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Article

Theoretical approaches to managing complexity in organizations: A comparative analysis

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ABSTRACT

This paper aims to identify the differences and similarities in the way to explain self-organization from the different theories of complex systems used in management, which we have grouped as complex systems theories, complex adaptive systems (CAS) and organizational cybernetics. For this purpose we suggest three parallel and complementary dimensions to delimit the conceptual spaces where these theories can be placed. Using this classification as an analytical lens we summarize the core arguments suggested by each of these complex systems approaches, regarding the ideas of emergence and new order. This analysis helps us to conclude that the three theories coincide in their interest for studying nonlinear complex systems, but diverge in the nature of the complex problems studied. Finally we analyze the consequences that recognizing the similarities and differences between these approaches have, when using them for the study and research of social and business organizations and their management.

Enfoques teóricos de manejo de complejidad en las organizaciones: un análisis comparativo

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RESUMEN

El propósito del artículo es identificar las diferencias y similitudes en las formas de explicar la auto-organización en las teorías de sistemas complejos, las cuales se han agrupado en ciencias de la complejidad, cibernética organizacional y sistemas adaptativos complejos (CAS). Para tal fin se proponen tres dimensiones paralelas y complementarias que permiten demarcar el espacio dentro del cual se ubican las distintas teorías. Usando como eje analítico esta herramienta de clasificación, se resumen los planteamientos realizados por cada una de las aproximaciones respecto a la emergencia de nuevo y orden; y se concluye que las tres teorías coinciden en el estudio de los sistemas complejos no lineales, pero se diferencian en la naturaleza de los problemas abordados. Finalmente se analizan las consecuencias que el reconocimiento de las semejanzas y diferencias entre los diferentes enfoques tiene para su utilización en el estudio y gestión de organizaciones sociales.

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Abordagens teóricas da gestão da complexidade nas organizações: uma análise comparativa

RESUMO

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Palavras-chave:
Auto-organização
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Ciências da complexidade

O objectivo do artigo é identificar as diferenças e semelhanças nos modos de explicar a auto-organização nas teorias de sistemas complexos, os quais foram agrupados em ciências da complexidade, cibernética organizacional e sistemas adaptativos complexos (CAS). Para esse fim propõem-se três dimensões paralelas e complementares que permitem demarcar o espaço dentro do qual estão situados diferentes teorias. Usando como eixo analítico esta ferramenta de classificação, resumem-se as análises realizadas por cada uma das abordagens a respeito do aparecimento de novo e ordem; e conclui-se que as três teorias coincidem no estudo dos sistemas complexos não lineares, mas diferenciam-se na natureza dos problemas em questão. Finalmente analisam-se as consequências que o reconhecimento das semelhanças e diferenças entre os diferentes enfoques têm para sua utilização no estudo e gestão de organizações sociais.

1. Introduction

Studying social organizations as complex systems had became more relevant over the last few decades, mostly as a result of strong critiques to the traditional mechanistic paradigm in which organizational theory was originally based, and of related questions about the lack of effectiveness of hierarchical control associated with it (e.g. Turnbull, 2002). In the globalized and open markets context where most organizations operate nowadays, the pressures for competitiveness, flexibility and dexterity has increased, and this demands for more adaptive structures. In this context, contemporary complexity theories that inspire managers with ideas about self-organization and neural network-like organizations are in demand, both in academic journals and in consultancy (e.g. Mitleton-Kelly, 2011). This is also the case with social science researchers, which are increasingly attracted to ideas of permanent innovation, co-evolution, decentralized decision making, among others (e.g. Allen, Maguire, & McKelvey, 2011; Axelrod & Cohen, 2000). Even if the outputs from complexity researchers have been significant in the last few decades, it has deep historical roots. Early works from Adam Smith ("The invisible hand"), Von Neumann (self-replicating systems), and Darwin (evolution theory), among others, provide clear traces of inspiration to the earliest theories on self-organization and complex systems.

Self-organizing systems are understood as systems that operate autonomously, and co-evolve between themselves through transitions between disorder and order: they have been studied from different schools of thought which include the *sciences of complexity*, *complex adaptive systems (CAS)* and *cybernetics*.[1] From an ontological point of view these three streams of thought understand self-organization as the spontaneous emergence of collective behaviors from the interaction between autonomous agents (Di Marzo Serugendo, Gleizes, & Karageorgos, 2011). Additionally they all agree that organizations are nonlinear systems that evolve over time. Various authors have considered self-organization as the central aspect of complex systems (Martinoli, 2001; Nitschke, 2005). Speaking of complex systems generally involves talking about self-organization.

However, there are theoretical and methodological differences in these three approaches to self-organization that have not been often spotted in the management literature (e.g. Battram, 2001; Etkin, 2009). On the contrary, most of the references to self-organization in the management sciences literature seem to assume that the sources are homogenous and sort of coincidental. We aim to clarify the differences and complementarities between the most advanced studies on self-organization in management sciences, in order to explain also the consequences of following one or the other theory and the possibilities each one opens for analyses and understanding of a business or social organization.

The differences in interpretation from the various theories is to be expected, given the plurality of phenomena both in the biosphere and in econosphere that seem to be governed by self-organizing principles, which have been studied by these currents of thought. Complexity sciences and complex adaptive systems (CAS) have studied natural and artificial complex systems (i.e. ants colonies, internet, informatics viruses, etc.). Organizational cybernetics has studied self-organization in businesses and social organizations. We suggest here that the differences between the ways of dealing with complexity from each theoretical proposal come from their different ways of understanding and their differing emphasis when studying complexity.

While there is an increasing interest in research in organizations using complexity theories, CAS and organizational cybernetics, there is not enough explanation on the differences between each of these theoretical approaches and the consequences that taking one or the other has for a particular research project or even academic consultancy. We consider that the lack of understanding of the similarities and differences between the theories has been the origin of misrepresentations, misunderstandings and unsupported criticisms. The similarities between these approaches have been noted when they get classified jointly as a single category of approaches to social systems (e.g. Jackson, 2000). The lack of recognition of differences between complexity management approaches may have the root of: (a) misinterpretations (e.g. to think that organizational cybernetics is founded in the hierarchical and mechanistic control paradigm); (b) critiques (e.g. to assume that complexity sciences study the same issues than organizational cybernetics, so in comparison have no much to offer to management sciences); and (c) confusion (e.g. to assume that given that organizational cybernetics, CAS and complexity sciences all have similar roots, therefore there are not major differences among them).

The specialized literature dealing with complexity in management, have sometimes took inspiration in concepts originating in other disciplines like chemistry, physics, biology, mathematics and computing. As many of these concepts are difficult to 'translate' to the field of management, metaphors have often been suggested (e.g. McMillan, 2008). However useful metaphors may be as learning devices, they not always offer the level of precision and the lack of ambiguity required to be useful enough to interpret complex

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[1] In this paper, we shall focus on the contributions of cybernetics to management sciences, so we will focus on Beer's – organizational cybernetics; Beer used insights on self-organization from the original contributions from cybernetitians Heinz Von Foerster and Ross Ashby.

situations in businesses. Sometimes the use of metaphors – if they are not clearly related to the situation or if they are not clearly understood –, may leave the user confused rather than inspired. We consider that this route (the use of metaphorical language inspired from other scientific disciplines explaining complexity principles) has not always been useful enough in fully understanding the relevance of complexity and self-organization to business. A key reason why metaphors borrowed from one domain (e.g. physical or biological) to the social domain may not be that useful is that any human social systems exhibit higher levels of complexity than other complex systems (e.g. physical systems, biological systems); therefore, the metaphorical comparisons would always be, by the end, somehow limited.

Also lack of knowledge on the underlying differences between the different complexity theories may mislead the practitioner to an inadequate use of the models and tools suggested by each theory. For example, if the purpose of a study is to know better on structural complexity, organizational cybernetics offer the best tools for modeling and diagnosis; for analyzing collective behaviors' emergence, complex adaptive systems offer more comprehensive methods. Aiming to use CAS to guide an organizational design may not be the best choice, as it would not be using viable system model (MSV) to explore dynamic social behaviors over time.

So our purpose here is to clarify the points of difference and similarity between these three approaches. In this paper we review the core arguments suggested by the pioneers of these three main complexity theories in management. From complexity theory we review the contributions from Lorenz (1963), Thom (1977), Nicolis and Prigogine (2007), Prigogine and Stengers (2002), Bonabeau, Dorigo, and Theraulaz (1999), Watts (2006); from complex adaptive systems we take insights from Gell-Mann (1994, 1995) and Holland (1992, 1995, 1998); and we follow Ashby (1962, 1964), Von Foerster (1981) and Beer (1981, 1988) from the cybernetics tradition.

After a careful review of different sources in the literature, the current authors summarized their observations on the key characteristics from each of the main approaches to dealing with complex systems and agreed on the key dimensions and features in which these theories coincide and diverge. The differences and similarities between complexity sciences, CAS and organizational cybernetics allow us to suggest six propositions about self-organization in the context of business and social organizations.

It is important to clarify that there are other approaches to complexity like Edgar Morin's one, focused on complexity thinking and summarizing the best French tradition on subjective philosophy. His work includes broad proposals on how to modify the subject relationship with the world or the world's attitude toward nature (Maldonado and Gómez, 2011). We did not include his work in the analysis as neither organizational cybernetics, CAS nor complexity sciences focus on subjective philosophy: different to Morin's complexity thinking, they all aim to explain how and why a phenomenon is complex and how an individual or team can better deal with such complexity.[2]

In order to clarify the context for discussion, we have defined, in the first part of the document, a three dimensional space, with three main conceptual axis that summarize the core differences and similarities between these complexity approaches. This space allows us to position the different theories and to facilitate an understanding of their varying ways of understanding self-organization.

The definition of the three dimensions comes from a summary of identified patterns in current debates at the complexity literature. Mapping such three dimensional spaces allows us to position the different proposals that have sought to explain self-organization in social systems – natural (e.g. an ant colony), human (e.g. a community) and artificial (e.g. cellular automata). It distinguishes between the varying emphases and focuses on the way of studying the core aspects of self-organization from each approach.

In the second part of this paper we emphasize the differences between complexity sciences, CAS and organizational cybernetics, as well as their characteristics and conditions for self-organization. We also suggest six propositions to help describing the implications that self-organization produces for business organizations.

We hope that the identification of the space within which the various approaches are positioned, increases the research interest on self-organization in human social systems, and contributes to valuing the potential contributions from each one, and to reducing unsupported criticisms to some of them. We also expect to contribute to the clarification of a path for the development of models from the various theories of complexity that improve their current understanding and facilitate the study of complexity in human social organizations.

The rest of the paper is organized in four sections: Section 2 describes the analytical dimensions suggested to compare the field of study of the main complexity approaches used in management sciences: organizational cybernetics, complex adaptive systems and complexity sciences. Section 3 presents the main arguments developed by each of these theories to complex systems, as well as their classification based on the suggested theoretical dimensions. The final section presents the discussion and conclusions.

2. Dimensions for the study of complex systems

Although the idea of complex systems has been used to describe a wide variety of chemical, physical, biological, technological and social phenomena, among others, there is no consensus about what is meant by a complex system or its characteristics or traits (Bedau, McCaskill, Packard, & Rasmussen, 2010; Cramer, 1993; Rescher, 1998).

Complex systems theories study systems that operate with nonlinear dynamics – characterized by emergence, self-organization and evolution. Emergent conditions allow the system to self-organize acquiring a new order, which is evolving. Self-organization becomes a mechanism (complementary to natural selection) for systems evolution: without self-organization there is no evolution (Johnson & Lam, 2010; Kauffman, 1995).

Emergence refers to new properties that were not present in, or predictable from, the initial conditions (Holland, 1998; Luigi Luisi, 2010; Stace & Goldstein, 2006). Emerging processes arise from the interaction between components of the system: even relatively simple elements interacting may generate new and surprising behaviors, which make it impossible to predict future states.

Self-organizing systems can be understood as a set of dynamic mechanisms in which global structures appear from a system of interactions between components at different levels (Bonabeau et al., 1999). The rules of interaction between the constituent units of the system are developed based on purely local information without reference to global patterns which are an emergent property of the system rather than a property imposed on the system (Holland & Melhuish, 1999). Self-organization occurs only in open systems that import energy or information from the environment and achieve limited instability states (Gell-Mann, 1994; Kauffman, 1995; Nicolis & Prigogine, 2007).

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[2] We will not include in our analysis the theory of auto-poiesis. Self-organization is widely different from auto-poiesis (Di Marzo Serugendo et al., 2011); auto-poiesis does not deal with the origin of order or the origin of life, according to Kauffman (1995), but it aims to define the common features that distinguish life from no life of what allows a system to keep alive (Luigi Luisi, 2010). Brocklesby and Mingers (2005) offer more detailed discussion on this topic.

Evolution is the process of change or transformation (Darwin, 2010; Gould, 2010), characterized in terms of macroscopic behaviors that emerge from the interactions that occur at the microscopic level (Bedau & Packard, 1992). The design and continued evolution over time arise from the adaptability to environmental conditions; it emerges from the efforts of individual agents adapting by trying to improve their own settings (Holland, 1992).

There is a plurality of theoretical perspectives that seek to understand complex systems and self-organization, coming from disciplines that study different types of complex systems such as the brain, the biosphere, the internet, insect colonies, society, and business organizations, among others. This research summarizes those theories of complex systems that have been used in the study of human social systems into three broad categories: sciences of complexity, complex adaptive systems (CAS) and organizational cybernetics, and identifies the way each of them explains emergence of new order.

The sciences of complexity are oriented to the study and understanding of phenomena characterized by turbulent fluctuations and instabilities in which order is broken though sudden changes leading to new forms, moments and behaviors. Complexity sciences include different theoretical approaches: non-equilibrium thermodynamics, chaos theory, fractal geometry, catastrophe theory, non-classical logics, artificial life science, and networks science. Authors like Anderson (1999), Andriani and McKelvey (2009, 2011), Eoyang (2011), Helbing, Yua, and Rauhut (2011), Lewin (1992), Lorino, Tricard, and Clot (2011), Maguire and McKelvey (1999), McKelvey (2004), Mitleton-Kelly (2003, 2005), Richardson (2008), Simpson (2012), Stacey (1995, 1996, 2000), Thietart and Forgues (2011), Tracy (2011), Vidgen and Bull (2011), and Wulun (2007); and others have contributed to incorporating these approaches into organizational theory.

Complex adaptive systems (CAS) are oriented to the study of systems in which global behaviors depend more on the interactions between the parts than the actions of each one (Gell-Mann, 1994; Holland, 1992). CAS are composed of agents in interaction that are described in terms of changing rules (to adapt) while the system accumulates experience. Consistency and persistence of these systems depends on the multiple interactions between the parts, the aggregation of the various elements, as well as adaptability or learning (Holland, 1995). CAS theory has been considered within organizational theory by authors like Amann, Nedopil, and Steger (2011), Boisot and Child (1999), Byrne (2009), Child and Rodrigues (2011), Mowles, Stacey, and Griffin (2008), Richardson (2008), Stacey (1995, 1996, 2000), and others.

Organizational cybernetics, developed by Stafford Beer, arises from the application of the principles of cybernetics – including insights on self-organization from pioneers as Ashby and Von Foerster – to the study and understanding of business organizations. It suggests the viable system model (VSM) as the theory of organizational viability. A viable system is one that has the ability to keep an independent existence, and therefore survive (Beer, 1981, 1988). The organizational cybernetics approach has been widely considered in the study of business organizations (Espejo & Reyes, 2011; Espejo, Schuhmann, Schwaninger, & Billelo, 1996; Espinosa & Walker, 2011; Schwaninger, 2007).

Organizational cybernetics, the science of complexity and CAS match the rejection of linearity that characterizes the Cartesian paradigm in which the whole is equal to the sum of the parts. Nonlinearity means that every problem can have more than one possible solution and thus refers to non-deterministic behaviors and processes; self-organization occurs through nonlinear, non-deterministic interactive processes that allow the increasing complexity that characterizes social systems, and particularly business organizations. Broadly speaking we can say that the field of study of organizational cybernetics, the sciences of complexity and CAS are all concerned with complex nonlinear systems, but that each focuses its attention on different domains, related but distinct.

In this paper we propose three parallel and complementary dimensions to define a conceptual space to classify the different theories and approaches about complexity and self-organization, aiming to facilitate their understanding. The proposed dimensions are: (a) ways to study nonlinearity, (b) forms of understanding evolution of a complex system, and (c) focus of interest for the study of complex systems. The first two dimensions are transverse features of complex systems and are closely related to self-organization. The third dimension describes the most important working lines considered in the study of complexity. Sections 2.1–2.3 explain details from each of these suggested dimensions for the study of complexity in business organizations and their management.

2.1. Ways to study the nonlinearity of the system

A nonlinear system is one whose behavior does not meet the principles of linearity: nonlinear systems' outputs are not proportional to their inputs: small changes can trigger large effects, and behavior of the whole cannot be explained from the sum of the parts.

Nonlinearity is closely related to the level of interdependence between components. It is possible to identify at least three factors that generate it: increasing or connecting new elements in the system, adding new connections between existing parts, and increased intensity between connections. Nonlinearity explains increase in the degrees of freedom of the system, information gain, and emergence of new properties and in general 'complexification'.

In the study of complexity it is possible to identify two broad alternatives of study. The first one, known as 'structural complexity', focuses on understanding the factors underlying nonlinearity, i.e. it emphasizes the system composition (the parts it is made of), the structure (how the components are connected), and the organization (the components interacting to maintain their identity as a whole). The second known as 'dynamic complexity' focuses on understanding the emergent behaviors exhibited by complex systems.

The study of structural and dynamic complexities constitutes two complementary perspectives for understanding nonlinearity and complex systems. Theories that focus on the understanding of nonlinearity from a structural point of view do not ignore the emergence of dynamic properties; and in the same way the theories that focus on the dynamic behavior of the system recognize the importance of the interaction between the parts. The difference between the different theories lies in the emphasis on interaction and/or dynamics.

2.2. Ways to understand the evolution of the system

As mentioned above, complexity is characteristic of systems that permanently move from one state to another, staying away from equilibrium. Ashby directly addressed this phenomenon when he sought to explain how the systems pass from having a bad organization to a good organization (Ashby, 1962), Prigogine and Stengers (2002) described it as order–disorder transitions and Kauffman (2000) meanwhile refers to the phase transitions between chaos and order. Complexity refers to the ability of a system to evolve over time (Nicolis & Prigogine, 2007).

There are two main approaches to studying evolution: evolution through continuous changes and evolution through sudden changes. Continuous changes result from a system's adaptation to a continuously changing environment: they come from the study of natural selection theory (originated by Darwin – see Darwin, 2010): it states that species highly adapted to their environment will have higher survival probabilities. Such characteristics can be inherited, which implies that they can keep and improve over time.

On the other side, abrupt changes happen when particular situations or behaviors are eliminated, allowing the appearance of new conditions that differ significantly from the original conditions. Abrupt changes – whose study is based on the proposal of Gould (2010) – explain evolution through punctuated, sudden changes or 'exaptations'. Gould and Vrba (1982) used this idea for the first time when explaining the origin of extremely complex adaptations without falling into pre-adaptation. For example the vertebrate animals' ears appeared originally as a residual result from a physiological structure destined to aspire water to the bronquials without opening their mouth (Brazeau & Ahlberg, 2006).

Continuous changes are often numerous and promote the system's ability to survive. Their impact depends on the environmental conditions to which the system is responding. As a consequence the level of change produced can be small or radical. These changes move organizations through different states, which differ from the previous ones, but maintain the features that guaranteed success (features can be inherited). Sudden changes are only a few, are sporadic, and stimulate drastic and quick transformations in varied directions.

Theories that study continuous changes do not ignore sudden changes, nor theories which study sudden changes ignore that continuous changes happen as well. The difference among theories is on the emphasis to study changes that they each have.

2.3. *Focus of interest for the study of complex systems*

In the study of complex systems we can identify two broad perspectives. On one side there is research aimed at understanding the effect of environmental changes on the system's options for viability. That is how the organization manages to survive as a result of interactions among its component agents and between these and the environment. On the other side are the researchers interested in studying the organization as a network interacting with other networks. The key issue of this second approach is to understand how networks evolve and co-evolve increasing over time their own complexities.

From this perspective, networks are understood as populations of individual components that develop a particular work while exchanging information and making decisions. The essence of this field of study is to consider networks not as static objects but as part of a self-organizing system that is constantly evolving (Watts, 2006).

The proposals that study the viability of the system also understand the system as a network in which different agents are interacting. But the proposals that are interested in studying the organization as a network interacting with other networks do not consider the viability of the broad network as the system's purpose. It simply evolves, moves within its own space of possibilities, always working toward the agents' advantages.

3. Theories for self-organization

The three dimensions proposed for understanding complexity allow us to build the space within which the different approaches about complex systems co-exist; and it enables the understanding of a wide variety of approaches regarding self-organization. While all the approaches coincide in understanding self-organization as the spontaneous emergence of collective behaviors from the interaction between agents, the differences in the named dimensions allow us to understand the differing emphasis that each one has when explaining self-organization. Sections 3.1–3.3 explain how each of the complexity theories explains the emergence of new order.

3.1. *Complexity sciences*

Included within the sciences of complexity are chaos theory, catastrophe theory, non-equilibrium thermodynamics, Boolean networks and the NK model (N refers to the number of agents and K to the number of connections between them), networks science, and collective intelligence, among others. These approaches study the nonlinearity of systems from a dynamic perspective; they understand evolution through sudden changes and are interested in networks interacting with other networks – not aiming for their viability or survival, but for their advancement in their space of possibilities.

- The mathematician Lorenz (1963) proposed *Chaos theory* in his paper "Deterministic non-periodic flow". Lorenz's proposal is supported by the Rayleigh–Bénard convection, which corresponds to movement of a fluid situated between two layers of different temperatures. Lorenz identifies a region that distinguishes deterministic chaos (R2) from that in which the gas molecules are stable (R1). The space between R1 and R2 is known as "the edge of chaos" and is the one in which complexity emerges: in this space the gas molecules exhibit dynamics that follow strange attractors. This space is characterized by the existence of multiple basins of attraction, and is there where new order may emerge. Continuous disturbances to the system make it reach permanently for new attractors generating sudden changes that show sensitivity to initial conditions and keep it in states far away from equilibrium. Major transformations happen when the system changes from one to another attractor.
- *Catastrophe theory* originated by the mathematician René Thom is consolidated in 1977 with his book "Structural Stability and Morphogenesis". Thom's work focuses on the study of behavioral discontinuities arising from bifurcations that provide the basis for changes in unstable structures. Catastrophe theory is a systematic way of talking about the sudden appearance or disappearance of an attractor when a parameter changes at a critical value. It deals with the understanding of ordered and disordered transitions occurring in a given space, qualitative changes that arise as a consequence of the control variables. The term 'catastrophe' is used by Thom to designate discontinuities in the forms. Catastrophes are generated by bifurcations implying transitions to new states of order occurring in the conflict between two or more attractors.
- Ilya Prigogine and the School of Brussels developed non-equilibrium thermo-dynamics, and it proposes that order is achieved in systems characterized by the constant production of entropy resulting from high level of exchanges with the environment. In such systems entropy production and fluctuations increase rather than disappear, leading the system to profound changes – i.e. its evolution toward more complex states (Nicolis & Prigogine, 2007).

In Prigogine's proposal, the "emergence of new order" implies that the system takes a completely different mode of operation, functionally organized and structured in time and space (Prigogine & Stengers, 2002). The point from which new order emerges is known as 'bifurcation' or 'phase transition': it corresponds to the moment in which random fluctuations are amplified by the steady flow of matter and energy while interacting with the environment. Dissipative structures are those when the system leaps to a new, higher level of "order": they would require more energy to sustain themselves than the simpler structures they replace, and would be limited in growth by the amount of heat they are able to disperse. They represent – at the molecular level – the process of self-organization of the system.

In systems far from equilibrium, as they are called, instability plays a critical role in generating new order – what has been termed by Prigogine '*order by fluctuations*'. The system can be in many different states and it is the fluctuation that determines which state it will ultimately achieve. From this perspective, living systems are complex, open systems: they are able to maintain their organization while adapting to an environment of increasing entropy. This in fact constitutes the thermodynamic cost of evolving into new states. That is to say that in systems far from equilibrium, the production of entropy and the generation of new order go together.

- *Boolean network and NK model*: Stuart Kauffman states that entropy and the general law of thermodynamics are inadequate for understanding the emergence of new order because they have limitations in explaining co-evolution of systems (Kauffman, 2000). He argues that dissipative structures allow us to fully understand where order arises but not to understand completely what the conditions for the emergence of order are.

Kauffman identifies two key components that explain the emergence of new order. The first one, aligned with the idea of dissipative structures of the Brussels School, is supported in Boolean networks: it states that order, and in general more complex behaviors, emerge at the edge of chaos. Boolean networks can be found in a system operating in a chaotic regime, or in a regime close to a phase transition between order and chaos. The second component is supported by the NK model: it suggests that in the biological realm, those processes that conduct the system to the edge of chaos work well only on landscapes that emerge through evolution in the building of niches, of search mechanisms and in general, searching for ways of earning their life to achieve both individual and specie's propagation (Kauffman, 2000).

The edge of chaos is a phase transition in which new events and properties can emerge and where there are waterfalls (avalanches) of local extinction events whose distribution follows a power law (Kauffman, 2000). At the edge of chaos, the flow in the state space is slightly convergent, allowing autonomous agents to make the maximum number of reliable discriminations and consequently actions, and thus developing more sophisticated natural games in ways which make their living (Kauffman, 2000).

In the biological reality, natural selection leads to chaos edge agents. However, and as demonstrated with the NK model, the selection, mutation and recombination work well only in highly adaptive or rough correlated relief's, i.e. in those where the high peaks tend to cluster and the slopes are relatively mild (Kauffman, 2000). Highly correlated adaptive landscapes emerge from self-organizing processes, from co-evolution of the biosphere. These coevolved processes allow the emergence of new (peaks) that increase diversity, expand the degrees of freedom, and constitute what Kauffman calls the space of the adjacent possible (Kauffman, 2000).

A peak represents an adaptation of a set of species: the higher the peak, the greater the adaptation. A valley represents low levels of adaptation and adjustment. Adaptation is the process of scaling high peaks and therefore natural selection is the process of pushing the species to such peaks. Self-organization generates the type of structures that can benefit the selection and therefore, it constitutes a precondition for the evolution of the system (Kauffman, 1995). Those structures that emerge from self-organizing processes are dynamic structures, because co-evolution leads to the landscape of species to be altered when species performs adaptive moves (Kauffman, 2000).

The progress of the system toward the adjacent possible – i.e. the process of climbing peaks, is made in Kauffman's words "as fast as we can." This constitutes one of the general principles governing the joint construction and co-evolution of both the biosphere and the econosphere (Kauffman, 2000). It implies both the existence of limits to growth of the biosphere, and endogenous processes that remain within these limits, so that they remain subcritical.

If the system's progress was too fast (supracritical) the system would destroy the propagative organization generated by autonomous agents, and thus it would contain the seeds of its own destruction (Kauffman, 2000). Thus the evolution of the system requires that agents – individually and local communities – remain subcritical (Kauffman, 2000). Sub-criticality allows natural selection i.e. it acts by establishing winners and losers, ". . . otherwise we would not be here to tell the tale" (Kauffman, 2000, p. 154).

Specifically self-organization generates the immense biodiversity, which is then acted upon by natural selection: it is a precondition for evolution. In Kauffman's proposal, selection and self-organization are complementary mechanisms for the evolution of species. Selection explains the logic of life by winners and losers and self-organization explains the origin of life. Consequently there is no conflict between self-organization and selection; these two sources of order are natural companions (Johnson & Lam, 2010; Kauffman, 1995):

- *Collective intelligence:* also within the sciences of complexity, Bonabeau et al. (1999) considered self-organization as a mechanism that explains the emergence of collective intelligence. Their approach emerges from the study of the behavior of groups of social insects such as ants, bees, termites, and more.

Interest in colonies of social insects arose because they exhibit the ability to act collectively, behavior that is attributable in part to their self-organization processes – in which there is no central controller (Bonabeau et al., 1999; Martinoli, 2001). Additionally the ability for self-organization of social insects can explain their high levels of robustness and flexibility in solving problems and/or performing tasks in teams. Flexibility refers to the ability to adapt to environmental changes, while robustness refers to the ability of the colony to survive even if some individuals fail in their tasks (Bonabeau et al., 1999).

These authors also suggest that self-organization is the set of dynamic mechanisms in which global structures appear in a system of interactions between components at different levels. The rules of interaction between the constituents units of the system are followed based on purely local information, without reference to global patterns; global patterns are an emergent property of the system rather than a property imposed on the system.

From this perspective, self-organizing systems require four basic components or elements that explain their nonlinearity: (a) positive feedback – represented in simple rules that promote the creation of structures, (b) negative feedback which helps stabilize collective patterns, (c) multiple interactions between the parts through direct and indirect communications that allow agents to be able to use both the results of its activities and those of others, and (d) amplifying fluctuations referred to randomness for discovery of new solutions and alternatives that facilitate growth and strengthening of the structure.

Further research in insect colonies have led these authors to assert that self-organizing systems are characterized by three key elements: (a) the creation of spatiotemporal structures as architecture of nests or social organization, (b) the coexistence of multiple states and convergence to one of them – for example if two identical food sources (attractors) are located at the same distance from the nest, one is eventually massively exploited while the other is abandoned; (c) the dramatic changes that a system can experiment with different disturbances.

- *Complex networks science*: it is an emergent discipline that studies all types of networks (electrical, social, biological, etc.), aiming to identify the principles governing networks behavior. In particular this new science aims to describe macroscopic behaviors in networks (global dynamics) resulting from interactions between the nodes. From this perspective new order is related to changes in the connectivity levels (agents create and breakdown links with other agents, and smooth or intensify their relationships); and to the system's co-evolution (agents influence and are influenced, by developing nonlinear behaviors – see Watts (2006)).

In the network science the emergence of new order happens when there is a group of nodes susceptible to be activated (i.e. to adopt a novel idea) that are interacting. If a particular behavior (i.e. innovation, idea, etc.) starts up somewhere in this grouping it will get diffused throughout the network rather than get extinguished. If it does not start up in such a grouping it is more likely it will disappear quickly.

3.2. *Organizational cybernetics*

Beer (1981) pioneered the organizational cybernetics approach, and developed the viable system model (MSV), based in the theories of self-organization, complexity and variety management from Ashby (1962, 1964) and (living) neural types of networks from McCulloch (1965). Beer studied nonlinearity from a structural point while focusing on the viability of the system, his theory observing the complexity of organizational units, doing their tasks while co-evolving with their niches, at different scales. At each scale a viable system represents the network of agents working together in a purposeful task. Viable systems are embedded within viable systems. Complex interactions between agents at a particular scale may result in emerging new levels of organization. A viable system is a system able to keep an independent existence. It evolves (and survives) through either progressive or abrupt changes. An organizational system is organized into networked, recursive sub-organizations that interact at different levels and scales.

Ashby was one of the first authors to conceptualize self-organization in systems. He suggested two ways for a system to self-organize: the first one is when its components interact in a self-organized way to constitute the system. The second way is when the system evolves from having a bad organization to having a good organization: this may happen as a result of autonomous changes in their organization that the system does in responses to changes in their environment (Ashby, 1962, 1964). From this perspective, self-organizing systems have the ability to modify their own organizational structures – the patterns of interaction between their components – and, as a result, the way they respond to their environment. These interactions allow the development of feedback loops in the system, which facilitate self-regulation and, thus, promote self-organization.

The proposal of self-organization and more specifically of self-regulation of the Austrian biologist and philosopher Ludwig von Bertalanffy complements those made by Ashby by introducing another way through which the systems can be self-organized. Bertalanffy (1968) identifies the possibility of self-organization through progressive differentiation, which allows the evolution of the system from one state to another. Self-organized systems, by progressive differentiation evolve from having less sub-systems with more general or less specialized functions to a larger number of subsystems that perform more specialized tasks or have more specialized individuals. Differentiation allows relationships between parts to raise their level of sophistication and additionally results in increased system complexity.

Ecological and natural systems are self-organizing as they have mechanisms, which select particular modes of organization that are survival worthy. McCulloch (1965) explained in great detail self-organization as the most massive variety inhibitor. He explained the nature of reflexive and homeostatic mechanisms in the brain and the way that a 'neural-network' type of organization is goal directed, self-regulated and can achieve purposeful behaviors.

Supported in the proposals of self-organization and requisite variety from Ashby and (living) neural networks from Warren McCulloch, Stafford Beer developed the viable system model (VSM) as a model of a (human) social organization. A viable system is one that has the ability to keep its organization and therefore survive while adapting to environmental changes. He developed his theory of organizational viability and self-organization through the application of cybernetics principles to the study and understanding of human social organizations.

For Stafford Beer self-organization becomes the mechanism that ensures the viability or survival of a complex system. A system is self-organized when the information flow is distributed in such a way that the command center can be anywhere in the organization: this "redundancy of potential command" was originally postulated by McCulloch, and means that teams have distributed autonomy to take decisions at any time regarding the modes of action of the organization (Beer, 1981). A prerequisite for any self-organizing system is the redundancy of potential command (RPC).

Warren McCulloch developed the RPC principle, which means that control is spread throughout the system (Beer, 1981). This distributed command capacity facilitates variety management: as decisions can be made in a distributed way, managers can decide at each moment on the best ways to handle the variety of the environment. As a result, RPC helps managers to keep the organization in a homeostatic state.

From a VSM perspective, once an operational task becomes too complex there is a need to re-organize it, and to re-distributing command capacity for handling its growing complexity; it may result in emerging task forces, levels of organization, etc.; this situation normally generates stress, and while sorted out, it can be the source of shock or even trauma – e.g. when a network of agents in charge of a task cease to act together due to overwork. At this point, there might be a transition to a new order, as a result of which a new organization may emerge, more capable of dealing with the environmental complexity. RPC and self-organized teams muffle the chaos produced by phase transitions, as they allowed redundancy to cover up for changing structures.

3.3. *Complex adaptive systems*

The third stream of thought is the work around complex adaptive systems (CAS) developed mainly by Gell-Mann (1994, 1995) and Holland (1992, 1995). CAS has features in common with both organizational cybernetics and the sciences of complexity. With organizational cybernetics it shares the understanding of evolution and with the sciences of complexity coincides in the study of nonlinearity from a dynamic perspective, and a particular interest in understanding networks in interaction with other networks.

Gell-Man's approach is supported by quantum entanglement whereby as a result of the interaction that occurs between the electrons, the quantum state is set in such a way that the states of the electrons are correlated. A given electron will be in a defined quantum state (pure) but can be found in several pure states of a single electron (mixed quantum state) each with a certain probability (Gell-Mann, 1995). That is, you do not need anything more to get something more (Gell-Mann, 1995): new conditions emerge from the entanglement of existing ones. As a result all electrons develop correlated histories, without any particular histories dominating over the others; therefore, quantum theory cannot assign probabilities of happening to one or more correlated histories.

With the term 'history' Gell-Man does not seek to give prominence to the past at the expense of the future, or refer to written records of human history; he simply refers to the history of a time sequence of past, present and future events. From quantum physics, emergent probabilities are the startup of new orders of matter. A change in state may be affected if any force disturbs the alignment of correlated histories. These are defined as complex systems or CAS (Gell-Mann, 1995).

The theory of CAS has also been addressed by John Holland who argues that the emergence of new order depends on the multiple interactions between the parts, the aggregation of the various elements, as well as adaptability or learning (Holland, 1995). The agents act and interact based on local rules that change through the accumulation of experience allowing the agent to adapt to its environment. The rules are the ways to describe the strategies of the agents to certain stimuli.

In the proposal from Holland, aggregation is one of the properties by which it is possible to generate scenes (new order) by recombination of familiar categories, or from the emergence of complex behaviors arising from interactions of aggregates of less complex agents. Identifying tags or labels (e.g. ideologies) facilitates aggregation and allows the selective interaction between agents or objects that are otherwise indistinguishable; it also provides the basis for discrimination, specialization and cooperation. The tags almost always delimit critical interactions in the networks, as agents with useful labels propagate, while agents with abnormal tags stop existing.

The persistence of an individual agent depends on the context provided by other agents. That way if a class of agent is removed from the system it will respond with a cascade of adaptation actions, resulting in the creation of other agents that provide missing interrelationships (Holland, 1995). In biology this process is called convergence and refers to the similarity in habits, forms or other attributes between species without some degree of familiarity in them. Thus the continuous adaptation to the context that develops the system promotes increased diversity. That is, each new adaptation opens the possibility of subsequent interactions, new classes of agents and niches.

The adaptive process of agents that facilitates the emergence of new order is also mediated – in Holland's proposal – by internal models and building blocks. Internal models arise from the selection of patterns that the agent makes from the torrent of information received and these determine their changes in structure. Such changes represent their internal models enriched by their experience (learning), and their ability to anticipate (i.e. forecast) resides on them. Holland suggests that the building blocks are the best technique for modeling: they arise from the decomposition of various situations by extracting those rules that enabled the agent to respond to certain stimuli. Consequently when facing new events the agent combines the most relevant and tested blocks to model the situation, facilitating in this way the identification of appropriate actions and of potential consequences (Holland, 1998).

Self-organization in complex adaptive systems results in continuous changes that not necessarily invalidate the patterns, agreements or behaviors previously established. In Gell-Man and Holland's approach there is accumulation and/or aggregation of experience (information) in the system, which allows it to go gradually adapting to new environmental conditions.

4. Discussion and conclusions

The sciences of complexity, CAS and organizational cybernetics are concerned with the study of complex systems that are characterized by nonlinearity. The central feature of complex systems is self-organization.

There are differences between the three streams of thought on ways to address self-organization. We affirm that these streams are studying related but different problems: they all study nonlinear complex systems, and agree on the importance of self-organization for system's evolution. However, they have differences in their ways to study nonlinearity to understand the systems' evolution and in the fields of interest, which focuses their attention. As a consequence, each theory leads to explain the emergence of self-organized behavior in various ways (Table 1).

Organizational cybernetics and CAS understand evolution as the result of progressive continuous change (not excluding sudden changes), while complexity sciences understand evolution as sudden changes. For organizational cybernetics a prerequisite for self-organization is the redundancy of potential command manifested in distributed control within the system (self-regulation). For the sciences of complexity, self-organization also arises through co-evolutionary processes characterized by the absence of central controller. And for CAS theory self-organization arises from the adaptive capacity of the system to changing environmental conditions – which are also described by organizational cybernetics. The three approaches coincide on the core ideas but study the phenomena with different lens (Table 1).

The review of key papers in complexity theories applied to businesses, and their comments on strengths and limitations from each of these approaches left us with the perception of generalized ignorance from most authors about the differences and commonalities between the various sciences and theories of complexity. The distinction between these theories helps us to dissolve many of the (not always well founded) criticisms made between followers of the different approaches. For instance, trying to classify them all under a unique paradigm, Jackson (2000) classified them all together as mechanistic, functionalistic approaches to management. We have explained here how the different approaches apply core complexity ideas at different realms (physical, biological, human social) and with different lens (mathematical, computational, semantic, etc.). Even the complexity approaches better known in management sciences (i.e. CAS, VSM) come from different theoretical backgrounds, so a finer way of comparing them is required.

As shown in Table 1, CAS and organizational cybernetics share several features and there are many similarities and complementarities between the way organizational cybernetics and CAS explaining complexity management in organizations; there are also clear differences between them and more traditional approaches to management (Espinosa & Walker, 2011). However, even if there has been an increasing interest from both VSM and CAS approaches to management (Paucar-Caceres & Espinosa, 2011), still to date the only comprehensive and fully developed theory and methodology available for the study and management of complexity in business organizations is the VSM proposed by organizational cybernetics.

The other approaches – i.e. sciences of complexity and CAS – have been developed in the realm of natural and artificial social systems, but have also been used to try and explain complexity in human social systems. There has been an increasing development of theory on how these approaches contribute to organizational management and studies. Nevertheless at the level of methodologies and applications, there are not yet comprehensive methodologies to apply these theories to businesses. There are some interesting contributions that use computer simulations to understand specific aspects of complex organizational processes, including new theories and software to make sense of complex social networks and narratives. But apart from these, other contributions from complexity theories are characterized by metaphorical descriptions of organizational systems, and by the lack of clear analytical models to guide analyses.

We consider that organizational cybernetics still provides the most developed theory, methodology and a large amount of

Table 1
Characteristics of complexity theory and conditions for self-organization.

Complexity theory	Features	Some evidences	Conditions for self organization
Organizational cybernetics	It studies nonlinearity from a structural perspective It understands evolution as either gradual or sudden changes The focus of interest is the viability of the organization	Emphasis on systems and/or subsystems that make up the organization Interactions between subsystems allow organizational transformations (from bad to good organization, from less to more specialized functions, from disparate parts to a more cohesive whole) A viable system is one that manages to maintain its organization and therefore survive	Self-organization contributes to organizational viability. Viability requires of co-evolution and adaptation A requirement for self-organization is the redundancy of potential command which is reflected in the extent of self regulation achieved
Complexity sciences	It studies the nonlinearity from a dynamics perspective It understood evolution from abrupt changes The focus of interest is the organization as a network interacting with other networks	Emphasis on the emergence of new states and/or emergent properties At the edge of chaos avalanches occurs local events whose distribution follows a power law The emergence of new states comes from systems in coevolution that move through the space of possibilities	Self-organization is a mechanism for evolution of the system A requirement for self-organization is the co-evolution of the system.
Complex adaptative systems	It studies nonlinearity from a dynamics perspective It understands evolution as gradual changes The focus of interest is the organization as a network interacting with others networks	Emphasis and the emergence of new order and/or global behaviors The system works based on local rules which change by accumulation, aggregation of experience The system adapts to changing environmental conditions The emergence of new order comes from stories correlated among agents.	Self-organization evidence adaptive capacity of the system Self-organizing systems emerge using correlation, aggregation, recombination of agents and/or systems A requirement for self-organization is adaptation

Source: Prepared by the authors.

empirical results on a wide range of international companies (e.g. Beer, 1975, 1979, 1981, 1983, 1985, 1989, 1994; Christopher, 2011; Espejo & Reyes, 2011; Espejo et al., 1996; Espinosa & Walker, 2011; Hoverstadt, 2008; Malik, 2006; Pérez-Ríos, 2012; Schwaninger, 2007), even though, Beer's original proposal could still be enriched by incorporating concepts from the sciences complexity and CAS (e.g. attractors, edge of chaos, phase transitions, etc.) – for an example on this line of research see Espinosa and Walker (2011).

On the other side, the sciences of complexity and CAS are stronger in the study of nonlinear dynamics; it is important to recognize that their fields of study have been physical, biological and artificial social systems. Their application to human social systems have enriched traditional management theories on issues like strategy, change management, social networks, innovation and leadership (e.g. McKelvey, 2004; McMillan, 2008; Mitleton-Kelly, 2003, 2005; Richardson, 2008; Stacey, 1995, 1996; Thietart & Forgues, 2011, etc.), but they still require more structured methodologies and methods to support more generic organizational analyses (e.g. to guide organizational change processes or performance management).

We have identified here the conceptual differences between current approaches to the study of complex systems and hence self-organization. Ignoring the differences between the theoretical perspectives allows a not always fruitful proliferation of metaphors coming from physics, chemistry, and biology – among other disciplines – in organizational studies; by acknowledging them we can further develop the complementarities between methodologies and tools developed by complexity sciences, CAS and organizational cybernetics. Acknowledging the complementarities, on the other side, open spaces for designing research projects that benefit from combining both approaches – see for example Espinosa, Cardoso, Arcaute, and Christensen (2011), Arcaute, Christensen, Sendova-Franks, Dahl, and Espinosa (2009), much can be learned from observing both structural and dynamic complexity when researching about complex social systems and undoubtedly each approach has much to offer. Nevertheless, by taking into account that the field of study of both complexity sciences and CAS have been natural and artificial social systems, more care needs to be taken when making assumptions on the transferability of all concepts to human social systems. This needs to be considered when combining complexity inspired methods and approaches in observing organizational human systems.

Conflict of interest

The authors declare no conflict of interest.

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