Service-oriented Communities: Models and Concepts towards Fractal Social Organizations

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***Abstract*—It is described an abstract model for the definition and the dynamic evolution of "communities of actants" originating from a given reference society of roles. Multiple representations are provided, showing how communities evolve with respect to their reference societies. In particular we show how such representations are self-similar and factorisable into "prime" constituents. An operating model is then introduced that describes the life-cycle of the communities of actants. After this a software component is presented—the service-oriented community—and its features are described in terms of the above mentioned models. Finally it is shown how such component can constitute the building block of a novel architecture for the design of fractal social organizations.**

***Index Terms*—Socio-technical systems; social organizations; collective adaptive systems; holarchies; fractal organizations.**

I. Societies as Complex Collective Adaptive Systems

Many scholars have studied the capability that societies of individuals possess to self-organize into higher forms of collective systems. Nature provides us with many examples of this phenomenon at different scales—for instance anthills, flocks, or cells. Societies of computer or hybrid systems are another well-known domain in which the emergence of self-organization has been thoroughly investigated. In his classic general systems theory paper [1] Boulding introduces such systems as social organizations, that he defines as "a set of roles tied together with channels of communication". We observe how even such a concise definition already captures several important aspects of the dynamics of social organizations:

A set. . . : Social organizations are (sub-)sets of societal constituents.

. . . of roles. . . : Such sets are characterized not by the *identities* of their constituents, but rather by their *role*: quoting Boulding [1], 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 other words, in Algebraic terms, social organizations may be modeled as *multisets of roles*.

. . . tied together. . . : The dynamics of the creation, operation, and destruction of this class of systems is governed by some force, or energy, that "ties together", that is autonomically specializes, differentiates, and partitions, the constituent multiset from the rest of society. Purposeful active behaviour [2] for the attainment of a shared goal is one such force. *Social energy* is the term referred to such force in [3]. In the same paper the term "community" is used to refer to social organizations while it is "network" in actor-network theory—a sociological method studying the dynamics of social organizations [4].

. . . with channels of communication: Such channels represent the media through which the constituents of a 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 knowledge and take part in

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decisions. By channel we interpret herein also the set of rules to make use of the channel and to take local decisions and local actions. The term used in literature for this set of rules is "canon."

Inspired by the Algebraic nature of Boulding's definition and by previous work on the dynamics of multisets [5], [6] we set to define a formal model for the dynamics of compliant societies and social organizations. Section II describes such model. After this, in Sect. III we extended this model by means of a case study and an abstract operating model for the life-cycle of social organizations. In Sect. IV then we briefly introduced the key ideas of a building block and an architecture for the definition of social organizations. Preliminary conclusions and future work are finally stated in Sect. V.

II. Algebraic Model for Social Organizations

In this section we introduce a formal model for the dynamics of societies of roles.

Let us assume we have a set of **roles**, uniquely identified by integer numbers, and a set of **actants** each of which is associated with one such role. 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 general practitioners (GPs), 2 nurses, and 8 patients,

collectively identified by multiset

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

Let us refer to multiset (1) as to a **society**.

Furthermore, let us consider operator concatenation ("·") to build "sequences" from the elements in the society.

In what follows we shall refer to any such 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 such 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 behaviour. The only aspect that is highlighted in this definition is the order and role of the constituents, as it is the case e.g. in DNA sequences of nucleotides. Another exemplification is a construction pipeline, where "something is done" by moving some data e.g. left-to-right through a set of actants identified by their role—that is to say their peculiar function. Yet another example is a table of instructions coded onto a Turing machine.

Now let us consider the onset of some **situation** [7] (endogenous or exogenous to the society) such that some reaction is triggered by or through some of the actants in the society. Such situations may be interpreted as opportunities (e.g. the onset of competitive advantage in the business domain), threats (e.g. an outbreak in the epidemiology domain), crises (e.g. an earthquake), or other circumstances or changes.

As an example, let us consider e.g. the onset of c, an alarming situation regarding one of the patients—for instance, the patient has fallen. Through some "communication channel" this situation triggers the intervention of 1 GP and 1 nurse. As a consequence, society (1) gets partitioned into two "blocks":

subset $L = \{0, 1, 2, 2, 2, 2, 2, 2, 2\}$ and subset $R = \{0, 1, 2\}$.

By construction, L is inactive with respect to c, while R is active with respect to c. In what follows we shall refer to an active subset of a society as to a **community** (when obvious from the context, situation c will be omitted). Being active means that the actants in R need to organize themselves (in some sense and here not specified way) so as to deal with the situation at hand. Summarizing, our exemplary society gets partitioned with respect to c into an inert subset L and some organization of community R—that is, an 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'.

Reorganization processes are called in [8] "dynamic restructuring processes."

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 c by finding resources within itself, possibly reshaping the flow of activities, but keeping the same roles. In mathematical terms R is closed with respect to perturbation c.

The repartitioning in step 2 signifies 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 as "*First*" a function defined as follows:

$$\begin{gathered} \textit{First} : \mathcal{B}(S) \to \mathcal{O}(\mathcal{B}(S)), \quad \text{such that} \\ \forall X \subset S : \exists n_0, n_1, \ldots, n_{r-1} : \\ \textit{First}(X) = 0^{n_0} \cdot 1^{n_1} \cdot (r-1)^{n_{r-1}}, \end{gathered} \tag{2}$$

where $\mathcal{B}$ is the Boolean function of a set 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 [5]). *Succ* takes as input sequence

$$\mathit{First}(L) \cdot R \tag{3}$$

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. Respectively we define Succ^{-1} as the function returning the previous organization. If applied to the first organization, Succ^{-1} returns the last one.

We now can model both cases of perturbations by "tossing a coin" corresponding to a relative non-zero integer number, say o, and applying $(\mathit{Succ})^o$ if $o > 0$ and $(\mathit{Succ}^{-1})^{-o}$ if $o < 0$[1]. *Succ* (respectively, its inverse) corresponds to perturbations that (in the absence of wraparounds) tend to let R grow (respectively, shrink) into a new R'.

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

$$\big(L(t), R(t)\big)_{t \geq 0} \tag{4}$$

defines a dynamic system corresponding to the dynamic life-cycle (that is, the evolution) of the possible organizations out of a given society of roles.

A. Properties

The just described model considerably extends the deterministic combinatorial model introduced in [5]. As it was done in the cited paper, here we can provide geometrical representations for the evolution of the dynamic system in (4). As an example, each orbit may be mapped onto an integer by interpreting roles as digits in some base. Another representation is obtained by mapping the differences between numbers corresponding to consecutive orbits—we call these numbers "delta steps."

As an example, Fig. 1 shows the dynamics of society $S = \{0, 1, 2, 3, 4\}$ throughout all possible organizations (*viz.*, all the permutations of multiset S). This corresponds to consistently applying *Succ* with $o = 1$ until the last organization is reached (no wrap around is shown). Ordinates here are delta steps. As can be seen from the picture, dynamics such as these are self-similar as they include the dynamics of smaller societies.

Self-similarity is also evident by applying other geometrical representations. One such representation arbitrarily breaks down organizations into m consecutive "chunks" of roles and interprets each of them as a base-r integer (*cf.* (2)). In turn, these numbers are used to identify points in m-dimensional space. An example for $m = 3$ is shown in Fig. 2.

A noteworthy property of the above shown 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. 3.

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. It is our conjecture that such "structured addition" of complexity is at the core of the robustness and resilience of systems and eco-systems based on such principle—the *dynamic equilibrium* pointed out by Webb and Levin in [10].

Preliminary evidence of the trustworthiness of our conjecture may be accrued by estimating the fractal dimension of our representation. To do this we counted the number of distinct orbits corresponding to families of self-similar societies. A family is self-similar in the sense that the dynamics of a smaller scale member is included in the larger scale ones. One such family is for instance

$$\{0^{2i+1}, 1, 2, 2\}, \quad i > 1,$$

that is the family composed by an increasing and odd number of role-0 actants (e.g. patients) as well as by 1 role-1 and 2 role-2 actants (for instance, a GP and 2 nurses). We interpreted i as the "scale" of the system and computed for each member the formula

$$\frac{\log(\text{actants})}{\log(\text{scale factor})}. \tag{5}$$

We found that for large societies formula (5) tends to become stable, which suggests a fractal dimension for this family of societies. This is portrayed in Fig. 4. Future work will encompass the use of other methods—for instance clustering or graph coloring methods—for estimating the fractal dimension.

We remark how not all families exhibit a similar trend—for instance family

$$\{0^4, 1^{2i}\}, i > 1$$

exhibits a quite different trend that can be seen in Fig. 5.

We have modeled the dynamics of restructuring of simple organizations by mapping organizations onto multisets of roles. Due to this assumption the resulting social organizations may be considered as ordered "chains" of sequential roles, similar in function to the stages of construction pipelines or to robot teams in spatial computing [11]. Representations of the dynamics of these organizations exhibit properties such as self-similarity and factorization into prime building blocks, in which complexity builds up through well-defined and well structured patterns. In what follows we make use of a case study to present an operating model for the definition of collective adaptive systems based on the just introduced dynamics of communities of actants.

III. Case Study and Operating Model

Let us suppose that Mary, an elderly woman, is living in her smart house. A smart house includes several devices, among which an accelerometer that is used to assess situations

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

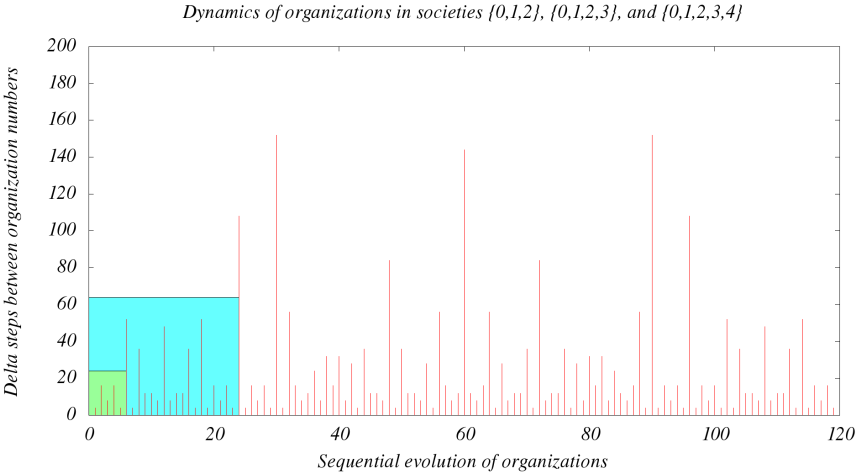

Fig. 1. Dynamics of society $\{0, 1, 2, 3, 4\}$. Rectangular regions correspond to society $\{0, 1, 2\}$ (green rectangle) and society $\{0, 1, 2, 3\}$ (cyan rectangle).

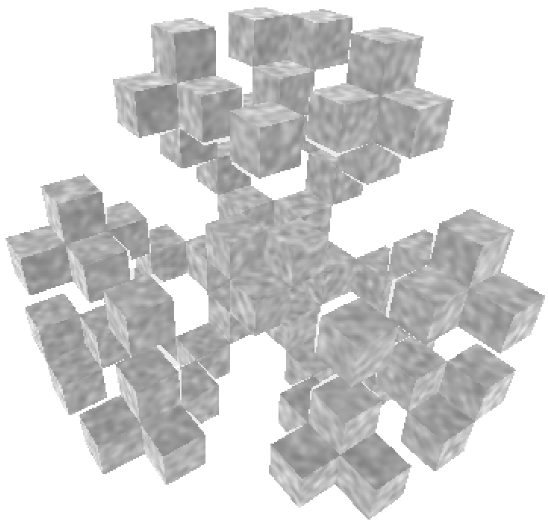

Fig. 2. POV-ray [9] picture generated by interpreting the orbits in (4) as coordinates in a 3D space. Again self-similarity can be observed.

such as "Mary has fallen" (situation c in Sect. II). The smart house service includes also a GP, who is timely informed of situations through some communication channel. Let us refer to the following roles as to society S_1:

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

in which δ_0 is the accelerometer, δ_1 is an alarm module (to be introduced later on) and $\delta_2, \ldots, \delta_d$ are other devices not relevant to the current case.

Let us now suppose that situation "Mary has fallen" takes place. Let us also suppose that δ_0 operates according to its specifications and correctly assesses the situation at hand. We shall then say that δ_0 becomes active. In terms of the model defined in Sect. II, this implies that S_1 is now partitioned into an L^1 set and an R^1 community as follows:

$$L^1 = S_1 \setminus \{\delta_0\}, \quad R^1 = \{\delta_0\}.$$

Becoming active means that δ_0 starts looking for pertinent activities—activities that is that are relevant for the situation at hand. 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 are being associated to the roles of S_1 through some mechanism (for instance, meta-data).

In what follows we shall denote activities as follows:

«situation : action».

Actions shall take the form:

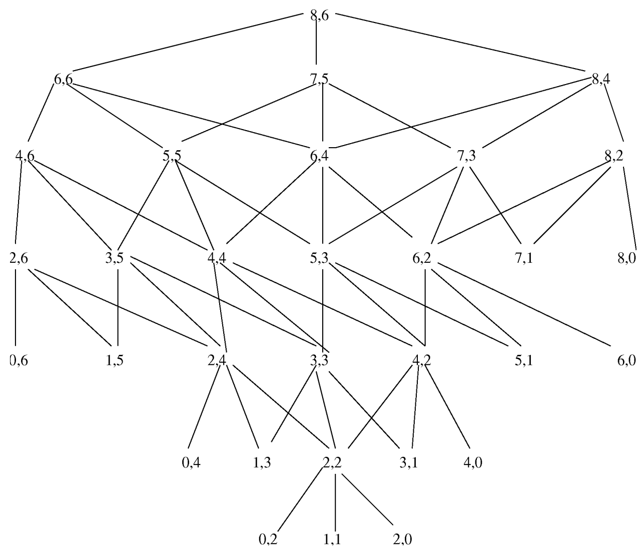

Fig. 3. Society $\{0^8, 1^6\}$, when represented bi-dimensionally, can be factorized into several instances of atomic societal nuclei, or "prime communities". Picture from [6].

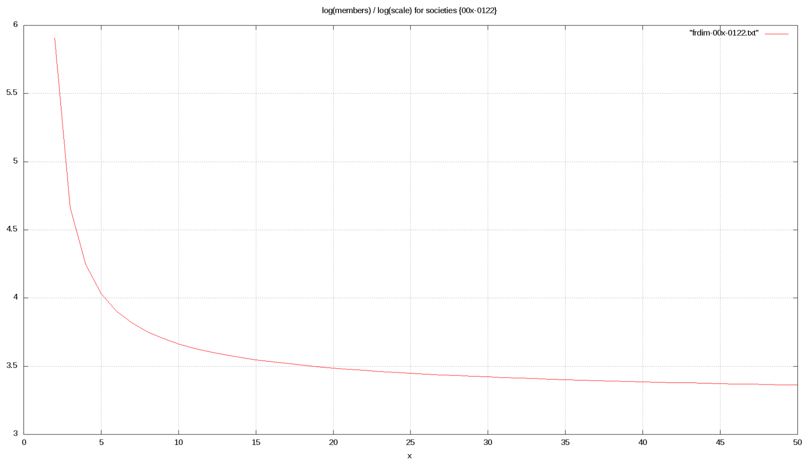

Fig. 4. Values of (5) for societies $\{0^{2i+1}, 1, 2, 2\}, i > 1$.

$$(\text{ role} \rightarrow \text{step}) \star$$

where "$\star$" 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:

$$\text{«fallen : } (\delta_1 \rightarrow \text{alarm(fallen))».} \tag{6}$$

Activity (6) states that, once δ_0 assesses condition "fallen", then δ_1 is to execute a single action step and raise an alarm.

It is worth remarking here how action steps *call for* actants. If a corresponding role can be found in organization R^1, that role is associated with the execution of the corresponding step. On the contrary a restructuring (called repartitioning in Sect. II) occurs:

$$L^2 = S_1 \setminus \{\delta_0, \delta_1\}, \quad R^2 = \{\delta_0, \delta_1\}.$$

Community R^2 can now execute (6). After this, R^2 dissolves back into the original society: $L^3 = S_1, R^3 = \varnothing$.

As it is sensible to do, we now suppose that activity (6) injects a new situation: "alarm has been triggered". The corresponding activity is assumed to be the following one:

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

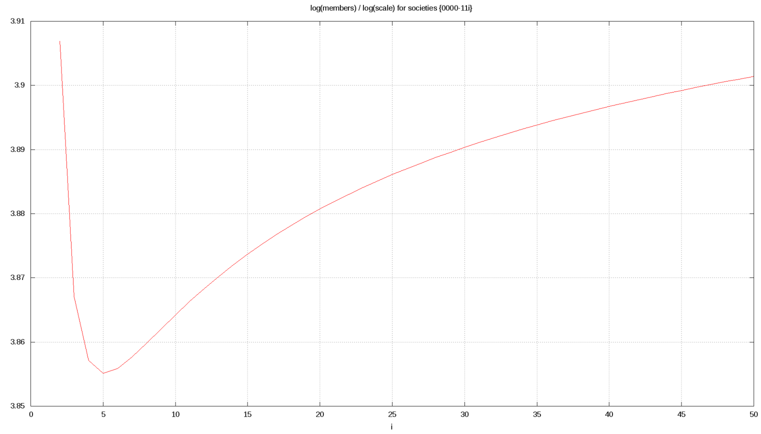

Fig. 5. Values of (5) for societies $\{0^4, 1^{2i}\}, i \geq 1$.

The first step implies a new partitioning as follows:

$$L^4 = S_1 \setminus \{\text{GP}, \text{Mary}\}, \quad R^4 = \{\text{GP}, \text{Mary}\}.$$

The treatment of this case is similar to what discussed above and it will not repeated in what follows. 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:

$$\text{«}\varnothing: \ (S_1 \rightarrow \text{up(neighbor,alarm(fallen))})\text{»}. \qquad (7)$$

Situation "∅" may be interpreted as an exception that either forwards the request to the next superset society that includes the current one—if any such society exists—or it fails—if no such society can be found.

Now let us suppose that the mentioned superset society does exist and be equal to

$$S_2 = \{S_1, \text{neighbor}, \textit{something else}\}.$$

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:

$$L_2^1 = \{\textit{something else}\} \quad \text{and} \quad R_2^1 = \{S_1, \text{neighbor}\}.$$

As a consequence, neighbor now can become active within R_2^1 and deal with the situation inherited from S_1. Note how this is a change of scale corresponding to moving up through a tree such as the one in Fig. 3. Note also how the life span of community R_2^1 is defined by the duration of the action step neighbor → fallenNeighbor(fallen). Finally, we remark how more than one exception may occur, leading to the participation of S_1 into more than one superset society at the same time.

We now provide the basic elements of an architecture based on the principles discussed so far.

IV. Service-oriented Communities

In Sect. II we have introduced a formal model for the dynamics of communities of roles and then in Sect. III an abstract operating model to describe how we envision the life-cycle for such communities. A practical use of the above results requires an architecture able to allocate dynamically roles to social members as well as the ability to manage dynamically those roles in function of the situation at hand and the characteristics of the available members. In what follows we provide the key ideas of such an architecture—namely its building block and its hierarchical organization.

As shown in previous sections, actants are characterized by significant *diversity*: actants can be smart devices or human beings; in the latter case, they may have a variety of purposes and a dynamicity of goals—for instance reaching a certain location within a given time, with a maximum budget of travelling costs, and with a minimum threshold of quality of experience. Furthermore they may be characterized by different features, e.g. 1) different know-hows (e.g. those of a GP, or those of a gardener), 2) different policies in providing their services (e.g. well-defined time schedules and fares, or dynamically varying availability to provide free-of-charge services as occasional informal carers), 3) different location, in that actants may be mobile, thus able to get dynamically closer to or farther from other actants, 4) different value systems making them more or less sensible to the onset of certain situations, and so on. Accordingly, a first service in our software model is to collect, manage, and classify the peculiar aspects and distinctive characters of a set of actants in proximity of one another. This is depicted in Fig. 6. We envision that people and devices compliant to our model publish their characteristics through some well-defined semantic representation called "viewpoint". Such viewpoints would be managed by some shared space organized e.g. as tuple spaces [12], [13]. According to some strategy one of the actants would temporarily assume a special "meta-role", namely that of manager of the viewpoint space. Replication and mutual watchdog mechanisms as in [14], [15] could be used to enhance the resilience of this managing actant. Here roles would be assigned to the actants and the onset of situations would be declared and broadcast. This special role would also include the local coordination of the activities associated to the known situations and the publishing of the community life-cycle events (that is, the creation of new L and R sets). Furthermore, this actant would manage the propagation of "role shortage" exceptions as described in Sect. III.

The just sketched component may be considered as the building block for an architecture managing dynamic hierarchies of communities of roles. The term used in literature to refer to such a component is "canon", while hierarchical organizations of these building blocks are known as "holarchies" and "fractal organizations"[2]. A SoC fractal organization is depicted in Fig. 7, which portray service-oriented communities at different scales—here identified as Layer 0, Layer 1, and Layer 2 members. An exemplary representation is shown in Fig. 8, whose layers include individuals, smart houses, hospitals, and communities of hospitals. The same triangle-shaped pattern of the SoC repeats itself in each scale. The right-hand side of Fig. 7 provides a representation of this phenomenon in terms of a fractal structure whose dimension is approximately equal to 1.5849625.

A multiplicity of such organizations may exist and—as it is the case in real-life—actants may be part of several such structures at the same time, possibly playing different roles.

V. Conclusions and Next Steps

Three models have been introduced to describe the dynamics of communities of actants, their life-cycle, and a building block for the definition of compliant fractal social organizations. We showed how such models are characterized by a structured addition of complexity, by self-similarity, and by factorization into prime constituents. Based on results of other researchers [10], [18] we conjecture how those properties may prelude to robustness, resilience, and self-organization capability. Preliminary research on "flat" (single-layered) communities suggests that they may also allow the exploitation of the "self-serve" potential of our societies [19], [20]. Future work will include a full-fledged design of the SoC and its validation through simulation models and real-life applications. Moreover, we intend to address the study of the social aspects of such systems and their modeling as "actor networks" [4]. Formal methods such as bigraphical reactive systems [21] are also being used [22] to describe the behaviours of fractal social organizations.

[2]Holonic and fractal organizations are compositions of autonomous building blocks, called respectively *holons* and *fractals*, which "are simultaneously a part and a whole, a container and a contained, a controller and a controlled" [8]. A same structure and a same set of configuration rules (the already mentioned *canon*) are repeated at different granularity scales. Those structures are autonomous entities that establish cooperative relationships and are characterized by the emergence of stability, flexibility, and by efficient use of the available resources. Examples of the above organizations are the Fractal Company [16], the Fractal Factory [17], and Holonic Manufacturing Systems [8].

Acknowledgments

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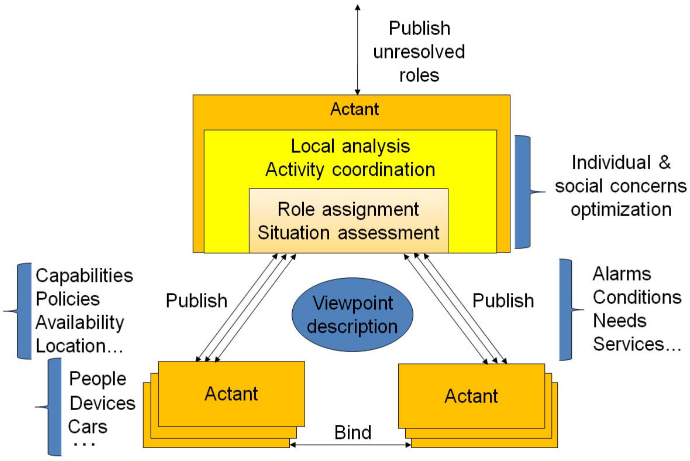

Fig. 6. Representation of the canon of the Service-oriented Community.

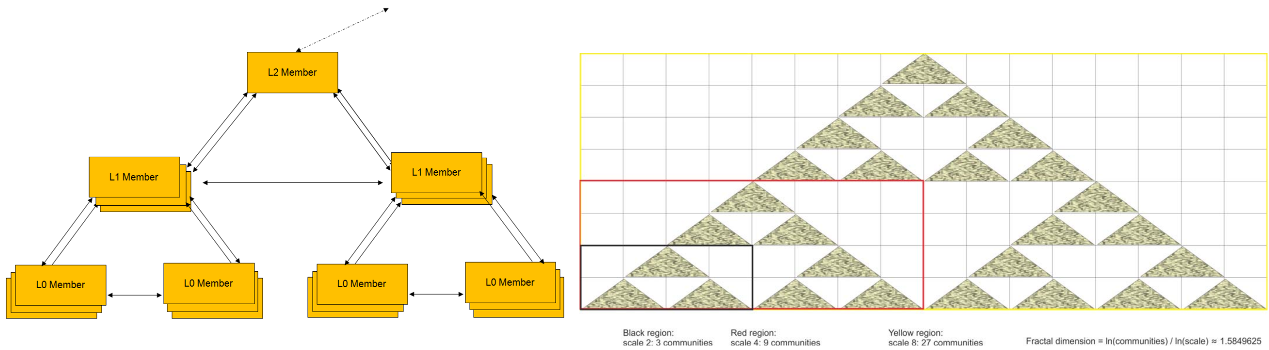

Fig. 7. The left-hand picture represents the SoC architecture. Resemblance with a known fractal is shown in the right-hand side.

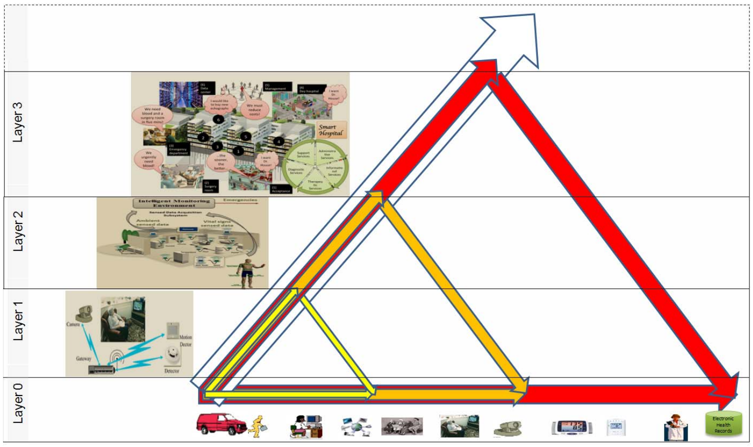

Fig. 8. Exemplification of SoC social organizations.