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Models and Concepts for Socio-technical Complex Systems: Towards Fractal Social Organizations

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SUMMARY

We introduce fractal social organizations—a novel class of socio-technical complex systems characterized by a distributed, bio-inspired, hierarchical architecture. Based on a same building block that is recursively applied at different layers, said systems provide a homogeneous way to model collective behaviors of different complexity and scale. Key concepts and principles are enunciated by means of a case study and a simple formalism. As preliminary evidence of the adequacy of the assumptions underlying our systems here we define and study an algebraic model for a simple class of social organizations. We show how despite its generic formulation, geometric representations of said model exhibit the spontaneous emergence of complex hierarchical and modular patterns characterized by structured addition of complexity and fractal nature—which closely correspond to the distinctive architectural traits of our fractal social organizations. Some reflections on the significance of these results and a view to the next steps of our research conclude this contribution. Copyright © 2013 John Wiley & Sons, Ltd.

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1. INTRODUCTION AND RATIONALE

Societal and technological progress have brought to a widespread diffusion of Internet-backed computer services characterized by an ever increasing complexity, pervasiveness, and social meaning (Fleisch, 2010). Ever more often people make use of and are surrounded by devices enabling the rapid establishment of communication channels on top of which people may socialize and collaborate, supply or demand services, query and provide knowledge as it had never been possible before. Such devices become our knowledge and social backbone by means of which

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new spontaneous forms of socialization and novel forms of self-organization may arise—as demonstrated by knowledge ecosystems (Bray *et al.*, 2008), cyber-physical societies (Zhuge, 2010), and mutual assistance communities (Sun *et al.*, 2006; Sun *et al.*, 2010). The virtually instantaneous diffusion of knowledge and awareness granted by such digital ecosystems is already producing novel forms of collective intelligence and social interaction, with tremendous significance in terms of marketing, economy, welfare, and social values (Pór, 2000).

The above mentioned novel forms of social organization and interaction are a promise of new wealth and quality for all; at the same time, they also constitute a covenant of new solutions against the many new problems our societies are experiencing. The overwhelming increase in the human population and in particular of the elderly; the dissipation of valuable resources such as water, energy, and clean air; the ill-considered management of waste are but a few examples that show how the current social organizations are proving to be ineffective and unable to scale to the sizes of our new "big world" (Hardin, 1968; Barabasi *et al.*, 2013). Assistance of the elderly population is a typical case in point: The share of the total population older than 65 is constantly increasing worldwide (Anonymous, 2011; Anonymous, 2012), while the current organizations still provide assistance in an inefficient and inflexible way. Though effective when the context was different and a large amount of resources were available to manage a smaller demand, this approach is now becoming too expensive and thus unacceptable. Merely expanding the current organizations without properly restructuring them is simply not working anymore (De Florio & Blondia, 2008).

Promising solutions to this problem come from the domain of control systems. Such systems have been traditionally crafted by using paradigms such as the centralized, the hierarchical, or the heterarchical (Dilts *et al.*, 1991). More recently additional classes of distributed control mechanisms have been introduced so as to enhance efficiency and reduce the bottlenecks characterizing the classical paradigms. The terms used in literature to refer to these classes is bionic, holonic, and fractal organizations (Tharumarajah *et al.*, 1996; Ryu, 2003). Said solutions have been successfully applied in several domains in order to achieve "smarter organizations", i.e. systems characterized by greater scalability, robustness, and manageability with respect to their traditional counterparts (Warnecke & Hüser, 1993; Tharumarajah *et al.*, 1998; Ryu, 2003). Our conjecture and major starting point in the current discussion is that the above distributed mechanisms may provide us with promising paradigms for the design of socio-technical complex systems able to make full use of the potential inherent in our societies so as to turn them into abundant sources of valuable assets, complex collaborative behaviors, and massive redundancy. A major challenge then becomes being able to master the complexity of said mechanisms and create models for the organization and the management of massively distributed open socio-technical systems based on their paradigms.

1.1. Contributions and Structure

Section 2 presents our first contribution in the above stated framework of problems, namely the definition of a class of socio-technical complex systems based on a distributed, bio-inspired, hierarchical organization. Said organization is characterized by a same building block that is repeated at different layers so as to manage both self-sufficient and inter-community collective behaviors. Its building block, called service-oriented community, is "simultaneously a part and a whole, a container and a contained, a controller and a controlled" (Sousa *et al.*, 2000) in that it represents the canon (Ryu, 2003) of a fractal organization (we refer the reader to Sect. 4.1 for more information on fractal organizations). This fact led to the name of "fractal social organizations" for systems compliant to our models (De Florio *et al.*, 2012).

A second contribution of this paper is reported in Sect. 3. In that section we describe a model of the collective behaviors within non-hierarchical and static socio-technical systems. A dynamic system is introduced to express the life-cycle of active behaviors within said socio-technical systems. Despite so simple a formulation, the resulting dynamics produce complex emerging properties. In particular,

- The geometrical representations of the orbits of the dynamic system exhibit a spontaneous emergence of self-similar patterns, some of which likely to be characterized by a fractal dimension.

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- A structured addition of complexity appears to emerge as complex structures reveal to be the result of a regular composition of “prime” (i.e., no further decomposable) building blocks.
- A hierarchical organization spontaneously shapes up.

It is worth remarking how several of the above properties closely correspond to the distinctive traits of our fractal social organizations. We conjecture that so pronounced a similarity may hint at the emergence of scalability and robustness in future socio-technical complex systems designed after our fractal social organizations.

This article is concluded by a discussion of related concepts and disciplines in Sect. 4 and by a summary of our preliminary results as well as our plans for future research in Sect. 5.

2. FRACTAL SOCIAL ORGANIZATIONS

The starting point of our discussion is the definition of social organization provided by Boulding in his classic General Systems Theory article (Boulding, 1956). In the cited renowned contribution Boulding provides a classification of system behaviors and—to the best of our knowledge—he is the first scholar to highlight explicitly the role and significance of socio-technical complex systems and their behaviors. Social organizations correspond to said systems and are classified by Boulding as the most complex system category. His definition for social organizations is “a set of roles tied together with channels of communication”. We observe how even so concise a definition already captures several important aspects of the dynamics of collective behavior:

A set. . . : Social organizations are selections of societal constituents.

. . . of roles. . . : Said selections are characterized not by the *identities* of their constituents, but rather by their *role*: Quoting again from (Boulding, 1956), in social organisations “the unit [. . .] is not perhaps the person but the role—that part of the person which is concerned with the organisation or situation in question”. In algebraic terms this translates in modeling social organizations as *multisets of roles*. One such model is introduced in Sect. 3.

. . . tied together. . . : Shared goals and common opportunities may lead individuals to join forces and constitute a new “social” entity able to exert purposeful collective behavior. We refer to such entity as a *community*. Reasons for individuals to tie together into a community may be temporary or permanent; moreover, they may be the result of purposeful active individual behaviors (Rosenblueth *et al.*, 1943) as a response to the onset of an environmental condition—for instance, a threat to survival or an opportunity for economical profit—or simpler forms of individual behavior such as those typical of animal instinct. Moreover, the resulting social entity may be a temporary or permanent one. All these factors influence the dynamics of creation, operation, and destruction of the community as a new “greater individual” able to exert purposeful active *social* behaviors—examples of which are the collective strategies discussed in (Astley & Fombrun, 1983). In (De Florio & Blondia, 2010) we used the term *social energy* to refer to the product of such collective behaviors. In the same paper the term “community” was used to refer to social organizations.

. . . with channels of communication: Such channels represent the media by means of which the constituents of social organizations timely share their individual goals, situations, and states. Channels also induce concepts such as proximity and membership: Depending on the characteristics of the communication channels members of the communities shall or shall not be able to access shared knowledge and take part in social decisions.

The just mentioned aspects all play an important role in a specialization of Boulding’s social organization that we called Fractal Social Organizations (FSO). In order to present the specific aspects characterizing FSO with respect to its *genus proximum* in what follows we first introduce, in Sect. 2.1, a number of preliminary concepts by means of a case study. Secondly, in Sect. 2.2, we enunciate a number of architectural elements underlying those preliminary concepts. Finally, in

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Sect. 2.3 and Sect. 2.4, we make use of the above concepts and elements to define respectively the building block and the control architecture of our FSO.

2.1. Case Study

Let us suppose that Jane, an elderly woman, is living in her smart house. Jane's smart house includes several devices, among which an accelerometer that is used to assess situations such as "Jane has fallen". The smart house service includes also a general practitioner (GP) who is timely informed of situations such as the above one through some communication channel. Let us consider the following set of roles:

$$S_1 = \{\delta_0, \delta_1, \delta_2, \ldots, \delta_d, \mathrm{GP}, \mathrm{Channel}, \mathrm{Jane}\},$$

in which δ_0 is the above mentioned accelerometer, δ_1 is an alarm module (to be introduced later on), Channel is a communication channel to transfer information between δ_1 and GP, and $\delta_2, \ldots, \delta_d$ are devices that though available are not relevant to the current case. We shall refer to sets of roles as to *societies*.

Let us now suppose that situation $s =$ "Jane has fallen" takes place. Let us assume that δ_0 operates according to its specifications and correctly assesses the situation at hand. We shall then say that δ_0 becomes active. According to Boulding's definition of a social organization this implies that S_1 is now partitioned into two running components:

1. The running selection of roles appointed to deal with s (let us refer to this series of selections as $R_1^1, R_1^2, \ldots$)
2. The remaining roles (namely, the set of merbers that are inactive with respect to s, identified by sets $L_1^1, L_1^2, \ldots$).

In the case at hand the initial partition is given by

$$L_1^1 = S_1 \setminus \{\delta_0\}, \quad R_1^1 = \{\delta_0\}.$$

As δ_0 is part of the current set R we shall say that δ_0 is currently active. Becoming active means that δ_0 starts looking for pertinent activities—activities that is that are relevant to s. Activities are interpreted here as well-defined protocols to deal with the situation at hand. In what follows we shall not consider the nature of these protocols and just assume that they are formal descriptions of common practice, specifications, or regulations, that have been associated to the roles of S_1 through some mechanism (for instance, meta-data).

In what follows we shall assume that one or more "reference domains" (RD) are semantically associated to activities and societies, and that selections of societies inherit the RD of their superset.

In what follows we shall refer to selections of a society S that are active with respect to a given situation s as the *communities* of S with respect to s. S and s will not be mentioned when obvious from the context.

In the rest of this section we shall denote activities as follows:

«situation : action».

Actions shall take the form:

(role → step)⋆,

where "⋆" stands for "one or more occurrence". Occurrences are separated by either "**;**" (for sequential execution) or by "**//**" (for parallel execution). Parentheses may be used to group occurrences.

We now assume the presence of the following activity among those pertaining to role δ_0:

«fallen : (δ_1 → **alarm**(fallen))». (1)

Activity (1) states that, once δ_0 "fallen" is detected, δ_1 is to execute a single action step and raise an alarm. It is assumed in what follows that for said activity RD is equal to string "Healthcare".

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It is worth remarking here how action steps *call for* roles to be played by some actants. If a corresponding role can be found in community R_1^1, that role is associated with the execution of the corresponding step. On the contrary a restructuring takes place. As an example, if "**alarm**(fallen)" calls for a communication channel, then this will lead to the following new selections:

$$L_1^2 = S_1 \setminus \{\delta_1, \text{Channel}\}, \quad R_1^2 = \{\delta_1, \text{Channel}\}.$$

The resulting new community R_1^2 can now execute (1). After doing so, R_1^2 dissolves back into the original society: $L_1^3 = S_1, R_1^3 = \varnothing$.

We now suppose that activity (1) injects the following new situation: "Alarm has been triggered". The corresponding activity is assumed to be the following one:

«alarm(fallen): ((GP → **fallenGP**(fallen))
// (neighbor → **fallenNeighbor**(fallen))
// (relative → **fallenRelative**(fallen)))».

The first step of said activity implies updating the L and R selections as follows:

$$L_1^4 = S_1 \setminus \{\text{GP}, \text{Jane}\}, \quad R_1^4 = \{\text{GP}, \text{Jane}\}.$$

The treatment of this case is similar to what discussed above and therefore it will not be repeated. What we now focus our attention on is the fact that action steps such as "(neighbor → **fallenNeighbor**(fallen))" can *not* be resolved within the current society: In fact S_1 does not include a "neighbor" role. When a society finds itself short of a role, a new "meta-situation" occurs and triggers the following default activity:

$$\text{«}\varnothing : \ (S_1 \rightarrow \textbf{up}(\text{neighbor}, \textbf{alarm}(\text{fallen})))\text{»}. \tag{2}$$

Situation "∅" may be interpreted as an exception that either forwards the request to any superset societies that include the current one (if at least one such society exists) or it fails (if no superset societies can be found). It is assumed that said selection is operated by creating a ranked list of the superset societies and selecting the top "best matching" candidates. Ranking is operated by considering a metric function measuring a "distance", i.e., a compatibility degree, between the RD of the activity and those associated to superset societies. Mission requirements, e.g. geographical proximity, may also be used to operate said ranking.

Now let us suppose that at least one compatible superset society does exist and be equal to

$$S_2 = \{S_1, \text{Neighbor}, \textit{Something else}\}. \tag{3}$$

Through the onset of the meta-situation in S_1, roles Neighbor and S_1 become active. As usual this translates into a partitioning of S_2 into the following two blocks:

$$L_2^1 = \{\textit{Something else}\} \ \text{ and } \ R_2^1 = \{S_1, \text{Neighbor}\}.$$

As a consequence, Neighbor now can become active within R_2^1 and deal with the situation inherited from S_1. We remark how this mechanism correspond to a change of scale. Note also how the life span of community R_2^1 is defined by the duration of the action step "neighbor → fallenNeighbor(fallen)".

Intra- and inter-community social activities—we conjecture—may be useful to express autonomic collaboration services among organizations. A distinctive advantage of such services would be, e.g., the intelligent and timely resource sharing among care departments and institutions (Waring *et al.*, 2006). An interesting system based on such principles is SHINE (Secured Health Information Network and Exchange), a web and mobile-based system for inter-facility health e-referrals[†].

[†]SHINE enables "health care providers and facilities to efficiently operate and communicate individual or aggregated referral and case records to the right people in a timely, accurate, and interactive manner" (Anonymous, 2013b). Operating in the Philippine, SHINE for instance eliminated "the long hours that a pregnant mother spends while looking for a hospital on a trial-and-error basis" (Valmero, 2011).

Lessons learned from the above simple case study allow us to identify already the following preliminary list of system requirements to the management of complex collective behaviors:

- Services and policies are required to associate social actants to roles.
- Actions and protocols are required to express and communicate situations, activities, and actions.
- Services are required to manage the dynamic life-cycle of communities.
- A hierarchical organization of societies and communities as well as services for managing exceptions and the ensuing propagation of situations are required.

The above requirements are complemented in what follows with a number of architectural elements and assumptions.

2.2. *Architectural Elements and Assumptions*

In previous section we introduced the concepts of exceptions and of hierarchies of societies and we identified a number of system requirements. Here we go one step further and sketch the basic elements and assumptions of an architecture based on the principles and requirements discussed so far. In what follows we shall purposely not distinguish between individual and social entities[‡].

Element 1 (Permanent and transient communities)
Let us consider two classes of communities: Permanent and transient communities. A community is permanent when it is to respond to a persistent situation; an example is given by hospitals, which answer the persistent necessity to provide medical care to people in need. Another example is S_1 in Sect. 2.1. On the contrary a community is said to be transient when it is dynamically constructed so as to respond to the onset of a new situation; subsets R_1^1–R_1^4 in Sect. 2.1 are all examples of transient communities.

Element 2 (Permanent and transient roles)
Let us consider two classes of roles: Permanent and transient roles. A permanent role is one constitutionally assigned to a permanent community—e.g., the logistics department of a hospital or the hospital itself. A role is said to be transient when it is played by a transient community or when it is different from those constitutionally assigned to a permanent community.

Element 3 (Hierarchical structure)
Societies and communities shall be structured as the blocks of a Russian nested doll (also known as "matryoshka doll"), with the following peculiar differences:

- Blocks may belong to more than one doll at the same time. This assumption corresponds to the hypothesis that actants may play at the same time different roles in different communities.
- Blocks may contain more than one other block.
- Permanent blocks are semantically annotated so as to publish one or more of their RD (reference context domains) as well as other information. As an example, through this mechanism a hospital block may publish its nature of "care organization" and for instance its policies of intervention.

Element 4 (Roles as references)
Blocks shall be represented as multisets of *references* to roles. Creating a new block from the roles in an existing block does not subtract the roles from the latter—it only copies their associated references.

Transient communities dynamically create new temporary blocks (i.e., new active R subsets) whose lifespan is the amount of time required to deal with their associated situations—e.g. "fallen" in (1). As mentioned in Sect. 2.1 such processing may result in two cases:

[‡] As well known, e.g., a human being may be regarded as either an individual entity or a social "body" of specialized modules— the organ systems. In turn, each organ system may be considered as either an individual—that is, non-dividable—module or another example of social organizations.

1. The temporary block can be created making use exclusively of roles available *within the parent block*. In this case the temporary block becomes a new sub-block of the parent block until it concludes processing its situation.
2. The temporary block requires roles that are available without the parent block. Through the exception mechanism discussed in Sect. 2.1 the situation and the call for roles is forwarded to the parent of the parent block. If the parent block has more than one parent, a selection is carried out by considering the reference context domains as well as possible constraints at individual, collective, and mission level. At the current, still abstract level of specification, we shall not discuss in detail how the selection is carried out and how the missing role is actually sought.
   Once all required roles are found, a new block is constructed.

Element 5 (Role templates)
Some mechanism may be foreseen such that, though transient in nature, temporary blocks leave a "trace" in the system—thus becoming new known "templates of roles". If a certain complex situation regularly repeats itself then a corresponding role template may be recalled and considered as a more compact (and thus, efficient) way to deal with it.

Role templates result in an elementary form of *learning through experience*, which corresponds to the ability to respond more rapidly and efficiently to challenging environmental situations. Instinct (innate behaviour) may also be based on predefined and genetically encoded role templates. We also conjecture that the adoption of mechanisms similar to our templates of roles may be associated to the widespread emergence of modularity in nature (Clune *et al.*, 2013).

More complex learning solutions may involve "scoring" the templates of roles with respect to their effectiveness while servicing a given recurring situation. By choosing the currently best matching candidate and by updating the templates' scores systems based on such strategy may autonomously improve their environment fit. A similar scoring mechanism may be applied when appointing the actants to be associated to sought roles—as it was done, e.g. in (Buys *et al.*, 2011; Buys *et al.*, 2012), to self-select the best software versions for an N-version programming composite (Avižienis, 1995).

Element 6 (Template roles)
A template of roles shall be considered as a special case of role. Similarly to the concept of subroutines in programming languages, template of roles may provide a way to refer concisely to complex roles and their corresponding activities.

Through the above assumption templates of roles allow complexity to build up into more and more "high level" roles (templates of templates, and so forth), which correspond to more and more abstract activities. Intuitively, such activities may be interpreted as the tokens of the higher level "languages" used by complex communities to play their roles.

Element 7 (Role permanentification)
When a template of roles (or of other templates) is repeatedly selected as an answer to a recurring situation, the corresponding role shall become permanent. A corresponding set of actants that specializes to play the template role may then be labeled as a new permanent community.

We now go one step further and make use of a subset of the just discussed requirements and architectural elements to sketch the elements of the societal "building block" of our FSO as well as its hierarchical organization.

2.3. *Service-oriented Communities*

Service-oriented Community (SoC) is the name we use to refer to the architectural element corresponding to the concepts of "community" and "block" introduced in previous sections. As described in (De Florio & Blondia, 2010), a SoC is a collective socio-technical system coupling services provided by smart cyber-physical "things" with services supplied by human beings. Actants that agree to join a SoC become their "members". Members of a SoC are *diverse*, which translates into a rich variety of services. By focusing for instance on human members only, diversity implies

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- different know-hows (e.g. those of a general practitioner, or those of a gardener);
- different policies for providing services (e.g. well-defined time schedules and fares, or dynamically varying availability to provide free-of-charge services as occasional informal carers);
- different location, in that members may be mobile, thus able to get dynamically closer to or farther from other members;
- different value systems,

and so on. Such attributes are called in what follows *features*. Finally, members may have different *goals*—for instance being able to reach a given location within a certain amount of time with a certain budget of travelling costs and with at least a given quality of experience.

We shall call *viewpoints* any well-defined and agreed representation of a member's features and goals.

The operational model of the SoC is represented in Fig. 1, in which members publish their viewpoints to other members in logical or physical proximity. Viewpoints may be issued, e.g., by an elderly member in need of assistance—such as Jane in Sect. 2.1,—by a bystander posting their tweets to describe an accident, by a monitoring device notifying the occurrence of some critical event, by the acceptance service of a hospital, and so forth. Control and adaptation are achieved by sharing viewpoints, unravelling semantic analogies among them and creating transient "networks of relations" (Latour, 1996) among members. A way to enact the above semantic processes is described, e.g., in (Sun *et al.*, 2007).

Following some strategy (e.g., the one described in (De Florio *et al.*, 2000)) one or more members are given the responsibility to host a viewpoint registry and act as temporary coordinator. The coordinators then become "collective members," namely members representing a whole community of other societal actants. Among their duties, the coordinators are to identify whether the viewpoints currently stored in the registry correspond to a known situation such as those discussed in Sect. 2.1. Analyses are performed by semantically matching new viewpoints with those already stored in the registry (De Florio & Blondia, 2010). Analogies between viewpoints are identified as shown in (Sun *et al.*, 2007) by making use of ontologies associated with the reference domains. Once a similarity is discovered the coordinator notifies the corresponding members. The shared knowledge enables the creation of "bindings", which may be spontaneous or mandatory depending on the context and the policies in use. A practical way to implement said bindings in a flat (that is, non-hierarchical) community was the so-called "Participant mode" described in (Sun *et al.*, 2007).

Through bindings, members create a new temporary community. In conformity with what assumed in Sect. 2.1 and Sect. 2.2 the coordinators also register the association between members and roles and appoint the execution of activities. Coordinators may also keep track of the effectiveness of the enacted communities in dealing with experienced situations through the "role templates" of Sect. 2.2, which could be labeled with a running "score" tag. As already suggested, the same principle could be applied in the selection of the actants to be enrolled for a new community derived from a role template.

An example of a Service-oriented Community specifically targeting Ambient Assistance Living services is given by the Mutual Assistance Community (Sun *et al.*, 2010; Sun *et al.*, 2007; Gui *et al.*, 2007). We refer the reader to the just cited references for more information on the technical design of a SoC.

2.4. Fractal Social Organizations

A FSO may be concisely described as a fractal organization whose building block, or canon, is a Service-oriented Community. The rest of this section in fact may be considered as an explanation of the just given definition. More information about fractal organizations and the concept of canon may be found in Sect. 4.1.

Fractal organizations are bio-inspired hierarchical distributed control architectures whose components are simultaneously an individual and a social entity, "a part and a whole, a container and a contained, a controller and a controlled" (Sousa *et al.*, 2000). Said components are autonomous entities corresponding to the communities exemplified in Sect. 2.1 and Sect. 2.2 and implemented

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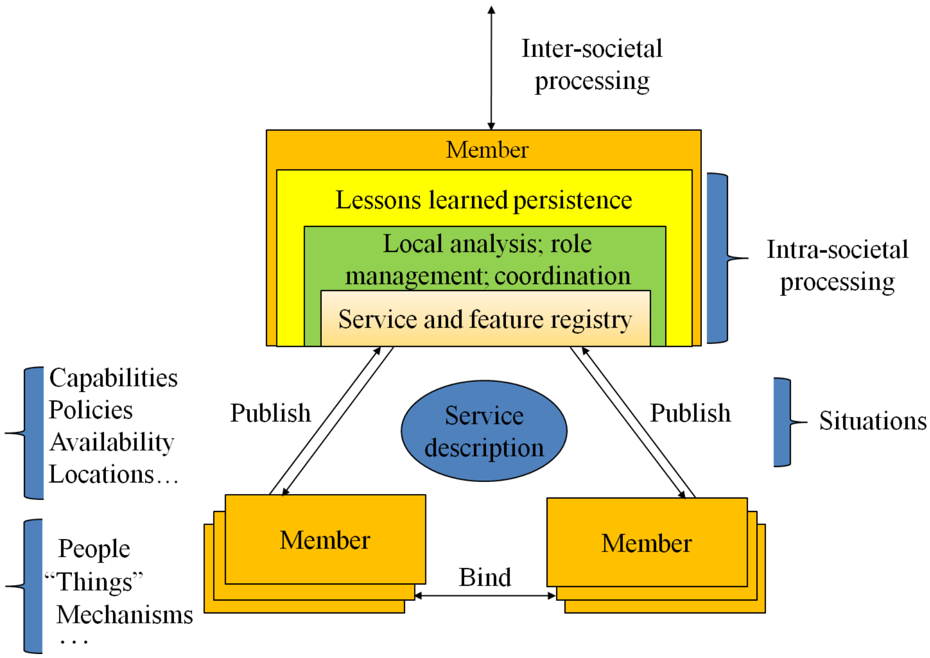

Figure 1. Representation of the canon of the Service-oriented Community.

as service-oriented communities as sketched in Sect. 2.3. By allowing SoC to become members of other SoC we come up with an architecture with the "matryoshka doll" structure suggested in Sect. 2.2, Element 3. Through the coordinator role the SoC assume a twin nature: They are at the same time social collectives and social individualities, as exemplified by S_1 in (3). This process is known as "personization" in Actor-Network Theory (Latour, 1996).

The coordinators are also responsible for declaring the onset of exceptions (see (2)) and for propagating the corresponding unresolved situations. This means forwarding the event to all superset communities the current community is a member of, and possibly to other nearest neighboring "higher-level" SoC. The "reference domain" meta-data may be used to define a metric function as suggested in Sect. 2.1. This is represented in Fig. 2.

An important aspect of adopting SoC as building block for our fractal social organizations is that, coherently with what discussed in Sect. 2.1, it allows multiple redundant responses to be considered and arranged at the same time. As an example, a request from an elderly man in need of assistance may be answered by (a) professional practitioners, (b) informal carers, (c) his relatives, (d) his neighbours, and so forth. These multiple, redundant "planes" of assistance supply independent service routes, which may be complemented by traditional (consolidated) service providers—e.g. social insurance companies or other healthcare bodies. Furthermore, this approach makes it possible to select a Pareto-optimal "plane" of assistance corresponding to the solution which provides the expected quality of services with minimal resource consumption. Evidence to this second statement has been obtained by simulating the social interactions of a single, non-hierarchical community (Sun *et al.*, 2007). In the same reference we showed how unraveling analogies via semantic reasoning promotes both a higher level of resource utilisation and a stronger quality of experience.

An exemplary FSO is depicted in Fig. 2, which portrays service-oriented communities at different scales—here identified as Layer 0, Layer 1, and Layer 2 members. A second representation is shown in Fig. 3. In this case the FSO layers include individuals, smart houses, hospitals, and inter-facilities of care. The same triangle-shaped pattern of the SoC repeats itself at each scale. The right-hand side of Fig. 2 provides a representation of this phenomenon in terms of a well-known fractal structure whose dimension is approximately equal to 1.5849625.

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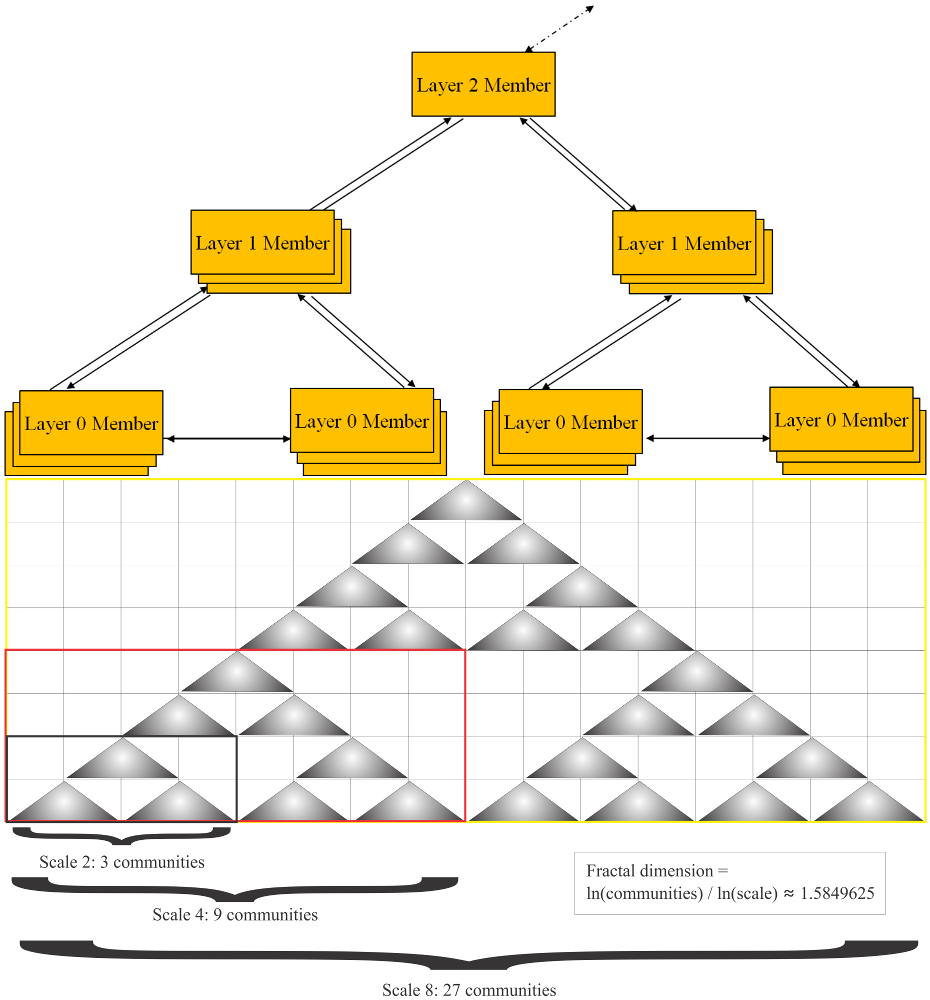

Figure 2. The top picture represents the SoC architecture. Resemblance with a known fractal is shown in the bottom picture.

We have just sketched the main characteristics of FSO, a socio-technical system with a complex fractal organization. As a preliminary way to evaluate the effectiveness of our architectural choices we now introduce a formal model based on Boulding's definition of social organization (see Sect. 2). A remarkable ensuing result is that several of the architectural elements of our Fractal Social Organization—including, e.g., self-similarity, the appearance of modular structures, and a hierarchical structure resulting from the recursive application of building blocks—emerge spontaneously.

3. ALGEBRAIC MODEL FOR SOCIAL ORGANIZATIONS

As we mentioned in Sect. 2, Fractal Social Organizations may be considered as a specialization of Boulding's social organizations, which in turn are defined as "a set of roles tied together with channels of communication". Inspired by the algebraic nature of Boulding's definition and by previous work on the dynamics of multisets (De Florio, 1995; De Florio, 2005) we introduce in what follows a formal model for the dynamics of the behaviors originating in social organizations. Said model is presented in Sect. 3.1 while its properties are discussed in Sect. 3.2.

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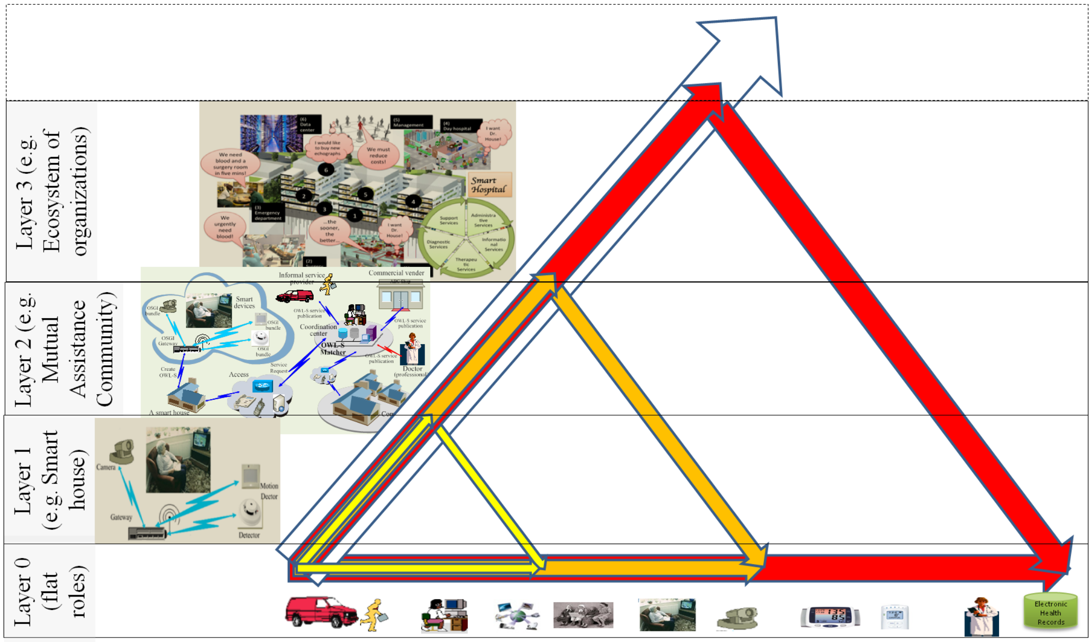

Figure 3. Exemplification of SoC social organizations.

3.1. *Formal Model*

Let us assume we have a set of *roles*, uniquely identified by integer numbers, as well as a set of *actants*, each of which is associated with exactly one of the above roles. In what follows for the sake of simplicity of treatise we shall assume this association to be static. As an example, let us say we have

2 GPs, 2 nurses, and 8 patients,

collectively identified by multiset

$$S = \{0, 0, 1, 1, 2, 2, 2, 2, 2, 2, 2, 2\}. \tag{4}$$

In accordance with what discussed in Sect. 2.1 we shall refer to multiset (4) as to a *society*. Furthermore, let us consider a concatenation operator, $\cdot$, to build ordered sequences of roles from a society. In what follows we shall refer to any such ordered sequence as to an *organization*. An example of organization is the following sequence:

$$0 \cdot 1 \cdot 1 \cdot 2 \cdot 2 \cdot 2 \cdot 2 \cdot 0 \cdot 2 \cdot 2 \cdot 2 \cdot 2.$$

We shall also refer to the above sequence as "$0 \cdot 1^2 \cdot 2^4 \cdot 0 \cdot 2^4$", or simply as "011222202222".

No specific meaning is given in what follows to organizations, their purpose, or their behavior. The only aspect that is highlighted in the above definition is the order and role of its constituents, as it is the case e.g. in DNA sequences of nucleotides. Another exemplification is an assembly line or a construction pipeline, where "something is done" by moving objects through a string of actants identified by their role (i.e., their peculiar function).

Now, as we did in Sect. 2.1, we shall consider the onset of some *situation* (Ye *et al.*, 2012) (endogenous or exogenous to S) such that some reaction is triggered by or through some of the actants in that society. Said situations may be interpreted as opportunities (e.g., the onset of some competitive economic advantage), threats (e.g., the outbreak of an infectious disease), crises (as a result, e.g., of a stock market crash), or other circumstances or changes.

Consistently with what we have discussed in Sect. 2.1 here we assume the onset of s, namely situation "one of the patients has fallen". Through some *communication channel* we further assume

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that situation s triggers the intervention of 1 GP and 1 nurse. As a consequence of said intervention, society (4) gets now partitioned into the following two blocks:

$$\text{subset} \quad L = \{0, 1, 2, 2, 2, 2, 2, 2, 2\} \quad \text{and subset} \quad R = \{0, 1, 2\}, \tag{5}$$

in which block L is inactive with respect to s, while R is active with respect to s. In what follows we shall use the same terminology we introduced in Sect. 2.1 and refer to an active subset of a society as to a *community*. When obvious from the context the firing situation will be omitted. Being active means that the actants in R shall need to organize themselves (in some sense and here not specified way) so as to deal with the situation at hand. Summarizing, multiset S is partitioned with respect to s into an inert subset L and some organization of community R—that is, some ordering of the active actants in S.

In what follows we shall model the dynamics of multisets L and organizations R. We shall assume that events occur at discrete time steps and are modeled as either processing events or perturbations: The former case stands for functional events corresponding to the processing of some workflow internal to the organizations, the latter is the onset of new situations leading to

1. either a reorganization of the elements within a community
2. or a repartitioning of the society into two new blocks L' and R'.

In what follows we model the reorganization in step 1 as a permutation of R—that is, a new ordering for its constituents. The rationale of this is that in this case the community responds to the onset of s by finding resources within itself, possibly reshaping the flow of activities, but keeping the same roles. In mathematical terms we say that R is closed with respect to s.

The repartitioning in step 2 means that the community calls for external resources—resources that were inactive (i.e., they correspond to roles in L) but now need to be enacted (entering R and thus constituting a new R').

Let us assume that a given society consists of r roles, identified by numbers $0, \ldots, r-1$, and that role i is played by n_i actants, $0 \le i < r$. Let us call "*First*" a function defined as follows:

$$\begin{gathered} \textit{First} : \mathcal{P}(S) \to \mathcal{O}(\mathcal{P}(S)), \quad \text{such that} \\ \forall X \subset S \, : \, \exists n_0, n_1, \ldots, n_{r-1} : \textit{First}(X) = 0^{n_0} \cdot 1^{n_1} \cdot (r-1)^{n_{r-1}}, \end{gathered} \tag{6}$$

where $\mathcal{P}(S)$ is the powerset of S (i.e., the set of all the subsets of S) and $\mathcal{O}$ maps sets onto organizations. Note that *First* generates the organization corresponding to the "smallest" number whose digits are the role identifiers. Let us refer to *First*(X) as to the "first organization" of X. Similarly we define dual function "*Last*" and refer to *Last*(X) as to the "last organization" of X.

We now recall the definition of function "*Succ*" (adapted from (De Florio, 2005)). *Succ* takes as input sequence

$$\textit{First}(L) \cdot R \tag{7}$$

and returns the sequence corresponding to the next organization in the lexicographically ordered set of all organizations of the input sequence. Applying *Succ* to the last organization returns the first one. Dually, we define *Succ*$^{-1}$ as the function returning the previous organization. If applied to the first organization, *Succ*$^{-1}$ returns the last one.

In principle any function producing all the organizations from a reference society could have been used instead of *Succ*, but making use of the lexicographic order has the advantage that it makes it easy to produce numerical representations that are all positive and monotonically increasing. Some of the geometrical representations introduced in Sect. 3.2 require the latter property.

We now can model both cases of perturbations by "tossing a coin" corresponding to a non-zero relative integer number, say z, and applying $(\textit{Succ})^z$ if $z > 0$ and $(\textit{Succ}^{-1})^{-z}$ if $z < 0$[§].

[§]In fact, due to the "wrap around" of functions *Succ* and *Succ*$^{-1}$, z may be substituted with $z \bmod p_S$, where p_S is the number of permutations of multiset S. This number also represent the amount of distinct orbits of *Succ* and *Succ*$^{-1}$, *i.e.* the length of their only *cycle*.

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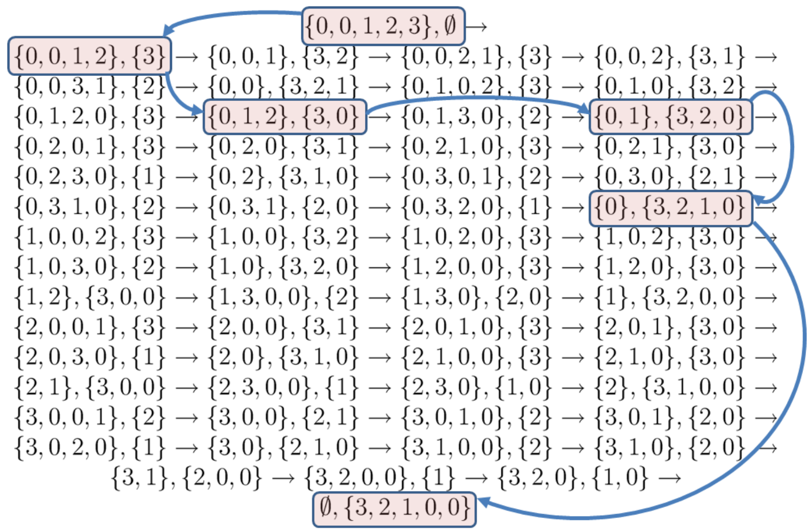

Figure 4. Exemplary life-cycle for the organizations of $S = \{0, 0, 1, 2, 3\}$.

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If we toss a coin and apply the above process at each time step t, the following series

$$\big(L(t), R(t)\big)_{t\geq 0} \tag{8}$$

defines a dynamic system corresponding to the dynamic life-cycle of all the possible organizations originating from a given reference society of roles. Figure 4 shows all the orbits of (8) for society $\{0, 0, 1, 2, 3\}$ as well an exemplary life-cycle of a community from that society.

It is also possible to define R_S as a relation between the organizations from a given society S such that, for any two organizations of S, say a and b,

$$a\, R_S\, b \quad \text{iff} \quad \mathit{Succ}(a) = b. \tag{9}$$

When doing so, the series of orbits in Fig. 4 represent the transitive closure of R_S. Note also how (8) may be described as a "random walk" through that series. Figure 4 depicts one such exemplary random walk.

3.2. *Representations and Properties*

The just described model considerably extends the deterministic combinatorial model introduced in (De Florio, 2005). As it was done in the cited paper, here we can provide geometrical representations for the evolution of the dynamic system in (8). In what follows we introduce some of said representations.

- A first representation is obtained by mapping successive orbits of *Succ* onto integer numbers. This is done by interpreting roles as digits and using the number of available roles, r, as base. We call the obtained integers "organization numbers". We shall use ν to represent the just introduced mapping. Figure 5 shows this representation for society $S = \{0^3, 1^{12}\}$.
- A second geometrical representation is derived by taking the difference between two consecutive organization numbers:

  $$\forall o \in \mathcal{O}(S) : \delta(o) = \nu(\mathit{Succ}(o)) - \nu(o).$$

  We refer to the obtained integers as to "delta steps". Figure 6 shows the delta steps of society (4).
- Figure 7 shows the logarithms of delta steps.

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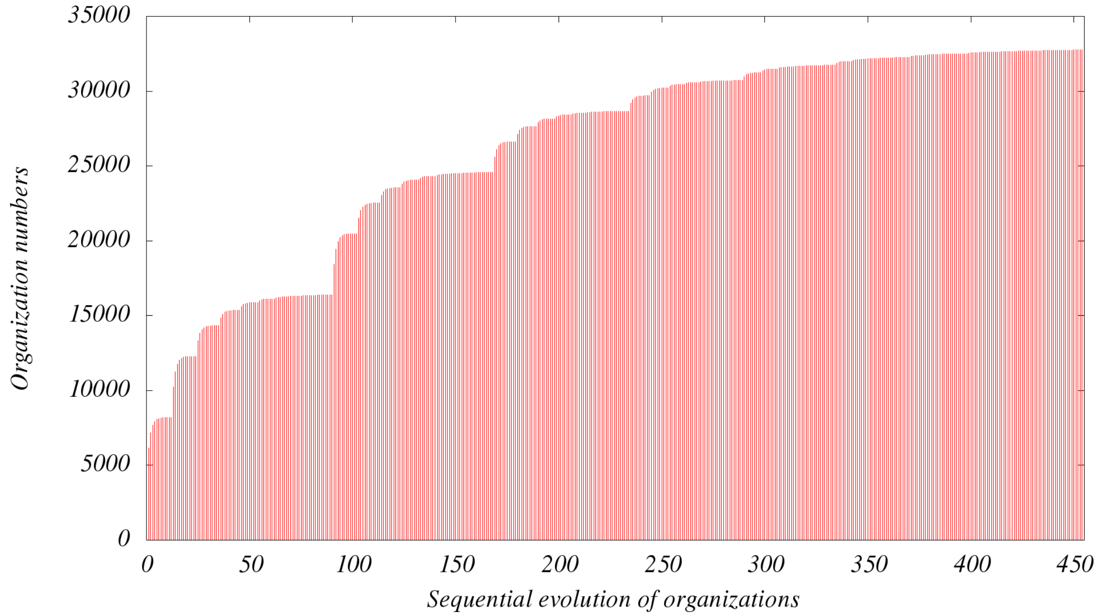

Figure 5. Organization numbers of society $S = \{0^3, 1^{12}\}$. Abscissa correspond to the successive orbits of *Succ* (no wrap around is shown). Ordinates are the corresponding organization numbers. Note how dynamics such as these are self-similar in that they include the dynamics of smaller societies.

- Finally, a family of geometrical representations is obtained by breaking down organizations into m consecutive "chunks" of roles and by interpreting each of them as a base-r integer. In turn, these numbers are used to identify points in m-dimensional space. Figure 8 shows this representation for $m = 2$ and society (4) while two examples for $m = 3$ are depicted in Fig. 9 and Fig. 10.

As evident from the just referenced figures, several of the above representations are characterized by some degree of self-similarity and by the emergence of modularity. This is particularly meaningful in view of the results of other researchers. Johns, for instance, remarked in (Johns, 2011) how self-similarity is a necessary condition to self-organization, while the widespread degree of modularity in the natural world has been associated by many with the emergence of evolvability—the ability to rapidly adapt to a turbulent environment (Clune *et al.*, 2013).

A second property of some of the just introduced geometrical representations is the fact that they are *factorisable*: Their structure can be shown to be governed by well defined rules reproducing the dynamics of simpler and simpler organizations, down to some atomic or "prime" organizations that cannot be further simplified. This is shown for instance in Fig. 11. An interpretation of this phenomenon is that factorization represents a *change of scale*: Prime organizations unite into a coherent and self-similar hierarchical organization. The higher we go in the scale the more complex is the organization. Such complexity though is not introduced arbitrarily but according to a well-defined general rule. Remarkably, the above behaviors and the resulting "structured addition" of complexity characterizing factorisable organizations are at the core of the concepts of Fractal Social Organization and Service-oriented Community introduced in previous sections. It is our conjecture that the above emerging traits and properties may hint at the emergence of scalability and robustness in future socio-technical complex systems designed after our Fractal Social Organizations.

A third noteworthy property of some of our geometrical representations is revealed when estimating their fractal dimension. For this we found a useful tool in Fractalyse (Vuidel, 2013), a software package that provides several classical methods to measure the fractal dimension of black-and-white images such as the one shown in Fig. 8. Available methods include box counting, radius mass, correlation, dilation, and others. Fractalyse was successfully applied to estimate, e.g., the fractal dimension of urban areas in Europe and China (Ma *et al.*, 2008). Figures 12–15 show some

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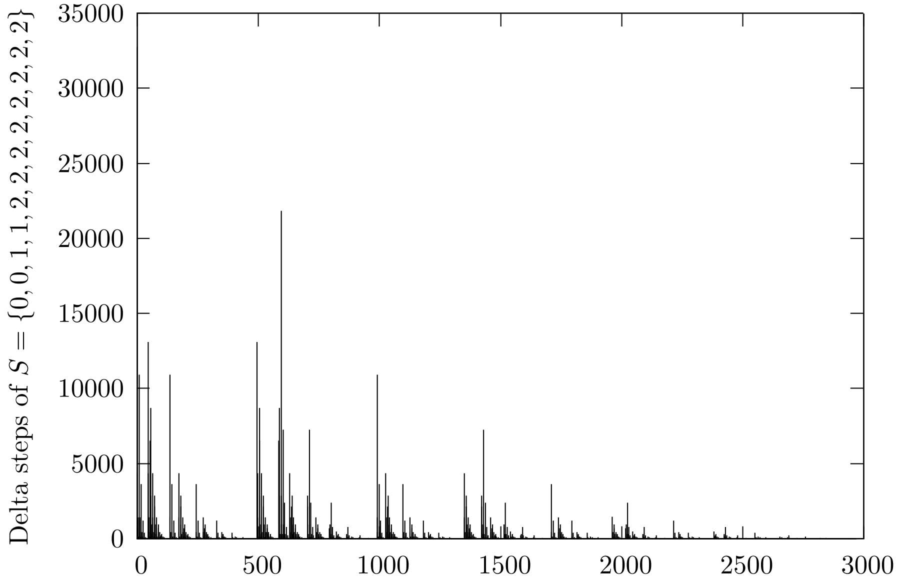

Figure 6. Delta steps of society $S = \{0^2, 1^2, 2^8\}$. Also in this case self-similarity can be observed.

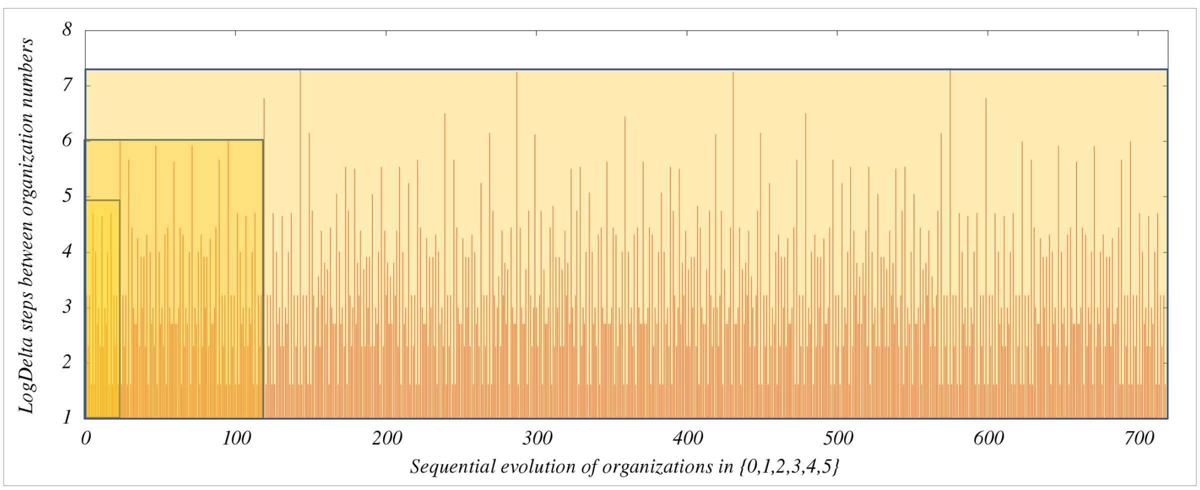

Figure 7. Logarithms of delta steps for society $\{0, 1, 2, 3, 4, 5\}$. Self-similarity is highlighted by emphasizing the representations corresponding to society $\{0, 1, 2, 3\}$ (small-sized region) and society $\{0, 1, 2, 3, 4\}$ (medium-sized region).

of the results we obtained with Fractalyse. As an example, the Box counting method with parameters $y = a \times x^d + c$ and exponential box size set to 2, applied to the bidimensional representations of society $S = \{0, 1, 2, 3, 4, 5, 6, 7\}$, estimates with nearly perfect correlation a fractal dimension $d \approx 1.792$ with $a = 9.5377 \times 10^{-3}$ and $c = 4.5496$ (Fig. 14).

4. RELATED CONCEPTS

Three major concepts related to FSO are the focus of this section, namely (1) organizational aspects, and in particular their nature being bio-inspired distributed organizations; (2) knowledge-related aspects, namely their relation with so-called knowledge ecosystems; (3) the FSO social dynamics,

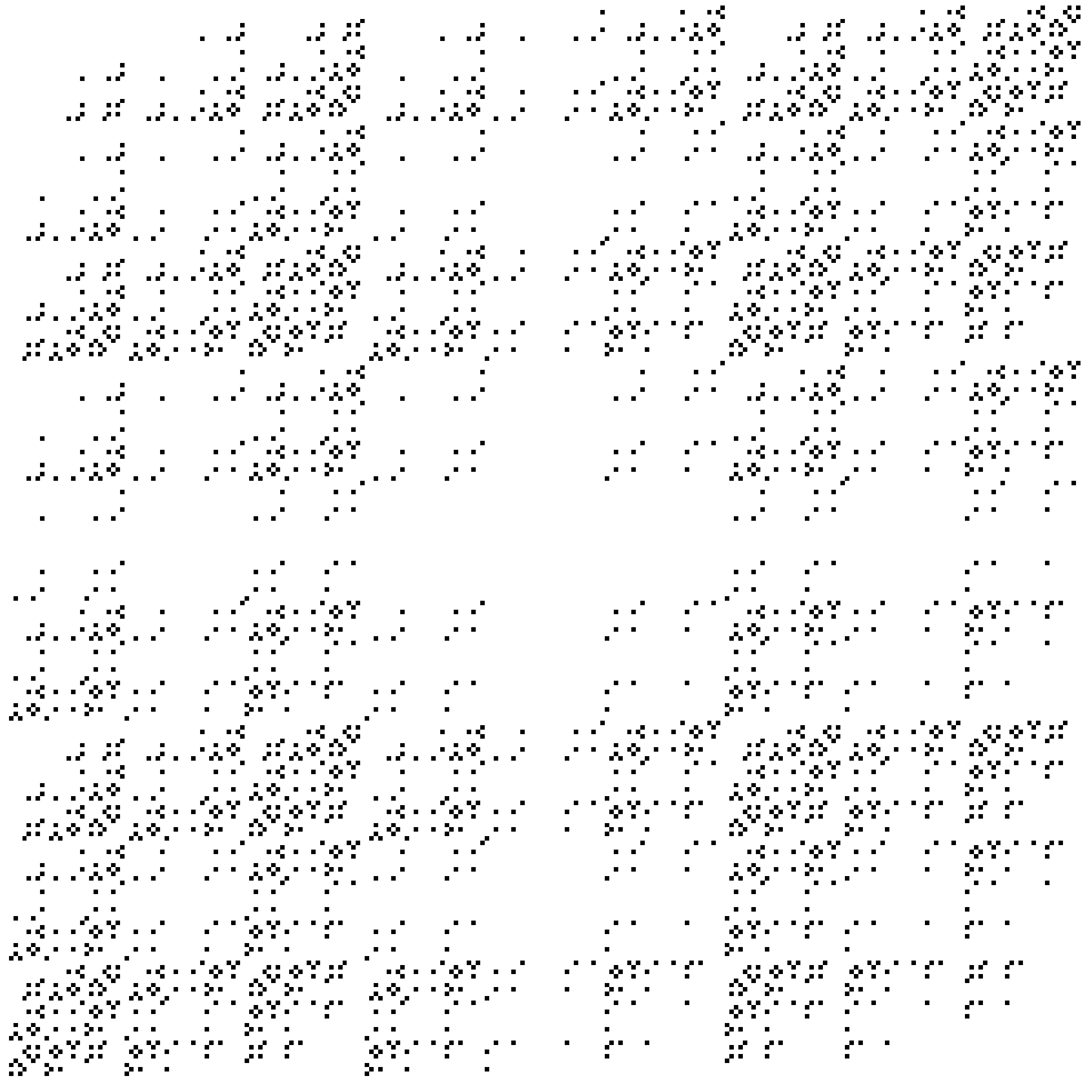

Figure 8. Bi-dimensional representation of the organizations in $S = \{0^4, 1^2, 2^4\}$ (equal sized chunks).

whose closest inspiration comes from the social theory known as Actor-Network Theory (Latour, 1996). In what follows we highlight very concisely the relationships between FSO and the above mentioned disciplines and subjects.

4.1. Organizations

A fundamental aspect for the effective emergence of desirable properties and behaviors—e.g. scalability, manageability, robustness, and resilience—is "the way a social union is structured and organized" (De Florio, 2013). Common terms to refer to such concept are "Partnership", "reference architecture", "organizational structure", "control structure", and simply "organization"—the latter being the term we shall use in what follows.

Commonly employed organizations include:

- Centralized control organizations, characterized by a single point-of-control-and-maintenance (PCM). The PCM is the "personization" of the whole organization. Simplicity is the main advantage of centralization, which is paid back by the introduction of a single-point-of-failure as well as a structural bottleneck.

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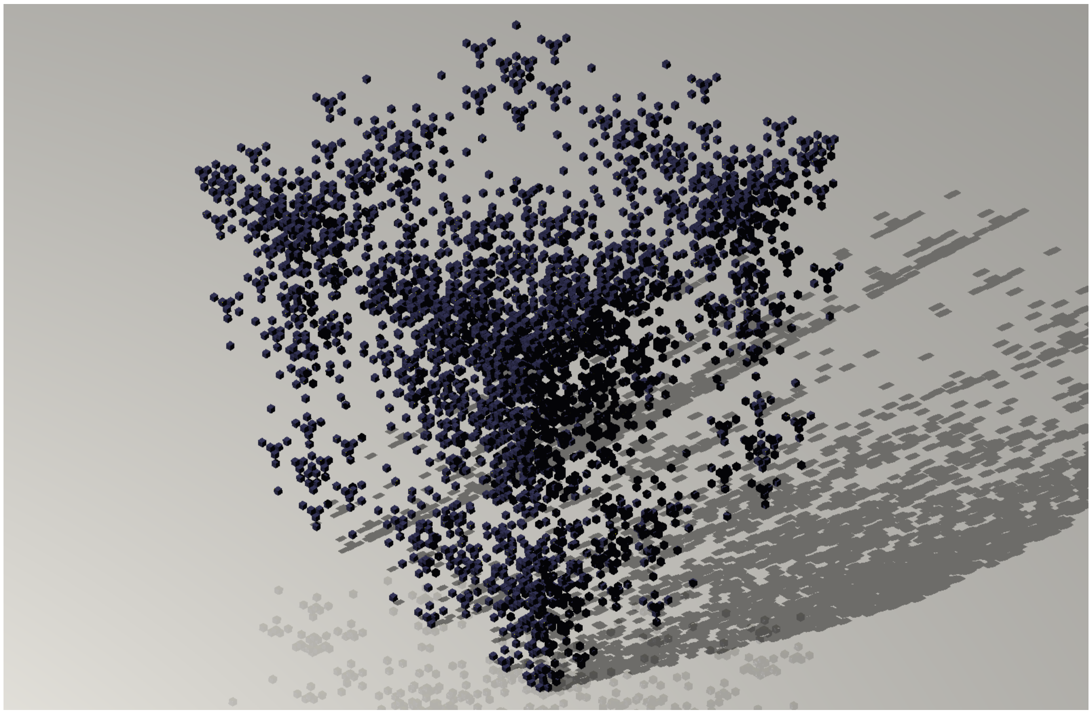

Figure 9. POV-ray (Froehlich, 2012) rendition of society (4) (equal sized chunks).

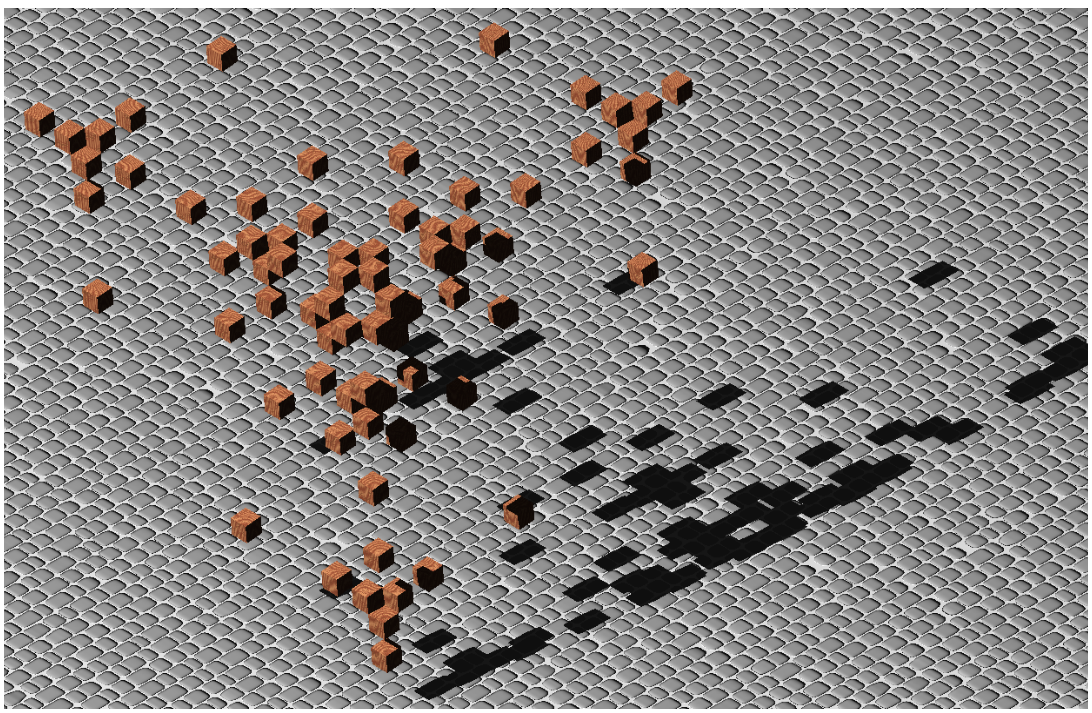

Figure 10. POV-ray picture of $S = \{0, 1, 2^7\}$ (equal sized chunks). Note how the depicted structure is one of the recurring patterns in Fig. 9. Note also how this closely corresponds to the concept of role template introduced in Sect. 2.2. This is because S is in fact a subset of society (4) (as shown e.g. in (5)).

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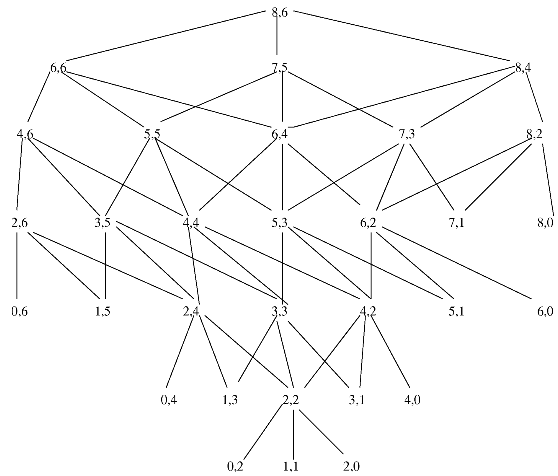

Figure 11. Society $\{0^8, 1^6\}$, when represented bi-dimensionally, can be factorized into several instances of atomic societal nuclei, or "prime communities". Note how this closely correspond to the concept of canonical "building blocks" such as the Service-oriented Community introduced in Sect. 2.3. (Picture from (De Florio, 1995)—copyright by Wolfram Research Inc. Used by permission.)

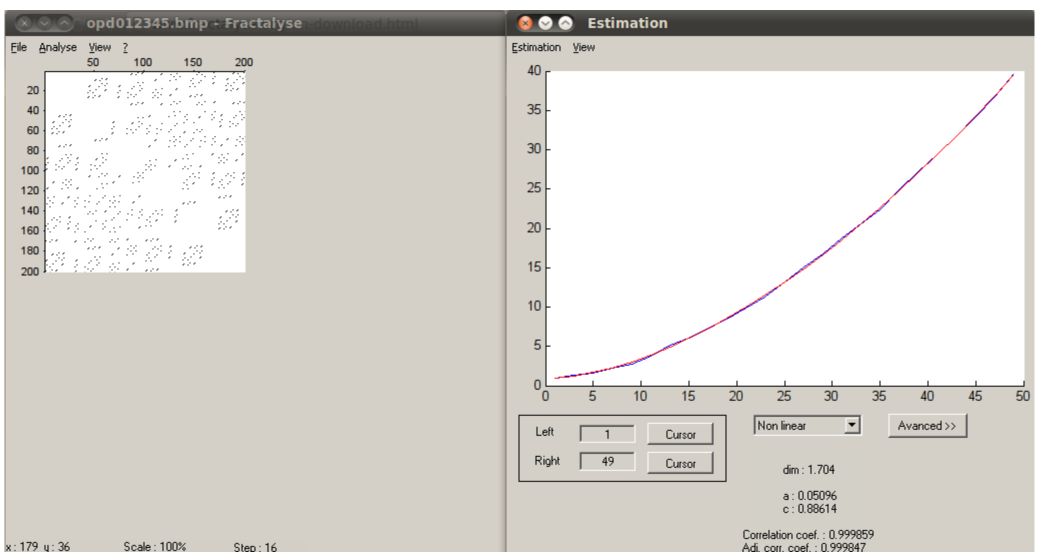

Figure 12. The Correlation method of Fractalyse applied to the bidimensional representation of society $S = \{0, 1, 2, 3, 4, 5\}$. The analysis reveals a fractal dimension of 1.704 with a correlation coefficient $c \approx 0.9999$.

- Hierarchical control organizations are characterized by a top-down flow of commands and a bottom-up flow of feedback information. These flows are limited to the immediate lower/upper level. Hierarchies scale better than centralized organizations though are not free of shortcomings; in particular information must flow throughout the hierarchy to reach the top control level, which translates in propagation delays and possibly propagation failures (viz. loss or corruption of commands and feedbacks).
- Heterarchical control organizations are those in which autonomous agents coexist in a flat structure with no predefined relationships. Information is distributed and there is no global knowledge nor fixed points of control. Such "heterarchies" (Stark, 1999) are characterized by the emergence of adaptability, by structural adoption of diversity, as well as by the ability to overcome so-called "lock-ins" (local minima of the system-environment fit).

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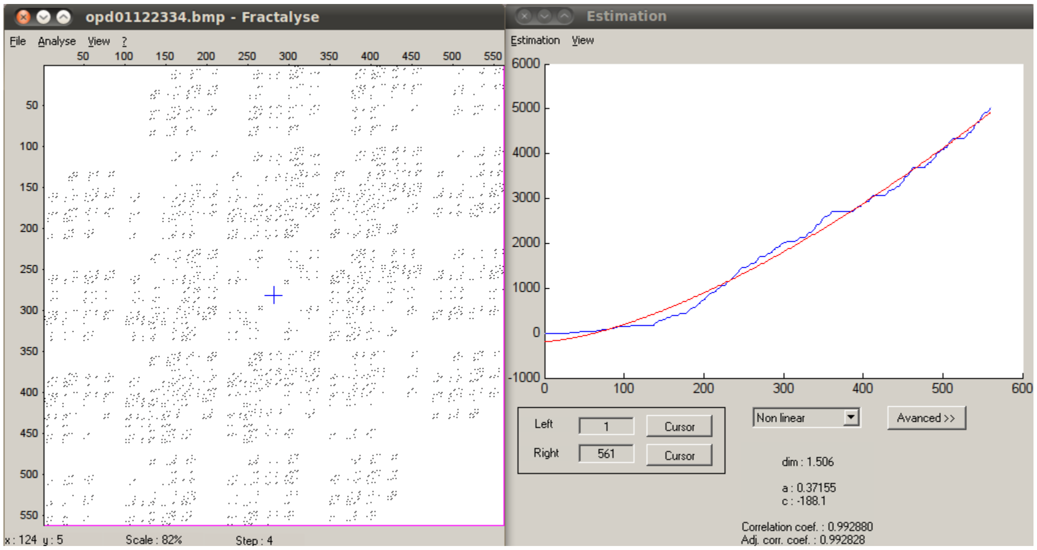

Figure 13. The Radius Mass method of Fractalyse applied to the bidimensional representation of society $S = \{0, 1, 1, 2, 2, 3, 3, 4\}$. A fractal dimension of 1.506 is suggested with a correlation coefficient $c \approx 0.993$.

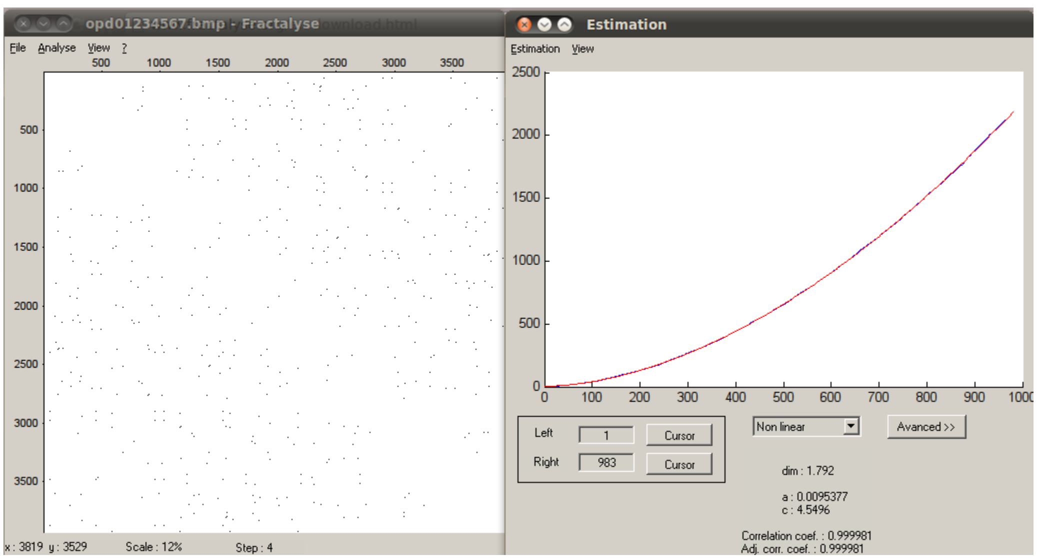

Figure 14. The Box Counting method of Fractalyse applied to society $S = \{0, 1, 2, 3, 4, 5, 6, 7\}$. Results suggest a fractal dimension of 1.792 with a correlation coefficient $c \approx 0.9999$.

A major shortcoming of heterarchies is that "central scheduling or resource planning is impossible" (Ryu, 2003).

Other organizations emerged as an attempt to reduce the shortcomings of the above mentioned ones. The main characteristics of said organizations are their bio-inspired origin and their distributed nature. Such class of mechanisms is particularly interesting in the context of this paper as it has been successfully applied to design of systems exhibiting resilience and robustness in the face of changes and failures. In particular here we shall briefly recall the characteristics of three classes of distributed control mechanisms—bionic, holonic, and fractal architectures (Tharumarajah *et al.*, 1996; Ryu, 2003).

Bionic organizations are based on a hierarchical composition of autonomous building blocks characterized by spontaneous behavior and local interaction called cells or *modelons*. Biologically

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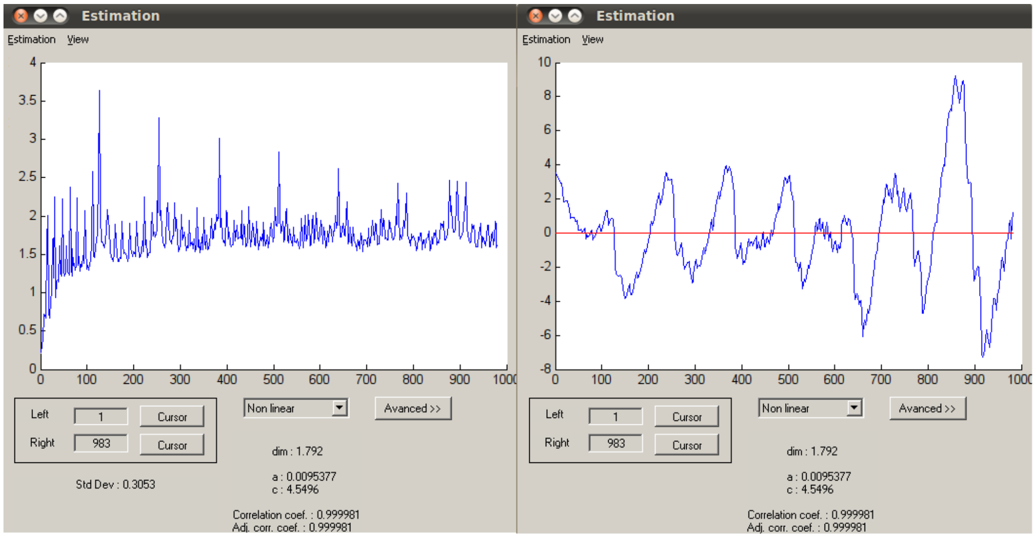

Figure 15. Scaling behavior and error curve produced by Fractalyse with the method of Fig. 14.

inspired concepts such as enzymes and hormones are used to model conflict resolution schemes. Attraction and repulsion fields are used to model collaborative tasks.

Holonic organizations are compositions of building blocks, called *holons*, which "are simultaneously a part and a whole, a container and a contained, a controller and a controlled" (Ryu, 2003). A same structure and a same set of configuration rules (the already mentioned called "canon") is repeated at different granularity scales producing so called *holarchies*. Holons are autonomous entities that establish cooperative relationships and are characterized by the emergence of stability, flexibility, and efficient use of the available resources. An example of said holarchies is given by so-called holonic manufacturing systems (Ryu, 2003).

Fractal organizations are similar to holarchies, but the canon is not statically defined in that it may freely evolve and differentiate. Local interaction and experience produce custom restructuring and regrouping as exemplified, e.g., in the Fractal Company (Warnecke & Hüser, 1993) and the Fractal Factory (Tharumarajah *et al.*, 1998).

4.2. *Knowledge Ecosystems*

Knowledge ecosystems (KE) are social organizations that aim at the emergence of collective intelligence through the mutual promotion of the individual and the social dimension. KE are based on the principle of social constructivism—the hypothesis that learning is a social process that takes place through the interactions in a society. In order to consolidate knowledge and produce wisdom, it is key that "information, ideas, insights, and inspiration cross-fertilize and feed one another free from the constraints of geography and schedule[¶]". KE comprise three overlapping layers or networks: (1) A social network whose members' "productive conversations" and collaborative behaviors create (2) "a knowledge network of ideas, information, and inspiration", sustained by (3) a technology network to communicate and persist ideas, knowledge, and lessons learned through experience. In order to function, KE must enable the quick sharing of the above ideas, information, and inspiration owned by the participating people, which is done through the technology network. This process is called by Pòr "electrification" of the knowledge network. Through such process the social network becomes a "web of distributed intelligence"—a sort of collective "nervous system" that is to enhance an organization's ability to tap into its own collective intelligence and thus formulate the most appropriate responses to turbulent environmental conditions. Said nervous

[¶]Here and in the rest of Sect. 4.2 quotes are from (Pór, 2000).

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system is “embedded not in computers and hardware, but in the interactions among people that bring the organization into existence day after day”.

4.3. Actor-Network Theory

Actor-Network Theory (ANT) is a complex social theory based on the above mentioned hypothesis of social constructivism and the central idea that “essences” (viz., individuals and societies) are to be interpreted not as “containers” characterized by a physical dimension, e.g., a surface or a sphere, but rather as *networks of nodes* that have as many dimensions as they have “ties” (i.e., connections)[‖]. Such ties are “weak by themselves”, though they achieve robustness (“material resistance”) through their social nature: “Each tie, no matter how strong, is itself woven out of still weaker threads [..] Strength does not come from concentration, purity and unity, but from dissemination, heterogeneity and the careful plaiting of weak ties”. “Strength” here refers to the ability of the “essences” to retain their identity in spite of environmental conditions affecting their ties and nodes. A fragile essence is one characterized by one or more points-of-diffusion-failures—as it is the case for the centralized and the hierarchical organizations discussed in Sect. 4.1; conversely, an essence is robust if it tolerates discontinuities and other information diffusion failures.

Be it an individual or a society, an ANT essence is not a static, immutable entity: It “starts from irreducible, incommensurable, unconnected localities, which [..] sometimes end [up] into provisionally commensurable connections”. Strength is sought by conserving identity despite the changes of scale that are necessary to counterbalance turbulent environmental conditions. The above mentioned “careful plaiting of weak ties” is meant to guarantee that a network “is the same”, though “stronger”. The *structured addition of complexity* that we observed in the organizations discussed in Sect. 3 may provide—we conjecture—a geometrical interpretation to the ANT concept of strength.

5. CONCLUSIONS AND NEXT STEPS

We sketched the main design elements of fractal social organizations—a class of socio-technical complex systems structured as fractal organizations and based on the recursive application of a same building block, the service-oriented community. Self-similar, modular, and fractal-like “by construction”, our solution—we argue—may provide our societies with a scalable and robust system structure able to match effectively the dynamically varying requirements and the turbulent environmental conditions that more and more threaten the manageability of traditional human organizations (Barabasi *et al.*, 2013).

As a preliminary way to prove the meaningfulness of our design choices we introduced a formal model for the dynamics of simple, non-hierarchical social structures organized as permutations of multisets of roles. Remarkably enough, we observed how the simple assumptions in our model resulted in the spontaneous emergence of a hierarchical and modular organization characterized by a structured addition of complexity and a fractal nature closely resembling the design traits of our organizations. By virtue of said resemblance and building on top of past results (Johns, 2011; Clune *et al.*, 2013) we conjecture that the concepts presented in this paper may be used to capture and conquer the complexity of traditional organizations that address vital services of our societies including, e.g., care, crisis management, goods and energy distribution, and civil protection. In the long run, should our conjecture prove correct, this may help fulfilling the visions of “smarter organizations” such as those expressed in (Anonymous, 2013a).

Considerable new challenges will need to be addressed in our future work. This will include investigating the effectiveness of FSO as a system structure for the intelligent sharing of resources, competences, knowledge, and goods. Moreover, scientific evidence shall be sought to verify the robustness, resilience, and self-management capability of socio-technical complex systems based on our models. We are already working in this direction by making use of Alchemist (Pianini *et al.*,

[‖]Here and in the rest of Sect. 4.3 quotes are from (Latour, 1996).

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2013)—a powerful tool for the simulation and verification of pervasive service ecosystems. Formal methods such as bi-graphical reactive systems (Milner, 2008) are also being used (Coronato *et al.*, 2012) to describe the behaviors of fractal social organizations.

Another "grand challenge" we plan to tackle is the design of knowledge ecosystems based on our models. Here the major property we shall investigate will be the emergence of forms of collective intelligence as well as advanced collective behaviors including, e.g., collaboration, collective strategies (Astley & Fombrun, 1983), co-opetition (Brandenburger & Nalebuff, 1998), and co-evolution (Adner & Kapoor, 2010).

Last but not the least, the current work provides us with a novel interpretation of the phenomenon of *modularization* as a spontaneous process governed by simple mathematical rules and initial assumptions. Further investigation shall be required to verify the relation between our results—and our "systems based on numbers" (Wolfram, 2002)—and the emergence of evolvability in natural organisms and biologically inspired artificial organizations (Clune *et al.*, 2013).

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