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Carlos Eduardo Maldonado
Nelson Gómez-Cruz

Universidad del Rosario
Facultad de Administración

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Carlos Eduardo Maldonado
Nelson Gómez-Cruz

Modeling and Simulation Laboratory

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Carlos Eduardo Maldonado
Nelson Gómez-Cruz

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When Management Encounters Complexity

Carlos Eduardo Maldonado*
Nelson Gómez-Cruz**

Abstract

This paper aims at showing how management has come to encounter the sciences of complexity. Therefore the various levels and domains of management are outlined which leverage from the study of complexity. This is not, however, a descriptive study. Rather, we focus on how management can benefit from knowing of the sciences of complexity. New tools and rods, new languages and approaches are sketched that show a radical shift in management leading from a once dependent discipline from physics and engineering, towards a biologically and ecologically permeated new management.Whereas the main concern for complexity consists in understanding complex phenomena and systems, at the end a number of successful applications of complexity to management and entrepreneurial consulting are considered.

Key Words

Complex systems, organizations, applications, entrepreneurship.

* Full Professor, School of Management, Universidad del Rosario. Email: carlos.maldonado@urosario.edu.co
** Adviser in logical modelling at the Modeling and Simulation Lab, School of Management, Universidad del Rosario. Email: nelson.gomez@urosario.edu.co

1. Preamble

The roadmaps are a recent and often useful way to grasp a whole and its relations and components. The following three schemes are different roadmaps that provide a comprehensive view of what complexity is about.

The first one, developed by H. Sayama, shows an organizational map open into seven sub-groups (Figure 1). Each sub-group refers to a wide set of phenomena and approaches that are sensitive to management. However, it should be clear that to every single component mentioned in a sub-group there is immediately a concern for mainstream management or business.

The second roadmap (Figure 2) has the merit that was developed by the first book ever on sociology and complexity, by B. Castellani and F. Hafferty (2009). Whereas Sayama's map is structural, Castellani and Hafferty's roadmap stresses the significance of time for the evolution of complexity. The arrows in the map provide a view of direct and indirect influences. In any case it should be noted that the frontier leads, according to Castellani and Hafferty, to non-linearity and the important role of the Internet and e-science.

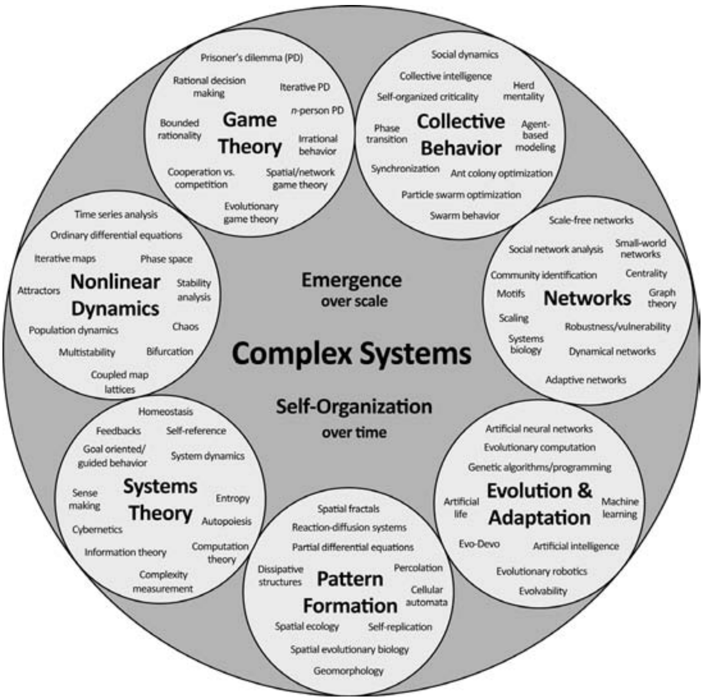
Finally, as a preamble, the third roadmap included here has been set out by NECSI, which is perhaps the most important Institute devoted to applied complexity. It is a three-dimensional map focused on the attributes of complex systems (Figure 3). It points out at the importance of cross-disciplinary approaches and hence to the dialogue among sciences and disciplines. Such a dialogue, however, is not to be taken as a matter of (good) will, but as the way to confront frontier problems.

2. Introduction

Markets have become increasingly complex – both for good and for bad. That is, markets have become not just perfect or imperfect but full of uncertainties, turbulences and fluctuations, as it happens. Accordingly, organizations, enterprises, companies, corporations, societies, and the states have witnessed nonlinearities, emergence, and unpredictability.

The word that best encompasses all these attributes is probably crisis; we are in the midst of a series of crises, whether financial, social, environmental, or others. It is, we claim, the situation in our world that the problems and troubles we are currently going into cannot be solved (just) by management. But these challenges cannot be solved without management, either. No other period in history has come to such awareness. To be sure, the title that allows us to grasp such a situation is "complexity".

Figure 1. Visual, organizational map of complex systems broken into seven sub-groups, by Hiroki Sayama (2010)



Taken from: http://en.wikipedia.org/wiki/File:Complex_systems_organizational_map.jpg.

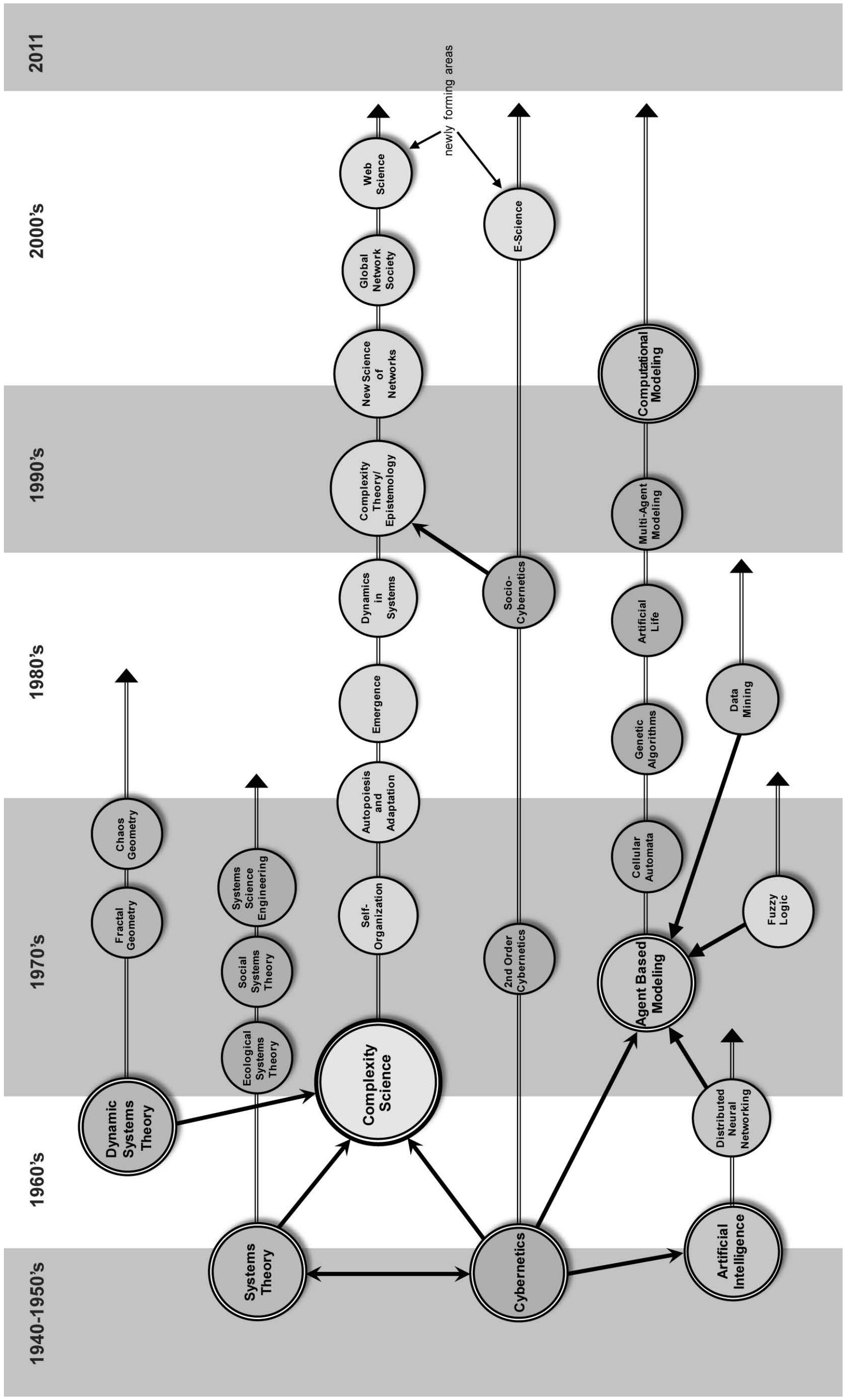
Complexity, however, is the subject of study of a series of tools, languages, disciplines, methods, and sciences. Management, in the broadest and largest sense of the word, has come to know of the sciences of complexity. This paper is aimed at providing a clear-cut roadmap of such an encounter.

A preliminary remark, though, is necessary. To state it straightforwardly, it is about distinguishing complexity from what it is not the case but is usually taken as equivalent, synonymous or alike.

Normally, when thinking about complexity people tend to avoid it or eliminate it by constraining or restricting the study to what is known, feasible, solvable, or practical. One way for doing so is by parameterizing the subject of concern or study. In contrast, it should be clearly pointed out that parameterizing is one of the most efficient ways of killing or avoiding complexity, namely uncertainty, non-linearity, self-organization, turbulence, and unpredictability, to name but some of the attributes of complex phenomena.

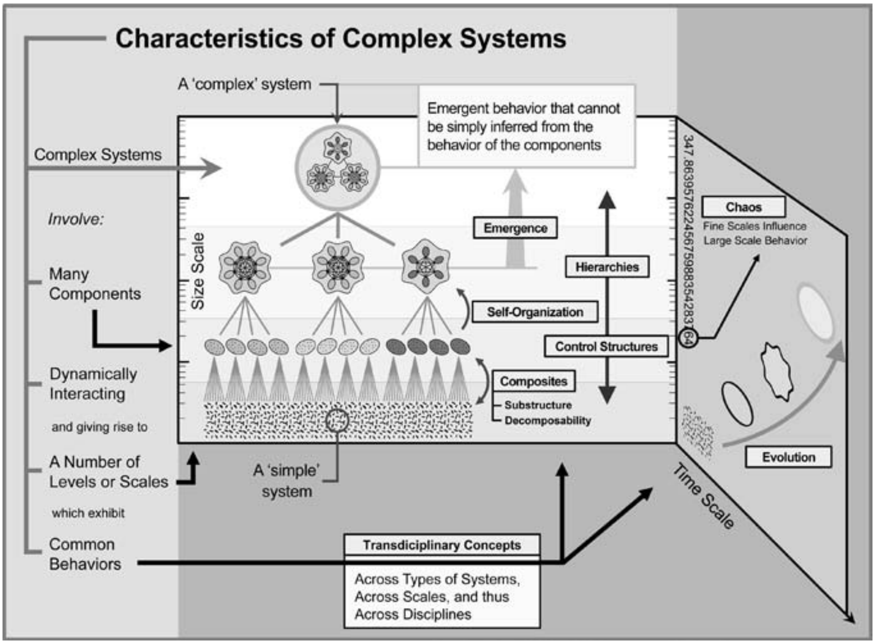
Complex systems are to be differentiated from complicated ones (Maldonado & Gómez-Cruz, 2011a). As a consequence, a larger number of variables are not to be taken as equivalent to higher complexity, for instance. In the same tenure, complex systems cannot be understood just in terms of vectors, statistics – whether descriptive, inferential or any other – averages, standards, or according to the law of large numbers, i.e. as normal distributions: as a Gaussian bell or a Bell curve.

Figure 2. Map of the new science of complexity (Adopted from Castellani&Hafferty, 2009).



Perhaps the greatest difficulty when dealing with complex systems comes not so much from linearity, reductionism or determinism – which are already serious hinders on their own. But the most subtle and hard impediment comes from the lack of criteria for demarcation within the so-called large family of complexity. Thus, both insiders and outsiders from that family tend to easily confuse the sciences of complexity with system science (Meyers, 2009), complexity thinking (Atkouff, 2000; Morin, 1998), and cybernetics (Wiener, 1948). The reason for such confusion comes surely from the fact that both cybernetics and system science appeared first in the scientific and academic scenes, as it can be clearly seen from Castellani and Hafferty's roadmap (Figure 2). Management has already incorporated quite well the systemic and cybernetic approaches as a striving to grasp complexity. A conspicuous case can be seen in Esiner (2005). And yet, the confusion remains at large among system science, cybernetics, and complexity(Espinoza and Walker, 2011).

Figure 3.Characteristics of complex systems, by Marshall Clemens



Taken from: http://www.necsi.edu/projects/mclemens/cs_char.gif.

On the other hand, complexity thinking, namely complexity understood as a method according to E. Morin is more or less contemporary to the sciences of complexity. By and large, especially in the French-speaking world as well as in the Portuguese and Spanish speaking worlds, Morin's understanding of complexity is the most popular one. The English-speaking world hardly knows of Morin's oeuvre. A recent re-take of Morin's ideas related to management in the French-speaking scenario is Le Moigne's writings (1995).

From the standpoint of view of systems science, cybernetics and complex thinking, the sciences of complexity are often accused of being too mathematically, physically or computationally founded if not dependent. Maldonado and Gómez-Cruz (2011a) offer a sharp view that shows how such accusation is flaw and false.

In any case, it must be clearly pointed out that complexity has nothing to do with the numbers of variables a systems has, exhibits or is grounded in. Instead, complexity can be understood in terms of the attributes that constitute the landmark of complexity, namely emergence, non-linearity, increasing complexity, evolution, power laws, free-scale networks, percolation, self-organization, far-from-equilibrium states, fractality, among others.

Being as it might be, with this paper we aim at showing how management has come to know of the sciences of complexity. Our scope however will not be historical or descriptive. In other words, it is not our purpose to trace here the origins, motivations, and history of such an encounter. PerhapsHelbing (2008) and Grote *et al.* (2008) offer a sufficient account of the origins and history of the encounter. It is neither the aim of this paper to focus on the description of the encounter, the pace and levels it achieves and has reached. In contrast, we will set out how after the encounter has been produced, management benefits from complexity and how and why complexity enriches the view, air and contents of management – management and business.

It is indeed our own contention here at the same time that we set out a sort of state-of-the-art of the interplay between management and complexity, to stress how management can leverage from the sciences of complexity.

We cannot help introducing our own perspective and philosophy along the lines that follow. This is due to the fact that this paper not only includes a phenomenological perspective[1] but a more propositional and attitudinal

1 For an inclusive view of what precedes, see http://www.carlosmaldonado.org

perspective supported on a series of studies that can be comprised in Maldonado and Gómez-Cruz (2011a), even though after that book other studies have continued being produced, as it happens. The process of research is a never stopping enterprise enriched, modulated or deepened along the studies that gradually are being published.

3. New languages, new thinking structures

Complexity, it should be mentioned from the outset, is not a fragmented domain. Instead, it is a cross-disciplinary field made up by a number of sciences – namely, non-equilibrium thermodynamics, chaos, artificial life, complex networks, and fractals. Therefore, it is also made up by numerous theories, such as catastrophe theory, turbulence, self-organization, fluctuations, percolation, or bifurcations theory. As a consequence, the approaches are varied and manifold, and science, the humanities, and engineering are inner peers in the field. As it has been pointed out, social systems are to be grasped in three scales that are methodologically distinguished but constitute a solid unit; these are natural social systems, human social systems, and artificial social systems (Maldonado, 2009). Broadly said, a theory of organizations – which is one of the pretentions if not of the assets of management should cross, incorporate or encompass all three systems. So far, however, only social human systems are considered, whichfrom the logical and epistemological point of view, is a very expensive enterprise – holding here, in the backstage,the principle of Ockham's razor. In contrast, the complex-minded approach to organizations demands and enables at the same time the integration of the three mentioned social systems.

It follows then that the sciences of complexity demand and allow from the start an open horizontal dialogue, as it happens, among domains, sciences, and disciplines that were traditionally separated, hierarchically split, and even indifferent to each other. Biology and management (Clippinger, 1999), mathematics and politics (Taylor &Pacelli, 2008), law and computation (Lodder&Oskamp, 2006), chemistry and ecology (Eisner &Meinwald, 1995), to name but a few, come together, reinforce themselves in positive loops, and advance in their joint research. This takes place, though, not just between two any given disciplines or sciences but as a real cross-disciplinary field. As a consequence, studying the role of complexity within management entails understanding the behavior of living systems, engineering-like phenomena, and social scaled systems.Indeed, when managing an organization, managers face day-after-day the paradox of having the control and not-having the control – of markets, prices, law governments, and the like (Streatfield, 2004). Streatfield's book is a particular case where management practice is grasped in the perspective of complex responsive processes. Self-organization and emergence become integral themes in thinking about life in organizations. The author highlights the importance and necessity of living with the paradox and managing such a paradox. Management is understood thus as participating in the construction of meaning in the living present.

Two additional references along the same line can be, firstly, Sargut and McGrath (2011), who deal with how to make sense of the unpredictable and the undefinable in today hyperconnected business world. Managers of complex systems face two problems: unintended consequences and difficulty making sense of a situation. In an unpredictable world, sometimes the best investments are those that minimize the importance of predictions, the authors argue. Secondly, Richardson (2008) explores the implications of complexity for the management of organizations. The paper claims that complexity is about the limits to what we can know about organizations. There are, the author claims, limits to what we can achieve in a pre-determined, planned way.

Being as it might be, there are a variety of links and fields within management that have come to encounter complexity. And yet, at the same time, complexity has come to pervade a number of sensitive domains and problems in management. The most conspicuous ones are:

- Complexity and organizational studies
- Complexity and leadership
- Complexity and strategy
- Complexity and innovation
- Complexity and resilience, i.e. sustainability

It must be said, however, that the way the encounter takes place and influences both terms is not even among them. Some of these relationships are more mature whilst others remain germinal if not tentative.

We will highlight in the following the most salient features, authors, and concepts worked out so far:

Complexity and organizational studies: First of all, we are to say that even though they are quite different, complexity and organizational studies are to be seen as complimentary; particularly when it comes about the group of studies comprised under the title of critical management studies (CMS)

(Alvesson, Bridgman &Willmott, 2009; Grey &Willmott, 2005). The reason that explains such complementarity lies in the fact that both approaches not only remain critical towards mainstream business and management, but they also strive to introducing new tools and concepts when dealing with the issues, concerns and questions pertaining to management at large; therefore also to business. Starkey and Tiratsoo (2007) show it well from the point of view of CMS taking as leading thread business. Most recently, S. Johannessen and L. Kuhn (2012) provide an in-depth view about the increasing relationships between organizational studies and complexity. The size and quality of these volumes certainly allows for new insights for future productive research. Maguire*et al.* (2006) study the relationship between complexity and organization studies, distinguishing the European and the North-American traditions about complexity. An important issue concerns the definition and measuring of complexity as an introduction to the core subject. It thoughtfully describes the implications of the most important concepts of complexity for management and business while focusing on the applications to organizations. The two main references of the text are the objectivist and the interpretationist approaches to complex science. Agent-based computational models (ABMs) are a key aspect in the study.

Complexity and leadership: Encounters just do not merely happen. They also occur in a specific terrain and circumstance. The medium where the meeting between complexity and leadership takes place is the concern for the ecological dimension of management and the consequences it entails for leadership. As a consequence, leadership is to be taken as a transformative capacity and dynamics wherein companies, corporations and organizations at large are to be transformed into *intelligent* organizations. Not only adaptation but also constant learning becomes key factors here. In Goldstein, Hazy, and Lichtenstein (2010) the touchstone of the encounter between leadership and complexity are the ecologies of innovation, precisely. The horizon, so to speak, where the encounter has come to take place is the transition from the third sector in economics towards the fourth sector, namely the knowledge-based economics.

***Complexity and strategy*:** Whereas strategy was traditionally conceived as a one part item in a double-sided if not multiple-sided landscape, a complex strategy must be viewed in a threefold way, thus: i) as two-sided or a double-implication. This is traditional strategy studies; ii) a many-body problem situation where nothing can be decided from the standpoint of any one of the components taken on its own or isolated. One way to set this out is our current multi-polar world including newcomers such as the BRIC countries (Brazil, Russia, India, and China) or the CIVETS (acronym for Colombia, Indonesia, Vietnam, Egypt, Turkey, and South Africa)– jointly with the USA andthe European Union, for instance; iii) as a constantly evolving and adaptive panorama due to the reciprocally influence of the nodes considered in a given situation or circumstance. This third way allows for the study of emergence, decadence, collapse, reserves-countries, and the like.

Complexity and innovation**:** Whereas modern or classical science is conceived in terms of just solving problems, complexity science is both about solving problems *and* formulating problems. To be sure, from the complexity standpoint, the best way to solve a problem consists in innovating, and one way for innovating is by both stating *and* solving problems. Therefore, we can safely say complexity is about innovating – and the sciences of complexity have since long ago been introduced as a scientific and technological revolution, very much in Kuhn's sense.

Complexity and resilience, i.e. sustainability**:** Whilst a serious question about how to best understand and describe the living of organizations remains as an unanswered problem, there is no unique or sufficiently well accepted term neither in the academic, nor in the scientific or in the financial world, for example[2]. The sciences of complexity are sciences of life in the sense that the most complex phenomena in any large or technical sense of the word are living systems (Maldonado, 2010). And yet, life is not to be grasped just in an organic sense, but rather as a behavior or a quality (Stewart, 2007). Evo-devo offers a most fruitful approach for the interplay between complexity and management and it goes about resilience, perdurability or sustainability, for it is a view that does not separate the organismic from the species perspective or vice-versa, but it integrates both in one and the same grasp. A recent study, not necessarily from the point of view of complexity, on perdurability has come to conceived it *post-mortem*, namely in the sense of the *post-mortem* businesses and organizations (Walsh &Bartunek, 2011). Eskinen, *et al*. (2003) claim:

[2] There are, indeed, a variety of terms not always well grounded or sufficiently explained like *perennité* (among the French), sustainability, perdurability, or resilience, we leave the question about semantics aside and take, just for the sake of the discussion two concepts as equivalents, namely resilience or sustainability.

> In an organizational context, complexity provides an explanatory framework of how organizations behave. How individuals and organizations interact, relate and evolve within a larger social ecosystem. Complexity also explains why interventions may have un-anticipated consequences. The intricate interrelationships of elements within a complex system give rise to multiple chains of dependencies. Change happens in the context of this intricate intertwining at all scales. Often one can become aware of change only when a different pattern becomes discernible. But before change at a macro level can be seen, it is taking place at many micro-levels simultaneously. Hence micro-agent change leads to macro system evolution.

Plainly said, organizational complexity means the end of linear management approaches. From a different perspective, Wilson and McKiernan (2011) have called the attention to the same issue.

4. Computation, complexity, living systems and management

H. Pagels (1988) was probably the first one who pointed out how complexity is somehow the outcome of computation, but at the same how it helps enrich and develop computation and computer science. There is, indeed a deep and robust interplay between the sciences of complexity and computation (Mainzer, 2007) in that complexity is a new kind of science, namely it is not just inductive or deductive which were and have been the two normal ways on science in modern age. Rather, complexity is science via modeling and simulation, whence the strong and positive feedback between complexity and computation (Axelrod, 1997). This, however, is not to be taken as if there was kind of reductionist approach in the sciences of complexity, which is the external judgment of the outsiders of complexity.

Within the frame of managerial studies and concerns, computation has an array of ways of development, namely natural computation (Brabazon& O'Neill, 2006), computational intelligence (Fink &Rothlauf, 2008), artificial life (North &Macal, 2007), and, most notably, adaptive business intelligence (Michalewicz, Schmidt, Michalewicz&Chiriac, 2007).

When differentiating business from management, the complexity approach becomes relevant in that it helps understand the broader scope of management without, however, turning the back to the business. The latter is considered as business intelligence, whereas the former is taken within the framework of biology or ecology. Indeed, organizations can be fully explained and managed as living organisms or living systems. Epidemiology, population biology, swarm intelligence, artificial life, and Evo-devo become particularly meaningful thanks to the encounter of management and business with complexity.

Living systems do compute, it has been argued (Gómez-Cruz& Maldonado, 2011). Computing, however, does not happen nor can be explained in terms of a black box, which is the usual understanding of the Turing Machine, in spite of Turing himself. If so, management gets enormous and fruitful insights when managing everyday practical situations in companies and organizations at large. To say the least, managers, workers, CEOs, and stakeholders incorporate metaphors from both biology and ecology (Bonabeau& Meyers, 2001; Clippinger, 1999; Cowan, Pines & Meltzer, 1999). Metaphors become important tools for the understanding of new behaviors, emergent properties, and surprising new systems, and yet help understand and solve real case problems in the day-to-day life of managers, CEOs and workers.

Such a view, though, should not give the impression that it is *just* a matter of metaphors, i.e. language. Not only do we use metaphors both in science and in everyday life, but, the leverage of tools, concepts, and categories from ecology and biology help managers to trace a distance vis-à-vis traditional mechanical, physical, and engineering-like explanation and management of companies, enterprises, and organizations.

Provided the fact that management originated firstly from engineering and physics, given the advances of science and knowledge in general, the very relationship of management with physics and engineering must be overturned. As a consequence, the management of engineering and the engineering management arise which shed new lights in the practical and pragmatic activities of managers. Digging deep into these, we come to encounter complex engineered systems (CES) and all bio-inspired rods and explanations (Braha, Minai& Bar-Yam, 2006; Gómez-Cruz& Maldonado, 2011). Complexity ceases to be a mere metaphor to become a real and useful new framework and rod at large.

This scenario can, indeed, beillustrated with the transition from traditional engineering, grounded on classical physics and logics, towards CES where the groundfield are the sciences of complexity and the non-linear sciences (Mainzer, 2007; Scott, 2007). Whereas traditional engineering designs and builds perfectly controllable systems, well defined, predictable, stable, trustful, optimal and transparent in their structures and processes, CES tries to provide engineering-like systems with more organic capacities, such as evolution, adaptation, learning, self-organization, flexibility/robustness, scalability, resilience, endurability, self-monitoring and self-repair, among others (Braha, Minai,& Bar-Yam, 2006). Generically said, the search is not centered any longer on predictability and control of organizations but in their possibilities vis-à-vis uncertainty and the constraints of the environment. The challenge for current management is, therefore, without any doubt the leverage and harnessing of complexity. Such a shift from classical engineering towards CES to biology and ecology can be safely recognized as a process of complexification of engineering (Maldonado & Gómez-Cruz, 2012). Management grows and moves nowadays in the midst of such a complexification.

Intelligent complex management is structured in biologically-minded way that looks not just for profitability, efficiency and efficacy, but for learning, adaptation, transformation and quality-of-life. If so, a new paradigm has arisen in management at large. As a matter of fact, in 2006 (innovation) and 2008 (change) IBM Global CEO studies, CEO´s agreed on the need and importance of assuming change as a cultural trait. In a larger 2010 study carried out by IBM, CEO´s of a number of companies and corporations (60 countries and 33 industries) came to the conclusion that it is now time to capitalize complexity.[3] Capitalizing complexity is to be taken as a radical assessment of what in a different context Axelrod and Cohen call "harnessing complexity" (1999). The 2012 study concerns "Leading through connections".[4]

According to the 2010 study, complexity is only expected to rise, which poses serious challenges for CEO's and managers. The study clearly points out the limits and constraints for coping with such a complexification of the world. Correspondingly, creativity emerges as the most important leadership quality. All in all, the escalating complexity is to be seen rather as an opportunity to create a brand new world.

The Rods Provided By Complexity

Since complexity is both spearhead science and a scientific revolution (Campos, 2009; Kuhn, 1996), the use of tools is not just a question of implementing or applying already proved and existing techniques, i.e. technologies, but rather a matter of developing and enhancing new rods. Without any doubt, the most salient rods in complexity are (Maldonado, 2011a; Maldonado 2011b).

- Measuring entropy (Shannon, Boltzmann, Zurek). Provided that the entropy of a system consists in a quantitative measure of its order (or lack of order), measuring the entropy of a system means establishing how random or not a systems is. In other words, for management entropy means measuring the levels, scales and topology of an organization.

3 http://www-935.ibm.com/services/us/ceo/ceostudy2010/index.html
4 http://www-935.ibm.com/services/us/en/c-suite/ceostudy2012/

- Measuring uncertainty (Heisenberg). We can know where a system is, but not where it is going. Thus, the measure of the uncertainty does not depend on any technical rod (i.e. subjective), but it is the intrinsic impossibility of determining both the speed and the situation of a body or phenomenon. Differently said, uncertainty means that future is not given behorehand, but it can be constructed.
- Measuring randomness (Kolmogorov, Gödel, Chaitin). The randomness of a complex system can be its very probabilistic state, its incompleteness, or its impossibility to be decidable. Since we live in a non-ergodic universe – that is, an irrepitable world, then the arrow of time becomes fundamental in that it opens up systems to randomness.
- Power laws (Zipf's law). Over against a Poisson or a Gaussian distribution, power laws are the landmarks of complex systems. A power law focuses on the extremes of a normal distribution, where innovation and surprise happen. Many actions can occur that do not a have a serious impact, but one or justa few actions might take place that can radically alter a system or a situation in time and space.
- Metaheuristics (Talbi). They consist in working with sets of problems looking for their spaces of solutions; one way is, for instance, by identifying isomorphism among the sets of problems. While traditional or normal science can be viewed in terms of a given heuristic, the sciences of complexity teach us how to combine different heuristics in order to better grasp the spaces of solutions not just of a given problem but of a set of problems according to their patterns, structures or dynamics that must be clearly identified. We will dig into this later on: See "Solving Complex Problems", below).
- Modeling and simulation. Modeling is about classical and complex systems. Simulation is properly concerned with complex systems. Whereas modeling allows us an application of a given model –whether conceptual, mathematical or logical, or also informational, on a real system, simulation enables understanding complex systems.Regarding simulation, it is important to differentiate it from mere computational graphics. More particularly, it is a *model* which can and must be modeled and/or simulated, which constrives both researchers and managers to develop and cope with a certain model, and not just with objects, subjects or relations.Whereas models are intrinsically static, simulations allow us to see the dynamics of a system or phenomenon.

- P versus NP problems (Lewin, Cook, and Karp). One the well-known "Millennium Problems" in mathematics, the P versus NP problems set forth the fact that complex systems require a logical thinking that goes far beyond usual symbolic or mathematical logic. Thus, the door is open to the non-classical logics. Some of the most remarkable non-classical logics are many-valued logics, paraconsistent logic, modal and multimodal logics, time logic, quantum logic, epistemic logic, and dynamic logic.
- The theory of recursion and iteration. All computational mathematics and logics are included within the theory of recursion. This clearly shows that complex systems are positive loops. Iteration is one of the transformations in geometry and sets up the importance of topology and fractals for the understanding of complex phenomena.

5. Solving complex problems

There has been a long discussion about the epistemological status of management. The question about the scientific status of management, not to mention, in terms of the numerous schools around the world, the concern about the distinction between management schools and business schools has been a sensitive issue implying a variety of decisions, relations, accreditations, prestige, and impact.

Being as it might be, what remains true is that science – in any sense of the word – is about solving problems. Not by chance, one of the key aspects in any scientific project remains the question about the identification or the formulation of a problem.

In the case of systems characterized by increasing complexity problems are identified and worked out within the frame of P, NP, and NP-complete problems, particularly (Maldonado & Gómez-Cruz, 2011b). This characterization of problems refers to the way in which computational problems in the standard sense of computation are solved. Thus, a P problem is the one that can be solved exactly, i.e. in a deterministic way using time and space, limited resources (namely, seconds, days, or at most weeks). These problems are known as easy problems, and thereafter as irrelevant. On the other hand, those problems that require an exponential time (i.e. up to hundreds of years!) to be solved with accuracy, even making use of the most powerful computers currently available are known as intractable problems (Fomin&Kratsch, 2010). When an intractable problem gets to be solved with limited resources but only approximately it is known as a NP problem. These problems are known as difficult – and thereafter also as relevant. The difficulty remains about distinguishing and proving whether P problems are equal or different from NP problems, or also whether those are included within these, or vice versa. And yet, what is sufficient here is the fact that management can move by understanding P problems as managerial ones, and NP problems as the one that concern, in and for, direction.

There are a wide range of traditional models and techniques that are applicable to organizations. In fact, a large number of problems find acceptable and appropriate solutions within the framework of the reductionist, deterministic and analytical approaches of classical science. Nonetheless, the most relevant problems in and for organizations are nowadays complex and they refuse to be treated, explained or solved throughout such techniques. Notable examples of such a trend are the problems associated with decision making, products distribution, the prediction of economic dynamics, the optimization of processes, programming turns, the detection of failures, keeping up clients, and the design of strategies, among others. According to Michalewicz et al. (2007), this group of problems shares a set of generic features that characterize them as complex. The most relevant ones are:

- There are so many potential solutions available that evaluating them all in a reasonable time becomes simply impossible.
- The solutions dependon a highly dynamic environment which makes that a certain decision made rightly today might break down tomorrow an organization. Hence, solutions ought to be dynamic and not just as sort of “joker”.
- There are a series of constraints that must be satisfied. These can be economical, ethical, obey to internal regulations, governmental policies, or just the preferences of the decsions makers.
- A problem must respond to many –usually conflicting – goals. Minimizing time and the waste of a process of manufacturing is a simple example in which the goals can be directed towards contrary directions.

A meaningful fact can be summed up to what precedes. This has to do with the role information and computational systems play in and for organizations. Directors and managers have long ago recognized and valued the role of information in the decision-making processes and in strategic planning. The organizations that do not have, and rely on, an information system, even a basic one, are nowadays scarce and few. However, what is still to be recognized is the distinction between having good information and the decision made rightly. It is currently not sufficient with having detailed information concerning a variety of aspects and operations in a given organization. Nor is it enough having the capacity of extracting knowledge, for instance in the form of graphics and tables that can support the decision-making – which is precisely what business intelligence is concerned with. Notably, the next step consists in extracting the best choices – not necessarily optimal – and being able to evaluate their impact in particular contexts. This is a highly complex task that cannot be undertaken manually. The new computational paradigms – which constitute the core of adaptive business intelligence, are greatly supporting such an endeavor (Michalewicz et al., 2007).

Furthermore, expressed in the language of game theory, it must be acknowledged that there is no perfect or complete information. At best, we can count on information burdened with noise, incomplete information or more simply in situations where we lack information. As game theorists have put it out clearly, pretending to have all information or gather as much information as possible or feasible might become in an irrational action or lead to an undesirable outcome.

The first and foremost wide road open to solving problems within a complexity approach has been set out, without any doubt, by metaheuristics (Talbi, 2009). These consist of a set approach – very much like in set theory – where problems are identified and worked out in terms of homology, isomorphism, and maps. As a consequence, the search for solutions goes accordingly in terms of the dynamic and structure of the problems. With time, hence, metaheuristics have developed into hybrid metaheuristics – that include hyperheuristics and adaptive metaheuristics – along with parallel metaheuristics. Multilevel metaheuristics can be also mentioned as recent trends that take a growing distance vis-à-vis traditional or common heuristics (Doerner et al, 2007).

Numerous fields within the sciences of complexity study metaheuristics and their applications to both management and business, among other fields of the social sciences. One of the most remarkable branches in natural computation, for example, is the development of computer programs and computational algorithms motivated by biology capable of solving complex problems in the real world. This is known as bio-inspired computation (De Castro, 2007). Close to bio-inspired computation stands computational intelligence (Engelbrecht, 2007; Fulcher& Jain, 2008), where the goal consists in providing techniques for problem solving that require intelligence, in principle. A similar field is adaptive business intelligence, which seeks to provide tools that allow make better decisions in management as well as in business (Michalewicz et al., 2007). Among the most important techniques and paradigmsthat the fields mentioned above share, we find:

***Artificial neural networks*:** These are highly sophisticated computational models that seek to capture and explore behaviors and characteristics of the natural nerve system aiming at theoretical and applied goals. Some of the main features that are abstracted are adaptation, learning, memory, flexibility, robustness, generalization and content-based retrieval (Floreano&Matiussi, 2008). In other terms, these are sets of neurons or nodes interconnected such that they form architecture of layers. The input channels in a neural network represent dendrites and the output channels the axons. The synapses among neurons are modeled via adjusted weighs. These networks simulate the natural excitatory and inhibitory actions aimed at processing information and solve problems. The kind of problems that are solvable thanks to artificial neural networks, particularly in the framework of business and decision-making, can be ranked in three types, thus: recognition of something (for instance patterns, failures, etc.); inferring something (f.i., price trends, clients fidelity), and setting some things within classes (namely, ranking and classifying) (Forbes, 2004). A recent representation of the field can be found in chapter 3 of FloreanoandMatiussi (2008).

***Evolutionary computation*:** It is a computational paradigm inspired in natural selection and genetics. From the point of view of problem-solving, evolutionary computing can be extended as a search and optimizationmeta-heuristic (Dumitrescu, Lazzerini, Jain &Dumitrescu, 2000; Talbi, 2009). It is particularly interesting when supporting processes and systems of decision-making. The algorithms designed under this paradigm are known under the generic name of evolutionary algorithms (Dumitrescu et al., 2000). In wide general terms, evolutionary algorithms are made up of a population of individuals (many times called chromosomes) in which each of them represents a candidate solution to a given problem. Once the population is defined, it evolves throughout selective pressures and mutation, recombination, concurrence and investing. Evolutionary computation has been successfully applied in domains where operations research and classical artificial intelligence are not efficient or, simply, fall short of satisfying answers.

***Swarm intelligence*:** It is an innovative form of solving computationally complex problems (Bonabeau, Dorigo, &Theraulaz, 2000), and a de-centralized, parallel and self-organized thinking model. The concept of swarm intelligence has been inspired by the behavior and capacities emerging in social insects (ants, termites, bees, wasps) as well as by animals living in community (bird flocks, school of fish). There are a good number of algorithms and simulations inspired in swam behaviors that have been successfully applied in dealing with problems in logistics and markets modeling, to name but a couple of examples. More exactly, swarm intelligence is fostering new ways for thinking about business (Bonabeau& Meyers, 2011). Two meaningful contributions of swarm intelligence to management have to do with de-centralized control mechanisms – self-organized –rather than with hierarchies well set out, and with collective decision-making.

Immune computing: It is a computational paradigm that considers the immune system as a sophisticated complex adaptive system capable of processing information in a distributed and parallel way (Dasgupta&Attoh-Okine, 1997). This domain is also known as artificial immune system. Diverse algorithms, models and computational systems based on the immune system haven been suggested in the literature (Dasgupta& Niño, 2009). Some of the fields where it has been applied are of interest for management and business such as pattern recognition, informational security, detection of anomalies in time series, optimization, machine learning, adaptive and feedback control, data mining, adaptive programming of computational systems, and the diagnosis of failures, among others (De Castro &Timmis, 2002).

Membrane computing: It is a field that belongs to natural computing which seeks to abstract ideas and computational concepts based on the structure and functioning of living cells, as well as on their organization in higher-order structures (Păun, 2006). This domain is about parallel and distributed computational models that simulate the living cell organization in a variety of behaviors and membranes set out hierarchically or as membrane network. It is also about the way in which cells in multi-cell organisms are organized to form tissues capable of undertaking a variety of functions (Bernardini, Gheorghe, Krasnogor&Terrazas, 2005) – including those of the brain. The structures based on membranes are technically called P systems (or also membrane systems). Notably, membrane computing is applied to optimization problems. A remarkable case is its application to control time-varying unstable plants (Huang, Suh& Abraham, 2011).

Fuzzy logic**:** Fuzzy logic and fuzzy control are well known rods in management partially due to the inner relationship existing between management and engineering.While its first, and by far large, influence of fuzzy logic has been in technology, and therefore in managing optimization and soft and yet accurate behaviors in operations, it has remained as a valuable tool that helps make flexible measurements and indicators, as mentioned in (McNeill and Freiberger, 1993). As it will be mentioned at the end of this paper, the sciences of complexity have a larger tray to offer to management when dealing with logics. Indeed the non-classical logics that include among others paraconsistent, epistemic, dynamic, relevant, quantum, and many-valued logics, among others, are to be seen as useful criteria in the processes of decision-making, arguments, and measurements and indicators in organizations striving in the midst of a complex world (Maldonado, 2012).

6. Understanding complex phenomena

There are many times when decisions are made and actions are undertaken in organizations without really knowing neither the dynamics of a given phenomenon that are going, nor the consequences of the decisions and actions. Agent-based modeling and simulation enter in the field to help cope with such situations. Moreover, the truly important contribution of modeling and simulation consists in developing *experimental management*, namely decisions, actions and processes before applying them in the real day-to-day world.

A fundamental distinction must be made here, though. Only complex systems, behaviors and phenomena can be simulated (Maldonado & Gómez-Cruz, 2010). Modeling can be referred to complicated as well as to complex systems or phenomena.Simple and/or complicated systems cannot, by any means, be simulated. At best they can be computationally graphed. Most of the so-called simulations are sheer computation graphics, and this is even true when viewed for most modeling.

It is, indeed, a *model* which can be properly simulated. Modeling refers to the works with software and programming aimed at applying in a real system the achievements computationally carried out and discovered. Simulation, on the other hand, is not directly or immediately aimed at an application, for its goal consists in understanding the characteristics and behavior of a complex system.

Agent-based modeling and simulation (ABMS) has provided wonderful insights and cleared up numerous conundrums in management and business as well as in the social science at large (Bonabeau, 2002a; Gilbert &Troitzsch, 2005). One of the most conspicuous achievementshas been developed by Axelrod in trying to understand and solve the challenges posed by the Prisoner's Dilemma and the feasibility of cooperative games (Axelrod, 1997). As it is well known, game theory is the economic language for what in management is called as strategy.Bonabeau (2003) presents the importance of trusting one's intuition in the process of decision-making. New analytical tools have been develop which enable us to have more confidence in one's own guts, such as agent-based modeling, artificial evolution, interactive evolution, open-ended search. All in all, it is a call to recognize the value of computational tools based in accordance to evolution.

ABMS originates within and from the sciences of complexity, artificial life and swarm intelligence (Macal, 2009). An agent-based model usually defines the environment in which individuals interact on the basis of static or dynamic “simple” rules. In its most elaborated form AMBS represent systems of heterogenic individuals (agents), autonomous and adaptable that interact generating emergent non-trivial behaviors at the global scale of the studied phenomenon. More accurately, ABMS seek to recreate, i.e. simulate emergent complex dynamics after local and individual interactions among the agents of a given population. A notable example vis-à-vis organizations consists in explaining the dynamic of an economic or strategic sector according to the behavior and interactions among the agents – in this case, the organizations – that intervene in such a sector.

ABMS, therefore, becomes useful when capturing highly non-linear interactions and emergent behaviors. Differently said, ABMS is most suitable just when traditional analytical and systemic techniques, such as statistical modeling, risk analysis, operations research, systems dynamics, standard participating simulation, or traditional events simulations come to acknowledge their own limitations (North &Macal, 2007). The hybridation of agent-based models with metaheuristics and other optimization techniques is already a common avant-garde practice within the frame of organizations and engineering. The use of metaheuristics and the hybridation mentioned are the core in the companies that currently work with and on complexity.

The most important applications of ABMS in management and business include flow management (of clients, traffic, evacuation), strategy simulation, improving manufacturing and operations processes, chain administration and supply networks, stock markets modeling, predicting the response of clients to specific marketing programs, design of shopbots and software agents, improving commercial benefits, operational risks management, organizational design, and innovation diffusion, among others (Bonabeau, 2002a; North &Macal, 2007).

The difficulty lies, as it happens, in the capacity of developing or achieving a model. This is, to be sure, by and large, the most important consequence of the encounter of management with the sciences of complexity. The agent-based modeling techniques, most notably, are easily implementable and yet they are non-trivial from a conceptual standpoint (Bonabeau, 2002a). Building models under this paradigm implies facing its counter-intuitive and non-predictable nature of increasingly complex systems (Bonabeau, 2002b; 2003). Being from its very origins an applied field on its own, management has mostly worked with "borrowed" models, for instance, financial, economical, sociological, psychological and others. Being spearhead science, the sciences of complexity bring to the fore the significance of working with, developing, and tearing down models, if necessary.

The robustness of a company or organization consists in significant direct relationship with the strength of the models it works with. We all are wishing companies and organizations had their own models, developed by themselves. This is however not the case. On the contrary, most so-called models are just copied, imitated or borrowed – from elsewhere. Porter has called the attention on something like these (Porter, 1998).

7. Applications of the sciences of complexity to management

So far, we have focused on the conceptual and theoretical framework of the encounter between management and complexity. But it must clearly be pointed out that even though scarce, there are a series of applied studies of the sciences of complexity to management besides those that have been mentioned along this paper. The domains where it has happened most fruitfully are logistics – particularly in the study of transportation, traffic, design, and route programming. However, other applications within logistics deserve to be mentioned such as chain supply, and manufacture. The reason lies in that logistics is concerned from the start with optimization problems and dynamics.

Two fields where conspicuous contributions and applications have been made are finance and economics. Within the normal frame of current management micro-economics could be sufficient. And yet, enormous contributions also in macro-economics are to be brought to the fore (Anderson, Arrow & Pines, 1988; Arthur, Durlauf& Lane, 1997; Blume&Durlauf, 2005; Lagi, Bertand& Bar-Yam, 2011; Ormerod, 2005).

In Brabazon& O'Neill (2006) a variety of bio-inspired algorithms are applied, mainly motivated by Darwinian evolution, to a series of case studies that include the modeling of financial markets, the development of contract systems, the creation of predictive systems of solvency, and the creation of credit-rating models.

Finally, the third rank of application of complexity to management is in marketing, especially when studying turbulent markets and processes. Perhaps the best studies so far are Holbrook (2003) and Lambin (2000), who get close to complexity theory using a language that helps understand fluctuating markets. As an example, Prokhorov (2008) presents the state-of-the-art in computational intelligence (CI) in automotive technology by leading authors in the field. Even though each chapter is self-contained, the chapters shed new lights on the directions where CI can and should make impact. Thus, better vehicle diagnostics/vehicle system safety, improved control of vehicular systems and manufacturing processes to save resources and minimize impact on the environment, better driver state monitoring, improved safety of pedestrians, making vehicles more intelligent on the road, are conspicuous cases of applications of CI. When published it was the first book on the field. Furthermore, Michalewicz *et al*. show how thanks to a development of a software system, optimization and decision-making in an auto manufacturer has helped improve the company. Adaptive solution is clear-cut complex problem, and can be identified as a clear successful case of adaptive business intelligence.

Table 1. Interactions between management and complexity

New languages, new thinking structures	
Organizational studies	Johannessen& Kuhn, 2012; Maguire, McKelvey, Mirabeau &Ötzas, 2006; Uden, Richardson&Cilliers, 2001
Leadership	Goldstein, Hazy & Lichtenstein, 2010; Plsek& Wilson, 2001
Strategy	Kraus, 2001
Innovation	Fonseca, 2002; Gloor, 2006; Pyka& Scharnhorst, 2009
Resilience, i.e. sustainability	Walsh &Bartunek, 2011
Solving complex problems	
Finance and economy	Anderson, Arrow & Pines, 1988; Arthur, Durlauf& Lane, 1997; Blume&Durlauf, 2006; Brabazon& O'Neill, 2006; Brabazon& O'Neill, 2008; Chen, Wang &Kuo, 2007; Meyers, 2011; Mount & Reiter, 2002
Transport, Logistics, and Supply Chain	Fink &Rothlauf, 2008
Marketing	Fioroni&Titterton, 2009
Industry and manufacturing	Liu, Sun, Tong Loh, Feng Lu, & Lim, 2008; Marti, 2007; Wang, et al. 2001; Xhafa& Abraham, 2008
Understanding complex organizational phenomena	
Prediction and decision making	Bonabeau, 2002b; 2003; Cook, Noyes &Masakowski, 2007; Michalewicz, Schmidt, Michalewicz&Chiriac, 2007; Qudrat-Ullah, Spector &Davidsen, 2008
Modelling and simulation	Axelrod, 1997; Axelrod, & Cohen, 1999; Bonabeau, 2002a; Bonabeau& Meyers, 2001; Ito, Zhang, Robu, Fatima, & Matsuo, 2009; North &Macal, 2007; Schredelseker& Hauser, 2008
General references	
Management, organizations and business	Dotlich, Cairo &Rhinesmith, 2009; George & Wilson, 2004; Helbing, 2008; McMillan, 2004; McMillan, 2008; Richardson, 2008; Sargut& McGrath, 2011; Stacey, 2005; Stacey, Griffin, & Shaw, 2000; Stacey & Griffin, 2005; Stacey & Griffin, 2006; Steger, Amann&Maznevski, 2007; Streatfield, 2004

Gaudiano *et al*., (2003)deal with how unmanned air vehicles (UAV) can be understood and developed based on swarm intelligence. The authors expose a model they achieved and the strategies suggested. It is an agent-based model of decentralized control strategies for swarms of UAVs. Pathak*et al.* (2007)bring the applicability of complexity theory and CAS into sharper focus, highlighting its potential for integrating existing supply chain management (SCM) research into a structured body of knowledge while also providing a framework for generating, validating, and refining new theories relevant to real-world supply networks. The authors propose that the SCM research community adopt such a dynamic and systems-level orientation that brings to the fore the adaptivity of firms and the complexity of their interrelations that are often inherent in supply networks.

8. Entrepreneurial consulting based on the sciences of complexity

Some of the most re-known consulting companies are currently taking profit from the sciences of complexity (table 1).

Several aspects that characterize these companies are the following:

1. They are set up by well-known researchers in the fields of management, engineering, computation sciences and, more remarkably the sciences of complexity;
2. They have a research and development team and worldwide-acknowledged scientists advise staff or them;
3. They make use of, or harness, the sciences of complexity as base knowledge;
4. They have strong policies of scientific and applied publications with high standards;
5. They use technology and spearhead methods, usually motivated by biology, for solving complex organizational problems;

They work with measurable results i.e. indicators. As one example, Munroe*et al*. (2005) show in a typical case study how delivering a hybrid system combining both agent-based technology with evolutionary computing techniques, NuTech Solutions provided a state of the art optimization and production scheduler that helped Air Liquide America maintain their position as the market leader in the highly competitive energy transformation market.

9. Future directions: experimental management

Experimental management means both an informational and computational working with creating artificial study cases, fictional and still fruitful scenarios, situations and circumstances where workers, managers, CEO's or stakeholders have to decide, act, and earn or loose assets, for example.

The informational working refers to the use of general software already existing, such as Excel, or scientific software or languages such as Wolfram Mathematica, Java, LISP, NetLogo, or MatLab to name but a few. On the other hand, the computational working implies developing new software along the working with fictitious decisions, actors, drivers or roles in a given circumstance or situation, created artificially as well. In any case, the very conceptual or theoretical understanding of phenomena and behaviors in computational terms is to be seen as a working with experimental management aiming at developing new models, concepts, approaches that make possible to formulate and solve (new) problems.

The recent crises that started with the DotCom at the early 2000s, and the other ones up until now (hedge funds, sub-primes, etc.) show that both from a financial and managerial points of view – not to mention from the standpoint of social and environmental dynamics – managing the crisis has become a post hoc if not an ex post affair. At its best, mainstream science just has been able to retrospectively predict the crises and their outcomes, always unpredictable. It is in contrast with this normal procedure that experimental management is a new useful complex approach thanks to modeling and simulation. Experimental management can help the public, the private and the third sectors alike.

Table 2. Consulting companies based in complexity science

Company	Foundation date	Offices	Science, technology, methods, and tools	Applications, solutions, and products	Some customers	Web
SolveIT Software	¿2005?	Adelaide, Melbourne, Brisbane, and Perth, Australia; Chisinau, Moldavia	Agent-based systems; ant systems; evolutionary computation; fuzzy systems and rough sets; neural networks; swarm intelligence; simulated annealing; tabu search	Advanced planning and scheduling; supply chain network optimization; demand planning and forecasting; predictive modeling	Ford; Australian Department of Defense; Government of South Australia; United States Office of Naval Research	[1]
AntOptima	2001	Lugano, Switzerland	Ant colony optimization; bayesian and credal networks; genetic algorithms; tabu search; simulation	Vehicle routing; scheduling; data mining; transportation and logistics; case history	Pina Petroli; Number 1 Logistics Group; City of Parma; Migros, Switzerland; Trenitalia; Carnini	[3]
Icosystem	2000	Cambridge, MA, United States	Agent-based modeling; genetic algorithms; complex networks; complexity science	Product design: benefit plan design, consumer clustering; marketing: social networks, strategic communications, blog analysis; operational strategy: portfolio management, personnel management; network analysis: network diffusion, vulnerability testing	United States Office of Naval Research; United States Defense information systems agency; NASA; Unilever; Intel; Pepsico; Nike	[7]
NutechSolutions	1999	United States; Germany; Poland	Neural networks; fuzzy systems; data mining; evolutionary computation; agent-based modeling; discrete event simulation; simulated annealing; tabu search; ant colony optimization	Data preparation and data mining; modeling; simulation; forecasting; optimization	ChevronTexaco; BMW; Dutch Ministry of Traffic; General Motors; Oxy; Polish Ministry of Agriculture; Polish Air Force Academy; Procter & Gamble; SAP; Siemens	[4]
Eurobios	1999	Gentilly, France; London, United Kingdom	Complexity sciences; agent-based simulation; ant algorithms; genetic algorithms; neural networks	Supply chain, production, inventory management, load and distribution optimization; R&D project management and project planning optimization; customer relationship management and marketing portfolio optimization; risk quantification and predictive analysis; industrial advanced design multi-criteria optimization; populations behavior or financial markets simulation	Southwest Airlines; United Airlines; Boeing; Airbus; Honda; Ford; Peugeot; Disney; Zurich Financial Services; United States Army; Texas Instruments; Microsoft	[5]
Natural Selection, Inc.	1993	San Diego, United States	Evolutionary computation; fuzzy systems; neural networks	Factory scheduling; agent-based combat simulations; homeland security; drug design	United States Army; Eli Lilly; Isis Pharmaceuticals; United States Federal Aviation Administration; United States Marine Corps	[6]

Managers – hence leaders, strategists and decision-makers in the future-to-come ought to incorporate metaheuristics, CES, some of the non-classical logics, P versus NP problems, agent-based modeling and simulation in order to better stand fluctuations, uncertainties, unpredictabilities, surprise, and emergence. This is what Axelrod and Cohen (1999) exactly have in mind when talking about harnessing complexity. To be sure, harnessing complexity does have organizational implications that are accurately the concern of managers, namely of those managers that have come to know of the sciences of complexity.

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