CONCEPTUAL MODELING OF EMERGENT PROCESSES IN DYNAMIC COMPLEX SYSTEMS

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Abstract: - The proper study of Dynamical Systems (DS) considers phenomenal dynamics, from which it is possible to reach an approximate description of its operation and an explanation for their behavior, often complex and unpredictable. Studying dynamic systems (DSs) currently requires an integrated framework of concepts, which should allow analysis from a broader perspective. In response, this work expands the vision of Dynamic System (DS) from its complexity way and from the related dimensions of its Self-organization and Emergence, in addition with Homeostasis, and Autopoiesis dimensions (SEHA approach). Thus, in this document, firstly, DS is described and supported on the basis of its SEHA and, secondly, develops notions for each of the SEHA phenomena, which are described in detail based on its integration to a concept map model that facilitates the observation of their relations, especially regarding DS self-organization. This approach is a synergic and promising way to understand processes and mechanisms that govern surrounding or constructed DS-SEHA, at the time it sets up the bases for a future formalization with modeling aims.

Key-Words: - Complexity, Self-organization, Homeostasis, Autopoiesis, Emergence, Conceptual Map, Dynamical System's Structure.

1 Introduction

Dynamic systems raise great interest due to their variety and cosmopolitan existence in the physical universe as well as in the laws universe that supports much of the sciences created by humanity. The basic trait of any DS is the change of state in time, according to a law governing its evolution [1]. From this start point, in DSs with a large set of components, the presence of other peculiarities has been observed, including high interconnection level, mutual interdependence, role plasticity and adaptability, and pattern generation, among others [2]. Based on these characteristics and the autonomous behavior of its elements, DSs can accomplish tasks with considerable difficulty. This is possible, as rules evolving from simple to complex and being independent from any superior level instruction or central control, direct its elements. Such condition determines DS capacity to establish its own organization based on a *self-organization* process that has at the same time, as a common factor, the emergent dimension of its global order and behavior [3].

Starting from the self-organization and emergence processes, the particular fact of difficulty to explain the global order and behavior of DS based on the interactions of its individual elements arises [4]. This event, which defines the DS complexity, translates into modeling terms, as the property that challenges formulation of complete order and behavior of the system in a given language, even when reasonably complete information on its atomic components and interactions is available [5]. In other words, DS complexity relies on the difficulty of explaining and modeling emergent properties based on the system's self-organization. This situation turns equally complex when pretending to explain and modeling self-organization from the emergencies.

Although self-organization and emergence have been the basis of a promising approach in different fields (e. g. self-organization engineer, multiagent systems and adaptive complex systems [6]), it becomes necessary to expand the study to inherent and complementary phenomena, which at the same time support those basic features, such as the ones related to adaptability and autonomy. These are situations that favored the maintenance of the system structure

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and function. These phenomena correspond to Homeostasis and Autopoiesis. The former refers to an event that allows the establishment of a dynamic equilibrium among elements within a system, while the latter is as an extension of homeostasis, which is related to the self-maintenance of system integrity on the basis of self-organization development, conservation and production [7].

Even though the former ideas, definition of a DS in terms of Self-organization, Emergence, Homeostasis and Autopoiesis (SEHA) requires the generation of synergic notions that will allow a better description of its behavior and function. This becomes more relevant if considering the large amount of separated existent SEHA notions and interpretations, especially related to Self-Organization and Emergence, which have been even used as synonyms [4], that are not describe in this paper due its number. With this in mind, this document proposes a unified conceptual modeling framework of DS-SEHA notions to study and describe DS with complex traits, leading to a more integral vision of DS in its complexity way.

2 Problem Statement

DS have as interesting feature the ability to establish their own organization that at the same time the *emergent* dimension of its global order and behavior considered as complex. Although the self-organization and emergence phenomena have been keys to explain complexity in the DSs, due to their adaptation ability to environmental changes, it is important to consider that adaptation is achieved on the basis of a dynamic equilibrium or *homeostasis*, an intrinsic situation to self-organization, supported by regulatory mechanisms allowing self-organization to remain stable [8]. In addition to homeostasis, DSs self-organizing capacity is based on the process of interaction between system elements that regulate the production and regeneration of the system's components, i.e. *Autopoiesis* [9]. The phenomenon of autopoiesis has laid the theoretical foundations of self-maintenance, which leads to autonomy or maintenance of the entire system. In this sense, the system's structure and function would benefit in terms of the system permanence itself. All this is achieved by establishing autopoietic components networks, which have the potential to develop, to preserve and to produce their own organization [7].

The above perspective leads to consider that studying DSs, in terms of their complexity, should not rely exclusively on self-organization and emergence notions, despite their central role, but it is appropriate to integrate Autopoiesis and Homeostasis phenomena as well. This would result in a more comprehensive and synergistic notion of DSs and its related SEHA dimensions.

3 Conceptual Modeling of Proposed SEHA Notions

This item includes two subsections; the first one is related to the DS working notion, its elements and SEHA interactions as a general framework; the second one is related with SEHA proposed notions in the general framework. All notions are depicted by means of conceptual maps.

3.1 DS Working Notion under SEHA approach

3.1.1 DS Definition

Given a culture, a context and a linguistic game of an observer or subject that identifies itself a DS as a unitary phenomenon derived from its recursive relationship with its environment, which presents an interconnected set of homogeneous or heterogeneous elements occurring in spatial and temporal scales. These elements generate, from their interactions and subsequent relationships, diverse kinds of their own properties, organizations, patterns and/or behaviors, at different system levels, in order to achieve the global goal that the system has in itself.

3.1.2 Description of DS Working Notion Elements

A deeper analysis of the DS working notion leads to consider the existence of significant features such as:

The *culture* corresponds to the cultural matrix of the observer or subject (from now on referred as subject), i.e. the set of meanings from which the subject understands the world. This matrix is given, for example, by traditions, myths and/or stories that the subject incorporates to his worldview, from its experiences in one or more communities. It is remarkable that different cultures can include common facts in their matrix (e.g., the man-nature relationship), which may result in the same or different meanings, depending on the interpretation of each culture.

A *context* represents the field where the subject develops the modeling process and the resulting

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model. It is linked to the knowledge, intention and interest as well as the prejudices of the subject which represents the modeler. This field may encompass political, historical, cultural or other natural facts in the modeling process.

A *language game* is the specialized language that is built on the base of the subject's culture (or on what it remains of it, if it has decayed) in a specific context. This language game gives meaning and value to a word, phrase or fragment. In cultural matrices in good state, certain observations generated in one or another language game must be able to be transferred to the common language shared by the rest of society.

The *recursive relationship* between the subject and the observed object (system-environment pair) is one in which they both are in continuous feedback. From this relationship arises the reason to be of the system or phenomenon; without this connection the system is not what it is, or would cease being one. It is said that the subject and the observed object are made and remade continuously through this relationship.

The *environment* in which the SD is defined by the subject corresponds, among others, to members of the community of knowledge, as well as simulation models, theories, or the physical and social world.

The identification of SD as a *unitary phenomenon* relies on the determination, either implicit or explicit, of the system's limits or boundaries in relation to its surroundings, carried out by the subject. This event generates the acknowledgement of the system as a whole, where nothing is left out as a fact that cannot be understood and could generate interference. Instead, it is incorporated in the meaning of what has been understood. On the other hand, the subject that observes, imagines and abstracts the borders, might also be observed by another subject in the vicinity of a super-system.

Borders can be defined both by physical barriers or the continuity or discontinuity of its elements interrelationships of its elements. Thus, the boundaries can have physical and metaphysical meaning, respectively.

The *system-environment interaction* takes place through the recursive exchange of matter-energy and information flow across borders, so that the flow goes from outside into the system and it is exported abroad from the system.

The *elements interconnections* define their *interactions* topology that lead or don't to the consequent establishment of *relationships*, depending on strengthening or weakening events. The elements interactions are understood as short-term contacts and fleeting connections; while the elements relationships are understood as inter-union phenomena (association, combination of elements) of enduring nature. The interactions and relationships dynamics is a basic element of system's complexity. These dynamics conduct to changes in the not imposed system's organization (i.e. self-organization), according to the environmental changes and the possibilities of the system elements to adapt.

The *adaptability* of the system occurs individually and collectively in time and space as well as on the basis of the adaptability range of the system. From this point of view, the self-organizing system is based on interactions and relationships topology between the elements of a particular structure. Both the elements and the generated structure have an unknown potential to establish relationships with each other supported by its adaptability and evolution, which is another reason for the complexity of the system.

The spatial and temporal scales in which individuals occurs correspond with a particular dimension in space and time, i.e. the observation window of space and/or time that defines the importance of system elements, their characteristics and environmental parameters. These influence elements interactions and the selection among one or another self-organization. In these scales, operating variables and processes explain the patterns observed in a certain level system. The spatial and temporal scales are a basic feature of systems dynamism and complexity, because it requires the analysis of change, variability and heterogeneity in order to possibly explain and predict the observed patterns.

The generation of diverse kinds of organizations, patterns and behaviors from local interactions at different system levels in a particular spatial and temporal scale, clearly states the emerging nature of DS. From this perspective, a particular phenomenon considered as an emerging one, can also be the product of a given type of self-organization. Likewise, these features define the global system unit, which is the result of synthesizing qualities representing emergence.

DSs regularly have observation levels; the most common are both the local level or interactions level

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and the upper level or the level where emergent properties are observable, as a product of the dynamical interaction at the local level.

At the same time, self-organization indicates the ability of DS to regulate their behavior in adaptive terms, looking for a dynamic equilibrium or homeostasis. This way, homeostasis is important given that it controls the lack of regularity produced by flow dynamics between the elements and its environment. Homeostasis includes, articulates and integrates the system states with different and complementary conditions such as dynamic-stationary, stability-instability, and synthesis-degradation, among others. The homeostasis functionality is to keep self-organization within limits which would secure their autonomy, integrity, compatibility and other essential attributes, while flow of matter, energy and/or information in the system goes on. All these events occur within the adaptability framework of the system.

Consistently, it is estimated that an important homeostatic mechanism in DS is the autopoiesis, a process where the self-maintenance, in the context of the synthesis-degradation relationship, is achieved through the interactions between system components. This property is the basis of the system autonomy and promotes self-organization through self-regulatory mechanisms that maintain the system structure in line with a changing environment.

The unveiled SEHA phenomena composing this DS working notion are a mean for the system to *persist* in space and/or time, i.e. the essential purpose of the system. Invariably, the system persistence is achieved in terms of maintenance, adaptability, and evolution of its elements and the system as a whole.

3.1.3 SEHA relations in DS Working Notion

The above mentioned notion of DS has particular characteristics, which clearly support the existence of DS presenting SEHA features (DS-SEHA). This way, it is feasible to describe the recursive relationships between DS-SEHA phenomena suggested in Figure 1, where DS-SEHA approach is synthesized and integrated based on their circular causality relationships. Note that this is one of multiple perspectives and representations for DS-SEHA approach.

An explanatory narrative circuit of Figure 1, which starts from the subject concept of the subject, indicates that an observer or a subject, in a specific culture and context framework, acquires a language game that allows it to identify a DS in a recursive relationship with the environment as a unitary phenomenon. This unitary phenomenon has elements, which in particular combinations form the structure of the system. This structure supports self-organization which is based on the interactions and relationships of the system elements.

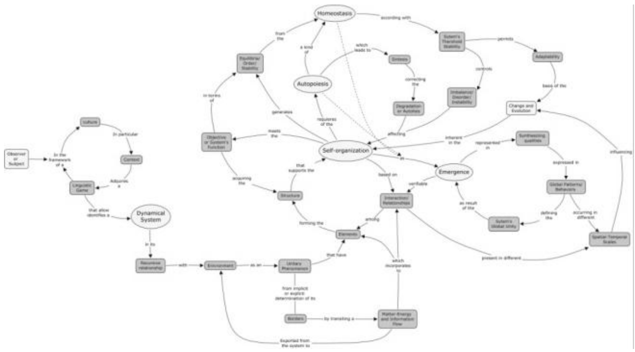

Fig. 1. Integrated processes in the DS-SEHA approach. The interaction between concepts maintains a circular and recursively disposition. It is recommended to start the reading from the subject concept.

The unitary phenomenon detected by the subject, comes in addition by determination, either implicitly or explicitly, of the system borders. Across these borders, a matter-energy and information flow transits. This flow is incorporated both to the elements and the interactions and relationships between them. This flow is bidirectional given the importing flow into the system and also the exporting flow to its environment.

Back to the self-organization phenomenon, it is estimated that it meets the objective or function of the system, which is acquired from the structure of the system. Similarly, the system function or object is met in terms of equilibria, order, and stability, which is generated by homeostasis.

In addition, homeostasis, consistent with the stability threshold of the system, controls the imbalance, disorder and instability that can affect self-organization. The stability threshold of the system under homeostatic processes also allows adaptability in the system.

At the same time, adaptability is the basis for inherent change and evolution in the self-organization phenomenon. This change and evolution is influenced

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by spatial and temporal scales, at which interactions and relationships between elements occur.

The autopoiesis is a homeostatic mechanism required by self-organization, which leads to the synthesis that corrects degradation or autolysis (the ability to destroy while regenerates) affecting self-organization. Thus, autopoiesis also keeps the balance in the system.

As seen above, self-organization, homeostasis and autopoiesis can be seen as the system emergences. Such emergencies are verifiable in the interactions and relationships between system elements.

The emergence is also represented in synthesizing qualities that can be expressed as global patterns an behaviors, which occur at different spatial-temporal scales and define the global system unit, the same that results as the product of emergence itself.

3.2 SEHA Proposed Notions

In a conceptual model, notions developed in this work are shown in figure 2. From there, these notions are itemized in the next paragraphs of this section, so that they become clearer.

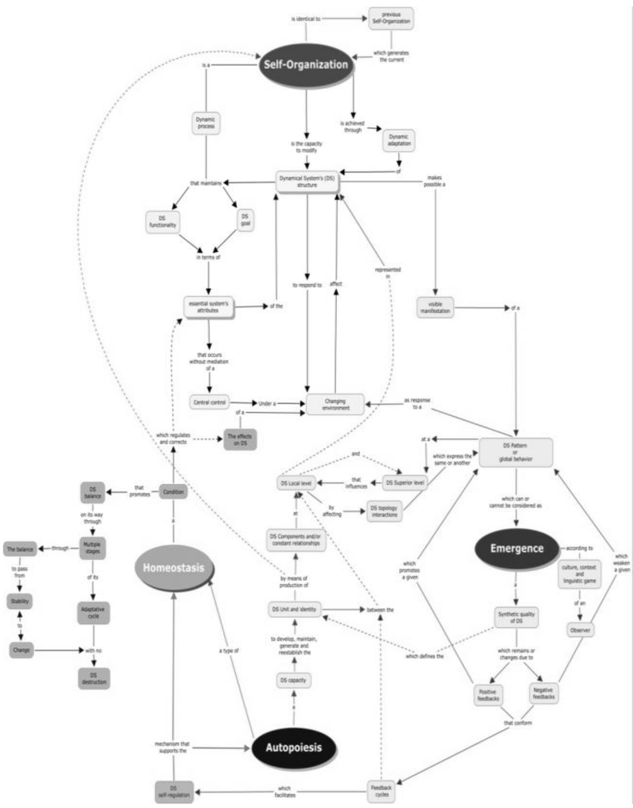

Figure 2. Integrated Conceptual Map of Self-Organization, Emergence, Homeostasis and Autopoiesis within a DS.

3.2.1 Self-Organization

Self-Organization (Fig. 2) corresponds to a dynamic process that maintains DS functionality and object in terms of essential attributes. These include autonomy, which should be understood as DS lack of dependence of external to reach its function and goal; persistence, referred as functionality maintenance; robustness, which is explicit in the tolerance to external pressures or internal failures; flexibility, related to the susceptibility to change structurally according to the circumstances or needs; and finally integrity, which defines DS as the unit in terms of the whole, the parts and their relations.

As an important trait, the self-organization process occurs without mediation of a central control and under changing conditions of the surroundings that affect the DS structure. Regarding the structure, self-organization defines the modifying capacity to respond precisely to the changing surroundings.

Self-organization can be achieved through adaptation of DS structure in time, which is represented in local variation of collective properties and topology of elements interaction in the DS (Fig. 3, left top box). This is where the static (relations among elements) and dynamic (relations among processes) components of this phenomenon are represented. In this point, the static (relations between elements) and dynamic components (relations between processes) of this phenomenon are represented. Resides, collective properties refer to elements composition of DS as well as to their qualitative and quantitative attributes. The composition represented by the type of element, (Fig. 3, right top box) whether homogeneous or heterogeneous, defines part of the qualitative attributes of elements, i.e. those that express a regularly non-measurable quality, defined by its internal-external structure. Depending on the type of DS to which elements belong, some qualitative attributes can be size, composing material, and gender. In statistical terms, there is a form to treat this qualitative attributes if defined numerically as proportions or percentages (e.g. percentage of small elements). On the other hand, quantitative attributes are referred as number, proportion, percentage, numerical diversity, numerical richness, or any other numerical estimative of each one of the defined categories of the DS elements, based on its identification and nomenclature (e.g. name assignment, code, reference, etc.) or any qualitative attribute.

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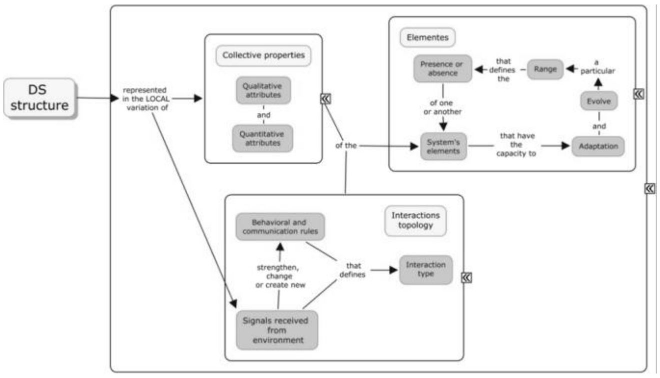

Figure 3. DS Structure Details.

In contrast, interactions topology (Fig 3, bottom box) refers to the form taken by the interactions network and its changes in time, where each node in the interactions map corresponds to a DS element. The particular shape of the interactions network is conformed, changes and evolves in response to signaling perceived from the surroundings by the DS elements. At the same time, the perceived signals reinforce, change or generate new behavioral and interaction-communication rules among elements. The set of perceived signals together with the behavioral and interaction-communication rules, define a posteriori the type of relation within and among the DS elements. In the case of relations among elements, in a symbiotic way, they can be defined in a general way as cooperative or not, considering that they can benefit both of the elements, one element only or no element at all. However, it is possible that in a given interrelation, one or more elements end up harmed while others benefit.

DS elements present shared characteristics and particular traits, which give DS adapting and evolving capabilities. These result in the possibility of responding to certain changes in the surroundings. These events define, among others, the presence or absence probability of any element in the DS.

3.2.2 Emergence

Emergence (Fig. 1) in an essential attribute of DS, which derives from dynamic adaptation of structure relying on interactions and interrelations among elements conforming it, as described in the preceding item on self-organization. Such dynamic adaptation of structure makes possible the manifestation of a pattern or global behavior that can or cannot be considered as emergence depending on context, culture, and linguistic game of an observer.

Therefore, emergence constitutes a synthetic quality of DS by being a product of the complementary interaction of its elements. These deliver diverse aspects to what emerges, in a way that consolidates the DS as a whole, which defines the global unity of the DS.

It is important to emphasize that the global pattern or behavior can or cannot be considered as emergent or emergence, according to context, culture and linguistic game of an observer that identifies the DS in its recursive relationship with its surroundings as a unitary phenomenon.

Maintaining or changing one or another emergent property results from the existence of positive and/or negative feedbacks. In general terms, the former promote continuity of a given global pattern or behavior of the DS, while the latter weaken it. These two types of feedback direct to the generation of feedback cycles that have as objective easing DS self-regulation.

The global pattern or behavior is observable at a superior level and arise as a response to the changing surroundings. Consequently, the resulting pattern or behavior influences the local level (where DS structure is represented) by affecting topologies of element interaction in the DS. This effect on topologies implies that the same pattern or its variant will be expressed recursively in the superior level. The basic mechanism for this is related to feedback cycles that occur between the local and superior level, which define utility or convenience of the pattern or behavior in terms of DS object and functionality.

3.2.3 Homeostasis

Homeostasis (Fig. 1), which is a mechanism supported by DS self-regulation, is defined as a condition that promotes DS equilibrium on its way through multiple states of its adaptive cycle, with no destruction. Having self-regulation as support, homeostasis controls disturbances and variation that can affect DS, maintaining this at viability limits that sustain its permanence.

Equilibrium promotion, on its way through multiple states, is reached through the required balance to pass from stability to change and vice versa, without DS destruction. To this effect confluence of diverse processes in self-organization of DS, which are mediated by homeostasis, is detected.

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Through homeostasis, DS obtains regulatory and correcting capacities of its already described attributes, on one side, and of effects on DS of changing surroundings produced by matter, energy and information exchange, among others, on the other side.

As a synthesis, it can be estimated that mechanisms through which DS or its elements face environmental changes without causing an unbalance in its essential attributes, correspond to homeostatic mechanisms. These are the same which generate order and stability in the system.

3.1.4 Autopoiesis

Autopoiesis (Fig. 1) is defined as DS capacity to develop, maintain, produce or establish its unity or identity. In other words, it corresponds to a pattern providing stability to DS self-organization and constitution in itself.

DS unity and identity is sustained by production of components and/or constant relations at local level, as well as of self-organization. Likewise, autopoiesis has a totalizing effect of unity and identity among local and superior levels of DS.

Self-organization revealed in a given moment will be identical to the former self-organization that generated it, which is possible due to the identity and self-generation principle that governs autopoiesis. In this sense, if self-organization doesn't regenerate in a permanent manner, DS disintegrates in terms of its interconnections and interrelations, as well as of its structure and components.

Autopoiesis, as the system capacity to maintain its unity and identity, is supported by self-regulation mechanisms of DS, which result from feedback cycles operating in the DS. Starting from them, autopoiesis in turn constitutes a homeostatic mechanism that reveals itself, especially in the constant dynamic of generation and regeneration of DS components, interconnections and interrelations, i.e. its own organization.

4 Final Comment and Future Work

The DS conceptual modeling developed in this manuscript following the SEHA approach, defines the essentials characteristics, components and processes for a large set of systems abstracted from the cosmos and the biosphere, as well as other built by humans. This way, the DS-SEHA approach finds applicability to both natural and artificial systems. On the basis of the DS working notion presented here.

The DS approach from the SEHA perspective developed defines and clarifies notions on essential phenomena form the maintenance of essential attributes of diverse DSs. This broader and synergic focus contrasts with formerly existent advances which consider only self-organization and/or emergence phenomena in DS. It is remarkable that inclusion of homeostasis and autopoiesis notions, based on a less restrictive perspective that goes beyond its applications on biological organisms, adds to its use more profusely in characterizing DS and studying its complexity. Its inclusion is absolutely justified by the central role played in the maintenance of self-organization.

Starting from the conceptual base developed in this work, it is expected to take this to the mathematical context in the short term. Thus, producing formalizations that support this conceptual base appropriately and that in consequence make feasible its application into modeling and simulation of real, complex and multi-agents DSs.

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