Leftrightarrow expr_1 \wedge \ldots \wedge expr_n$):

$$(X_1, \ldots, X_n) \subseteq (Y_1, \ldots, Y_n) \equiv_{def} X_i \subseteq Y_i, i = 1, \ldots n. \qquad (1)$$

$$\bigcup \{(X_1, \ldots, X_n) \mid expr_0\} \equiv_{def} (\cup \{X_1 \mid expr_1\}, \ldots, \cup \{X_n \mid expr_n\}) \quad (2)$$

2   The Population-Organization Model

The Population-Organization model of multiagent systems, introduced in [1], emphasizes the modelling of systems composed of a small group of agents, adopting an interactionist point of view [3,4].

In such model, the organizational structure of a system is implemented by the system's population of agents through two main mechanisms: the assignment of organizational roles to agents, and the realization of organizational links between roles by the social exchanges that are established between the agents that perform those roles.

Of course, in such model, the central components of the structural dynamics of the systems are the operations of creation and deletion of elements like organizational roles, organizational links and exchange processes, as well as the agents entering and leaving the system.

2.1   The Time-Invariant Population-Organization Model

The time-invariant Population-Organization model, $PopOrg = (Pop, Org, imp)$, is construed as a pair of structures, the population structure Pop and the organization structure Org, together with an implementation relation imp.

The Time-Invariant Population Structure. The *population* of a multiagent system consists of the set of agents that inhabit it. The *population structure* of a multiagent system is its population set together with the set of all behaviors that the agents are able to perform, and the set of all exchange processes that they can establish between them (for simplicity, we consider only pairwise exchanges).

Let T be a discrete sequence of time instants. A *time-invariant population structure* is a tuple

$$Pop = (Ag, Act, Bh, Ep, bc, ec) \tag{3}$$

where:

- Ag is a finite non-empty set of agents, called the *population* of the system;
- Act is the finite set of all *actions* (communication actions and actions on concrete objects of the environment) that may be performed by the agents of the system;
- $Bh \subseteq [T \rightarrow \wp(Act)]$ is the set containing all possible agent behaviors, modeled as functions that specify, for each time $t \in T$, a set of actions $X \in \wp(Act)$ that an agent may perform at that time, each behavior determining a sequence of sets of actions available for the agents to perform in the system;
- $Ep \subseteq [T \rightarrow \wp(Act) \times \wp(Act)]$ is the set containing all possible *exchange processes* that two agents may perform in the system, each process given by a function that specifies, for each $t \in T$, a pair of set of actions $(X_1, X_2) \in \wp(Act) \times \wp(Act)$, determining a sequence of exchanges available for any two agents to perform, by executing together or interleaving appropriately their corresponding actions;
- $bc : Ag \rightarrow \wp(Bh)$ is the *behavioral capability* function, such that for each agent $a \in Ag$, the set of all behaviors that a is able to perform in the system is $bc(a)$;
- $ec : Ag \times Ag \rightarrow \wp(Ep)$ is the *exchange capability* function, such that for each pair of agents $a_1, a_2 \in Ag$, the set of all exchange processes that a_1 and a_2 may perform between them is $ec(a_1, a_2)$;
- $\forall a_1, a_2 \in Ag \ \forall e \in ec(a_1, a_2) \ \forall t \in T :$

$$Prj_1(e(t)) \subseteq \bigcup \{b(t) \mid b \in bc(a_1)\} \ \wedge \ Prj_2(e(t)) \subseteq \bigcup \{b(t) \mid b \in bc(a_2)\},$$

  where Prj_1, Prj_2 are projection functions, so that the agents' exchange capabilities are constrained by their joint behavioral capabilities.

Given $t \in T$ and $a \in Ag$, we note that $bc(a)(t) = \{act \mid act \in b(t), b \in bc(a)\}$ is the set of all possible actions that agent a may perform at time t, given its behavioral capability $bc(a)$. We also note that, in general, the exchange capability $ec(a_1, a_2)$ of a pair of agents $a_1, a_2 \in Ag$ should be deducible from their respective behavioral capabilities $bc(a_1)$ and $bc(a_2)$, and from any kind of restriction that may limit their set of possible exchanges (e.g., social norms, inherited habits, etc.), but since we are

presenting an extensional model where such intensional, subjective restrictions take no part, it is sensible to include ec explicitly in the description of the population structure.

By the same token, the behavioral capability $bc(a)$ of an agent $a \in Ag$ should be deducible from any *internal description* of a where its set of behaviors is constructively defined, but since we are taking an external (observational) point of view of the agents, we include bc explicitly in the model.

The Time-Invariant Organization Structure. The *time-invariant organization struc-ture* of a time-invariant population structure $Pop = (Ag, Act, Bh, Ep, bc, ec)$ is a structure

$$Org = (Ro, Li, lc) \tag{4}$$

where:

- $Ro \subseteq \wp(Bh)$ is the set of *roles* existing in the organization, a role being given by a set of behaviors that an agent playing the role may have to perform;
- $Li \subseteq Ro \times Ro \times Ep$ is the set of *links* that exist in the organization between pairs of roles, each link specifying an exchange process that the agents performing the linked roles may have to perform;
- $lc : Ro \times Ro \rightarrow \wp(Li)$ is the link capability of the pairs of roles, that is, the set of links that the pairs of roles may establish between them;
- $\forall l \in Li \ \exists r_1, r_2 \in Ro : l \in lc(r_1, r_2)$, that is, every link has to be in the link capability of the two roles that it links.

Clearly, the PopOrg model adopts a relational, interactionist approach to organiza-tions [3,4].

The Time-Invariant Implementation Relation. Population and organization struc-tures are formally defined in a quite independent way. A population structure induces no more than a loose restriction on the set of organization structures that may be im-posed on it: the behavioral capability function bc constrains the set of possible roles that an agent may have in any possible organization and, indirectly, the set of possible exchange processes in which it may participate, thus, also the set of possible organiza-tional links that it may have with any other agent in a system.

The fact that a given organization structure is operating over a population structure, influencing the set of possible exchanges that the agents may have between them, is represented by an *implementation relation* $imp \subseteq (Ro \times Ag) \cup (Li \times Ep)$, where

- $Ro \times Ag$ is the set of all possible *role supports*, i.e., the set of all possible ways of assigning roles to agents, and if $(r, a) \in imp$, then the social role r is supported by agent a, so that a is said to play role r (possibly in a shared, non-exclusive way) in the given organization;
- $Li \times Ep$ is the set of all possible *link supports*, i.e., the set of all possible ways of supporting links, so that if $(l, e) \in imp$, link l is said to be supported (in a possibly shared, non-exclusive way) by the exchange process e, and so indirectly supported by the agents that participate in e and that play the roles linked by l.

We note that an organization implementation relation imp does not need to be one-to-one: many roles may be assigned to the same agent, many agents may support a

given role, many links may be supported by a given exchange process, many exchange processes may support a given link. Moreover, this relation may be partial: some roles may be assigned to no agent, some agents may be have no roles assigned to them, some links may be unsupported, some exchange processes may be supporting no link at all.

The agents that have at least one role assigned to them are said to constitute the *support* of the organization in the population. Agents that do not belong to an organization's support may interfere with the functioning of that organization by influencing the behaviors of the supporting agents.

This flexibility is important when defining the structural dynamics of MAS, because it allows for the definition of "improper" structural states, i.e., structural states where the system's organization is not properly implemented by the sytem's population, which is relevant for the end goal of dealing with the concept of *organizational integrity* [1].

A *proper implementation relation* is an implementation relation that respects organizational roles and organizational links by correctly translating them in terms of agents, behaviors and exchange processes. Given an implementation relation $imp \subseteq (Ro \times Ag) \cup (Li \times Ep)$, a social role $r \in Ro$ is said to be *properly implemented* by a subset $A \subseteq Ag$ of agents whenever the following conditions hold:

(i) $\forall a \in A : (r, a) \in imp$, i.e., all agents in A participate in the implementation of r;

(ii) $\forall t \in T : \bigcup \{b(t) \mid b \in r\} \subseteq \bigcup \{b'(t) \mid b' \in bc(a), a \in A\}$, i.e., the set of behaviors required by r may be performed by the agents of A (in a possibly shared, non-exclusive way).

A link $l = (r_1, r_2, e) \in Li$ is *properly implemented* by a subset $E \subseteq ec(a_1, a_2)$ of the exchange processes determined by the exchange capability of two agents a_1, a_2, whenever the following conditions hold:

(i) $\forall e' \in E : (l, e') \in imp$, i.e., every exchange process in E helps to support the link;

(ii) r_1 e r_2 are properly implemented by the agents a_1 and a_2, respectively; and

(iii) $\forall t \in T : e(t) \subseteq \bigcup \{e'(t) \mid e' \in E\}$, i.e., the exchange process required by l may be performed by the ones of E (in a possibly shared, non-exclusive way).

A time-invariant population-organization structure $PopOrg = (Pop, Org, imp)$ is *properly implemented* if and only imp is a proper implementation relation.

2.2 The Time-Variant Population-Organization Model

Time-Variant Population Structures. Time-variant structures change as time goes by. There are three main kinds of possible changes in the momentary population structure $Pop = (Ag, Act, Bh, Ep, bc, ec)$ of a multiagent system: (p1) a change in the behavioral capability $bc(a)$ of an agent $a \in Ag$; (p2) a change in the exchange capability $ec(a_1, a_2)$ of a pair of agents $(a_1, a_2) \in Ag \times Ag$; (p3) a change in the population Ag.

Changes of the kind (p1) may be due either to internal changes in the agent or to changes in the set of passive objects (e.g., tools) with which the agent operates. Changes of the kind (p2) may be due either to changes in the behavioral capability of one of the agents, to changes in the exchange medium (e.g., communication channel) used by the

agents, or to changes in some social norm that regulates the exchanges. Changes of the kind (p3) are due to agents entering or leaving the system.

Let T be the time structure, $\mathbf{Ag}$ and $\mathbf{Act}$ be universes of agents and actions, respectively, and $\mathbf{Bh}$ and $\mathbf{Ep}$ universes of behaviors and exchange processes defined over $\mathbf{Ag}$ and $\mathbf{Act}$, in a way similar to that in Sect. 2.1(3). A *time-variant population structure* is a structure $POP = (AG, ACT, BH, EP, Bc, Ec)$ where, for all $t \in T$:

- $AG^t \in \wp(\mathbf{Ag})$ is the system's population, at time t;
- $ACT^t \in \wp(\mathbf{Act})$ is the set of possible agent actions, at time t;
- $BH^t \in \wp(\mathbf{Bh})$ is the set of possible agent behaviors, at time t;
- $EP^t \in \wp(\mathbf{Ep})$ is the set of possible exchange processes between agents, at time t;
- $Bc^t : AG^t \rightarrow \wp(BH^t)$ is the behavioral capability function of agents, at time t;
- $Ec^t : AG^t \times AG^t \rightarrow \wp(EP^t)$ is the exchange capability function, at time t.

The state at time t of a time-variant population structure, denoted by $POP^t = (AG^t, ACT^t, BH^t, EP^t, Bc^t, Ec^t)$, fixes the population of the system, the set of possible behaviors of each agent and the set of possible exchange processes between each pair of agents, but not the behaviors and exchange processes themselves, which at each time will be chosen from among those possibilities according to the particular internal states of the agents, and the particular states of the (social and physical) environment. Note, however, that the intensional, subjective reasons for such choices are not modelled in the extensional PopOrg model.

Time-Variant Organization Structures.   There are five main kinds of possible changes in a momentary organization structure $Org = (Ro, Li, lc)$: (o1) a change in a role $r \in Ro$; (o2) a change in a link $l \in Li$; (o3) a change in the set of roles Ro; (o4) a change in the set of links Li; (o5) a change in the link capability lc of the pairs of roles.

A change of kind (o1) may be due, e.g., to a change in the behavior of a certain number of agents performing the role. A change of the kind (o2) may be due, e.g., to a change in an exchange process that supports the link. Changes of the kind (o3) are either the appearance or the disappearance of roles in the system. Changes of the kind (o4) are either the appearance or to the disappearance of organizational links in the system. A change of kind (o5) may be due, e.g., to a redistribution of the set of links between organization roles.

All such changes may be due to the so-called "reorganization operations" of multiagent systems (see Sec. 5, on related works). The reasons for such operations are essentially of an intensional nature and, thus, are not explicitly represented in the extensional PopOrg model (but their realizations as behavioral processes, and their possible extensional effects, may be explicitly modelled).

We note that Sect. 4 of this paper is mainly concerned with changes of kind (o4), that is, changes in the set of links of an organization structure.

Let T be the time structure, and $\mathbf{Ro} \subseteq \wp(\mathbf{Bh})$ and $\mathbf{Li} \subseteq \mathbf{Ro} \times \mathbf{Ro} \times \mathbf{Ep}$ be the universes of roles and links, respectively. The *time-variant organization structure* of a time-variant population structure $POP = (AG, ACT, BH, EP, Bc, Ec)$ is a structure $ORG = (RO, LI, Lc)$, where for all $t \in T$:

- $RO^t \in \wp(\mathbf{Ro})$ and $LI^t \in \wp(\mathbf{Li})$ are, respectively, the set of possible roles and the set of possible links at time t;
- $Lc^t : RO^t \times RO^t \to \wp(LI^t)$ is the link capability function at time t.

For each $t \in T$, the organization state $ORG^t = (RO^t, LI^t, Lc^t)$ fixes the sets of possible roles RO^t, links LI^t and link capability function Lc^t that the system may have at that time. Note that a time-invariant organization structure may be modelled as a constant time-variant organization structure.

Time-Variant Implementation Relations. As a consequence of any change (p1)-(p3) or (o1)-(o5), the implementation relation imp may be changed either (r1) in the way it relates roles and agents or (r2) in the way it relates links and exchange processes. Besides being changed in its mapping, imp may be changed also in its properness.

Let $POP = (AG, ACT, BH, EP, Bc, Ec)$ be a time-variant population structure and $ORG = (RO, LI, Lc)$ its time-variant organization structure. A *time-variant implementation relation* for ORG over POP is a time-indexed set of implementation relations IMP, with $IMP^t \subseteq (RO^t \times AG^t) \cup (LI^t \times EP^t)$. A *time-variant population-organization structure* is a structure $POPORG = (POP, ORG, IMP)$, where

- $POP = (AG, ACT, BH, EP, Bc, Ec)$, $ORG = (RO, LI, Lc)$ and IMP are, respectively, a time-variant population structure, a time-variant organization structure, and a time-variant implementation relation, as defined above;
- at each $t \in T$, the state of $POPORG$ is given by $POPORG^t = (POP^t, ORG^t, IMP^t)$, where $POP^t = (AG^t, ACT^t, BH^t, EP^t, BC^t, EC^t)$ and $ORG^t = (RO^t, LI^t, Lc^t)$ are such that $IMP^t \subseteq (RO^t \times AG^t) \cup (LI^t \times EP^t)$.

We note that this definition does not guarantee that the relation IMP is proper at each time. That is, we assume that time-variant population-organization structures may pass through structural states where the population improperly implements the organization.

Multiagent Systems with Structural Dynamics. The *structural dynamics* of a multiagent system [1] is the dynamics that deals with the way the structure of the system varies in time, thus, it is the dynamics of the system's population and organization.

Let $\mathbf{PopOrg} = (\mathbf{Pop}, \mathbf{Org}, \mathbf{imp})$ be the universe of all possible time-invariant population-organization structures, with $\mathbf{Pop} = (\mathbf{Ag}, \mathbf{Act}, \mathbf{Bh}, \mathbf{Ep}, \mathbf{bc}, \mathbf{ec})$, $\mathbf{Org} = (\mathbf{Ro}, \mathbf{Li}, \mathbf{lc})$ and $\mathbf{imp} \subseteq (\mathbf{Ro} \times \mathbf{Ag}) \cup (\mathbf{Li} \times \mathbf{Ep})$ being the universes of all possible time-invariant population structures, organization structures and implementation relations, respectively.

A *multiagent system with dynamic structure* is a structure $MAS = (\mathbf{PopOrg}, D)$ where, for each $t \in T$, $D^t \subseteq \mathbf{PopOrg} \times \mathbf{PopOrg}$ is the system's *overall structural dynamics*, such that for any structural state $PopOrg \in \mathbf{PopOrg}$, at time $t \in T$, there is a set of *possible next structural states*, denoted by $D^t(PopOrg) \subseteq \mathbf{PopOrg}$.

Given a particular initial population-organization structure $PopOrg^{t_0}$, the evolution of the system is given by a time-variant population-organization structure $POPORG$, where it holds that $POPORG^{t+1} \in D^t(POPORG^t)$, for any $t \in T$.

The choice of the particular next structural state $POPORG^{t+1}$ that will be assumed by the MAS at time $t + 1$ is made, at time $t \in T$, on the basis of various intensional,

subjective factors extant in the system, like, e.g., preferences of agents, social norms, political powers, etc.

In particular cases, it may happen that the system's overall structural dynamics may be separated into three coordinated sub-structural dynamics $D^t = D_P^t \times D_O^t \times D_I^t$: the *population* dynamics $D_P^t \subseteq \mathbf{Pop} \times \mathbf{Pop}$, the *organizational* dynamics $D_O^t \subseteq \mathbf{Org} \times \mathbf{Org}$, and the *implementation* dynamics $D_I^t \subseteq \mathbf{imp} \times \mathbf{imp}$.

In such special cases, the coordination between the system's overall dynamics and the three sub-structural dynamics may be given compositionally by:

$$(Pop', Org', imp') \in D^t((Pop, Org, imp)) \Leftrightarrow$$
$$Pop' \in D_P^t(Pop) \ \wedge \ Org' \in D_O^t(Org) \ \wedge \ imp' \in D_I^t(imp).$$

3   Systems of Exchange Values

In this section, we introduce one of the possible intensional, subjective factor that may influence the evolution of the dynamical structure of a multiagent system, namely, the system of exchange values with which the agents may assess the quality of the exchanges they are having in the system. We adopt here one particular model of system of exchange values [3], which we have used in previous works (e.g., [5]).

This exchange value-based approach to social interactions (cf. also [4]) considers that every social interaction is an exchange of services between the agents involved in it. Exchange values are, then, the values with which agents evaluate the social exchanges they have with each other.

A *service* is any action or behavior that an agent may perform, which influences positively (respect., negatively) the behavior of another agent, favoring (respect., disfavoring) the effort of the latter to achieve a goal. The *evaluation* of a service involves not only affective and emotional reactions, but also comparisons to social standards. Typical evaluations are expressed using *qualitative values* such as: good, very good, bad, very bad, etc. So, they are of a neatly subjective, qualitative, intensional character.

With those evaluations, a qualitative economy of exchange values arises in the social system. Such qualitative economy requires various rules for its regulation. Most of those rules are either of a moral or of a juridical character [3].

Exchange behaviors between two agents α and β can be defined as sequences of exchange steps performed between them. Two kinds of exchange steps are identified [3], called $I_{\alpha\beta}$ and $II_{\alpha\beta}$. Steps of the kind $I_{\alpha\beta}$ are steps in which agent α takes the initiative to perform a service for agent β, with qualitative *cost* (investment) $r_{I\alpha\beta}$. Subsequently, β receives the service, and gets a *benefice* (satisfaction) of qualitative value $s_{I\beta\alpha}$.

If β was to pay back α a return service immediately, he would probably try to "calibrate" his service so that it would have cost r equal to $s_{I\beta\alpha}$, so that α would get a return benefice with value s equal to $r_{I\alpha\beta}$, in order for the exchange to be fair (if the two agents were prone to be fair in their exchanges). The definition of exchange steps assumes, however, that the return service will not be performed immediately, so that a kind of bookkeeping is necessary, in order for the involved values not to be forgotten.

That is the purpose of the two other values involved in the exchange step: $t_{I\beta\alpha}$ is the *debt* that β assumes with α for having received the service and not having paid it back yet; , $v_{I\alpha\beta}$ is the *credit* that α gets on β for having performed the service and not having being paid yet. A *fair* exchange step ([3] calls it an *equilibrated* exchange step) is one where all the involved values are qualitatively equal: $r_{I\alpha\beta} \approx s_{I\beta\alpha} \approx t_{\beta\alpha} \approx v_{I\alpha\beta}$.

To take account of differences between qualitative exchange values, such values are assumed to be comparable with respect to their relative qualitative magnitudes. That is, if EV is the set of qualitative exchange values, it is assumed that values in EV can be compared by an order relation $\preceq$, so that $(EV, \preceq)$ is a (partially) ordered set. Thus, e.g., if it happened that $s_{I\beta\alpha} \preceq r_{I\alpha\beta}$, then agent α made an investment, during his service, that was greater than the benefice that agent β got from it.

An exchange step of kind $II_{\alpha\beta}$ is performed in a different way. In it, agent α charges agent β for a credit with qualitative value $v_{II\alpha\beta}$, which he has on β. Subsequently, β acknowledges a debt with value $t_{II\beta\alpha}$ with α, and performs a return service with value $r_{II\beta\alpha}$. In consequence, α gets a return satisfaction with value $s_{II\alpha\beta}$. Fairness for $II_{\alpha\beta}$ steps is defined similarly as for $I_{\alpha\beta}$ steps.

It is assumed that exchange values can be qualitatively added and subtracted from each other, so that *balances of temporal sequences* of exchange steps can be calculated. Besides the above mentioned conditions, one further condition is required in order that a sequence of exchange steps be fair: $\sum v_{II\alpha\beta} \approx \sum v_{I\alpha\beta}$, that is, α should charge a sum of credits which is exactly the total credit he has on β, no more, no less.

In summary, [3] introduces a qualitative algebra with which one can model and analyze social exchanges between agents, determining in a qualitative way the degree of fairness of those exchanges. Note that such algebra operates on 8-tuples of the form

$$(r_{I\alpha\beta}, s_{I\beta\alpha}, t_{I\beta\alpha}, v_{I\alpha\beta}, v_{II\alpha\beta}, t_{II\beta\alpha}, r_{II\beta\alpha}, s_{II\alpha\beta}). \tag{5}$$

4 Exchange Value-Based Dynamics of Social Links

This section illustrates one of the possible uses of our extensional model for the structural dynamics of organizations of MAS by showing how it can support the intensional rules of an elementary exchange value-based dynamics of organizational links.

4.1 An Elementary Exchange Value-Based Dynamics of Social Links

Other things being equal, the fact that a sequence of exchange steps between two agents is fair, or not, may be a determinant factor in the attitude of those agents toward the possibility of the continuation of the interaction. That is, given enough chances, self-interested agents will tend to establish continued exchanges only with agents from whom they may establish exchanges that are at least fair, if not beneficial, for them [4].

Particular personality traits and various social factors (power, prestige, etc.), however, may interfere with self-interests and lead the agents to seek social exchanges that happen to be far from equilibrium ([5] illustrates this in the context of multiagent systems).

To simplify the issues, we assume that a MAS of self-interested agents adheres to the following rationales concerning the dynamics of organizational links:

- *exchange value-based rationale for the* creation *of an organizational link*: a new organizational link in the MAS is created as soon as an exchange process is positively assessed by the agents playing the roles that will be linked by the link (the exchange process is said to be *officially incorporated* as a link into the organization);
- *exchange value-based rationale for the* destruction *of an organizational link*: a link stops to exist in the multiagent system as soon as the balance of exchange values involved in the exchange processes that implement the link stops to be beneficial to any of the agents performing the roles linked by link (the exchange process is said to be *officially excluded* from the organization of the multiagent system).

We leave open for the agents to apply subjective criteria to determine if any of the conditions mentioned in the above rationales "really" occurred or not. If the social organization has a central control, able to discover at each moment which are the links that the agents would like to establish next between them, then it is up to that central control to determine if enough has been observed in order to create or destroy a link in the organization. If the agents are autonomous, then it is up to them to determine that.

If the agents are autonomous, they may disagree on which links should be created or destroyed. In this case, the dynamics of links is open to argumentation and negotiation between them. Thus, for organizations based on autonomous agents, no general method can be given for the determination of how the dynamics of links should evolve. Such dynamics is tightly coupled to the personality traits and social biases that the agents may show with respect to the evaluation of their exchanges.

On the other hand, for organizations where the definitions of the roles prescribe not only the behaviors that the agents playing such roles must have, but also the criteria with which they should evaluate the interactions in which they get involved, it is possible to derive the dynamics of links from the evaluation rules embedded in the roles.

The former case characterizes organizations where the dynamics of links can only be established (at best) *a posteriori*, i.e., after knowing which agent is playing which role in the organization. The latter case characterizes more manageable organizations, where the dynamics of links can be established by an *a priori* analysis of the roles.

4.2   The Rules of the Elementary Exchange Value-Based Dynamics of Links

We introduce, now, a minimal set of intensional rules for the exchange value-based dynamics of organizational links in multiagent systems, formalizing the rationales for self-interested agents exposed above.

For simplicity, we consider the case where the organization structure is time-variant, the population structure is time-invariant, each role is implemented by just one single agent, and each link implemented by just one single exchange process.

Let $Pop = (Ag, Act, Beh, Ep, bc, ec)$ be a *time-invariant* population structure, $ORG = (EP, RO, LI)$ be a *time-variant* organization structure implemented by Pop, and let IMP be the *time-variant* implementation relation. They constitute a time-variant population-organization structure $PopORG = (Pop, ORG, IMP)$, which is assumed here to vary just in the set of organizational links, and in their implementations.

There may happen two kinds of changes in the set of links LI^t, at the time $t+1 \in T$: (1) either a new link l is created, so that $LI^{t+1} = LI^t \cup \{l\}$; or (2) a link l is removed from LI^t, so that $LI^{t+1} = LI^t - \{l\}$.

The problem we face here is that of the formalization of the conditions under which, at a moment $t + 1$, a link l is added to (or removed from) the set of links LI^t.

Let $EV = (EV, \preceq)$ be the scale of exchange values used by agents $a_1, a_2 \in Ag$ to evaluate their exchanges, and $BEV = EV^8$ be the set of 8-tuples of exchange values that represent balances of exchange values, defined in Sect. 3(5). Let $bal : Ag \times Ag \times Ep \times T \rightarrow BEV$ be so that $bal(a_1, a_2, e, t)$ is the balance of exchange values that agents a_1 and a_2 have accumulated, at time t, along the exchanges that they performed through the exchange process $e \in Ep$.

We assume that each of the agents $a_1, a_2 \in Ag$ is able to perform an analysis of every possible balance $bal(a_1, a_2, e, t)$ of exchange values that may arise between them, and judge if that balance is beneficial, fair, or harmful for himself. That is, we assume that there exists a (subjective) judgement function $jdg^t(a, bal(a_1, a_2, e, t)) \in \{+1, 0, -1\}$, which we may write as $a \models^t bal(a_1, a_2, e, t) \approx v$, for $v \in \{+1, 0, -1\}$ and $a \in \{a_1, a_2\}$.

Then, the dynamics of organizational links in the Population-Organization model of multiagent systems with self-interested agents is determined by a set of operational rules containing at least the rules introduced below.

Let $[\tau, \tau'], [\tau, \tau') \subseteq T$ respectively be a closed and a right end-open interval of time, with $\tau < \tau'$. Let $a_1, a_2 \in Ag$ be agents respectively playing roles $r_1, r_2 \in Ro$ during the interval $[\tau, \tau']$, that is, $(r_1, a_1), (r_2, a_2) \in IMP^t$, for all $t \in [\tau, \tau']$.

Consider a link $l \in \mathbf{Li}$ between roles $r_1, r_2 \in \mathbf{Ro}$ such that $l \notin LI^t$, for $t \in [\tau, \tau')$, and an exchange process $e \in Ep$ that may possibly support l during the interval $[\tau, \tau')$. Let IMP^t and LI^t be fixed, for all $t \in [\tau, \tau')$. Assume also that $l \in Lc^t(r_1, r_2)$, for all $t \in [\tau, \tau']$.

Let $jdg^t(a, bal(a_1, a_2, e, [\tau, \tau']))$ denote the judgement, at $t \in T$, of the balance of values accumulated in the interval $[\tau, \tau'] \subseteq T$, and let $jdg^t(a, bal(a_1, a_2, e, [\tau, \tau'])) \succeq 0$ mean $jdg^t(a, bal(a_1, a_2, e, [\tau, \tau'])) \approx 0 \vee jdg^t(a, bal(a_1, a_2, e, [\tau, \tau'])) \approx +1$.

In this context, the following rule, controlling the introduction of l in $LI^{\tau'}$, is compatible with an exchange value-based account of the link dynamics of the considered system:

$$\frac{a_1 \models^{\tau'} bal(a_1, a_2, e, [\tau, \tau']) \succeq 0 \qquad a_2 \models^{\tau'} bal(a_1, a_2, e, [\tau, \tau']) \succeq 0}{LI^{\tau'} = LI^\tau \cup \{l\} \ \wedge \ IMP^{\tau'} = IMP^\tau \cup \{(l, e)\}} \ LI_{intro(l)}$$

Analogously, consider an exchange process $e \in Ep$ that supported a link $l \in LI^t$ between roles $r_1, r_2 \in RO^t$ during the interval $[\tau, \tau')$, and that IMP^t and LI^t are fixed, for all $t \in [\tau, \tau')$. Assume that $l \in Lc^t(r_1, r_2)$, for all $t \in [\tau, \tau']$. In this context, for $a \in \{a_1, a_2\}$, the following rule, controlling the elimination of l from LI^τ, is compatible with an exchange value-based account of the link dynamics of the considered system:

$$\frac{a \models^{\tau'} bal(a_1, a_2, e, [\tau, \tau']) \approx -1}{LI^{\tau'} = LI^\tau - \{l\} \ \wedge \ IMP^{\tau'} = IMP^\tau - \{(l, e)\}} \ LI_{elim(l,a)}$$

Note, on the other hand, that the two rules should to be subject to the *proviso* that the interval $[\tau, \tau']$ is large enough to allow the agents to make sound judgements, the notion of "large enough" depending on intensional factors outside de PopOrg model.

As an aside, we claim that $\{LI_{intro(l)}, LI_{elim(l,a)}\}$ is the minimal set of rules upon which should lie any exchange value-based dynamics of organizational links, in the PopOrg model, when self-interested agents are considered. Of course, more realistic examples of link dynamics would require additional rules to take care of more complex situations, e.g., rules to deal with links implemented by two or more exchange processes.

On the other hand, issues such as the protection of the organization against malicious agents (e.g., agents that provoke the elimination of links by providing a negative evaluation to every exchange), are issues that concern intensional norms related to the security of the organization, which should be reflected in the extensional rules describing the dynamics of the organization, but which should not be dealt with initially at this extensional level.

5   Related Works

The investigation of the organizational dynamics of agent systems goes back to at least [6], where the dynamics concerned the coordination of agents in distributed problem solving systems.

The clear distinction between an organization structure and a population structure in MAS seems to have been first introduced in the PopOrg model [1], and subsequently adopted in some MAS organization models (e.g., [7]).

The main reason for the need of a structural dynamism in a MAS organization, and the corresponding changes in the organizational structure, have traditionally been considered to be the demands of the environment and the requirements of adaptability that they imply (e.g., [8]).

However, the PopOrg model was defined so that *internal reasons* for the dynamism of the organizational structures could also be considered in a suitable way, for instance, in the exchange value-based way proposed in the paper. The issue of the *internal forces* that may motivate a dynamics of organizational structure has also been addressed in [9].

The option for the set-theoretic language to model the dynamics of organizational structures, including the option for the signal-based notion of behaviors and interactions, adopted in the PopOrg model, contrasts with the more usual option for logic-based languages (e.g., [10]), and is justified by the goal of a direct formalization of the concrete features that constitute the PopOrg model, as a particular minimal organizational model.

Also, the option for the set-theoretic formalism is related to the choice of placing the extensional aspects of the organizational dynamics in the center of the PopOrg model, leaving the intensional (rule-based, subjective) aspects, including those expressed by the *organizational rules* introduced in [7], to a second layer – where they are introduced in specialized refinements of the model, as the need arises in particular applications.

For instance, we did not place at the core of the PopOrg model any of the various available methods for reorganization, such as role reallocation (e.g., [11,9]), task and resources reallocation (e.g. [12,13]), modifications in the hierarchical relationships between roles (e.g., [14]), composition and decomposition of groups of agents (e.g. [6]), reallocation of obligations (e.g. [15]), etc.

Full algorithms for the reorganization of MAS (as the ones studied in, e.g., [16,17,18]) where also left out of the PopOrg model. By the same token, we did not introduce in the minimal model the various ways in which organizational roles may be related to each other, in connection to issues such as power, prestige, control, etc. (as analyzed, e.g., in [19]).

The inclusion of such various structural relationships and reorganization mechanisms leads to organizational models that are not minimal in the sense the PopOrg model is, giving instead larger organizational models, as the ones proposed in, e.g., [20] and [21] (see [22] for a survey of the most important of such larger models).

In other words, we aimed at keeping PopOrg a minimal, extensional model, where every intensional aspect should be considered through complementary external rules operating on the basis of the combination of extensional and intensional features, as the dynamical rules illustrated in the present paper.

This is why, given that the analysis of organizations from the deontic point of view[23] places itself in the intensional perspective, concerning the expression of regulations (essentially constraints) about the structure and functioning of a multiagent system, norms and deontic notions also do not belong intrinsically to the PopOrg model: they should be added through complementary rules. For example, in [24], rules were introduced to support an exchange value-based operational notion of morality for MAS organizations.

Concerning the system of exchange values, we have been using it to analyze social interactions in MAS from the point of view of the equilibrium of the interactions (e.g., [5,25,26,27]). The same system has been used for other analytical and modelling purposes, e.g., in [28,29,30].

Finally, we notice that the work on the denotational and operational semantics of real-time and reactive systems [2] defined models for such systems which are formally keen to most models of multiagent systems. The similarity comes not from chance, for the agent-based systems were originally developed as models of reactive real-time systems [31].

One readily recognizes, for instance, that reactive programs in state-based specification languages for reactive systems [2] are similar in spirit to the so called procedural knowledge representation that was originally used to specify the behavior of BDI agents [31]: both are means for representing "reactive plans".

Since a signal [2] is essentially a temporal sequence of values of a certain type, signals are similar to the temporal sequences used in the PopOrg model. The similarity is not weakened by our using organizational objects as values of the temporal sequences, while the declarative languages designed for the specification of reactive real-time systems use simple data values in signals.

Such differences and similarities only stress the need to develop the study of multi-agent systems in the perspective of a situated approach, where the system is placed to operate in connection to a real environment.

6   Conclusion

We have presented a temporal extensional model to support a formal dynamics of multi-agent systems, by revisiting the PopOrg model and refining it with the notion that social

interactions are exchanges. We strived to clearly separate the extensional, structural aspects of the problem, from the intentional, subjective ones. The former deal with the set of possible ways the structure of a multiagent system evolves in time, while the latter deal with the possible subjective causes of the particularities of such evolution.

To illustrate the way the intensional and the extensional aspects of the structural dynamics of a multiagent system may be combined, we made use of an exchange value-based mechanism for the modeling of the subjective assessment of social exchanges, allowing the agents to decide on the start, continuation and termination of an organizational link, thus showing that an intensional mechanism may operate as a causal element in the extensional structural dynamics of the system.

The two components that one would like to add to the PopOrg model in the near future, to allow for the tackling of two essential aspects of MAS, are: first, a mechanism for constituting organizational groups of agents within a system; and, second, the notion of an external environment, the latter being the essential component for construing a MAS as a situated one.

Also, various aspects of the link dynamics as it stands in the present paper should be analyzed further, like the issue of the dynamics of organizational links implemented by multiple exchange processes, each such exchange process being evaluated in a different way by the agents involved in them. Or else, the impact on the whole model of the issue of periodicity in organizational interactions, that is, the restriction of organizational interactions to those that are periodic, as in the vast majority of the interactions that happen in human organizations.

Thus, it seems to us that the work we presented here produced the core elements for an adequate consideration of the structural dynamics of multiagent systems. They seem to be specially useful not only when we model the systems situated in real environments, whose structural and functional variations press the systems to keep their structures continuously adapted to the demands of those environments, but also when we model systems that themselves, through their agents, find reasons to change their organizational structures.

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