Complexity modelling in Economics: the state of art.

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Abstract

The crisis happened in the world in the last years, describing a whole of interdependencies and interactions, highlighted the theory's fundamental flaws of neoclassical economic theory: its unedifying focus on prediction and, above all, its inability to explain how the economy really works.
It is the time to investigate economic phenomena not as derived from deterministic, predictable and mechanistic dynamics, but as history-dependent, organic and always evolving processes. Because this view implies new challenges and opportunities for policy, we will focus the attention on innovative components of Complexity Theory for the study of economics and the evaluation of public policies.

Keywords: complex systems, economics, public policies

Introduction

The crisis happened in the world in the last years, describing a whole of interdependencies and interactions, highlighted the fundamental flaws of neoclassical economic theory: its unedifying focus on prediction and, above all, its inability to explain how the economy really works.

The reductionist approach, applied by this theory, overlooks the dependencies or interconnections among elements and their influence on macroeconomic behaviour, and it too often failed as an analytical approach (Morin, 1992). Its goal is to reduce the overall behaviour of a system to a number of essential elements and studying disjointedly these parts, the system can be analysed in every detail. The reconstructed behaviour of this system is obtained just re-aggregating its components (principle of overlap). The focus of reductionist approach is not to study the unfolding of the patterns its agents create, but rather to simplify its questions creating a separation between reality and its formal representation.

The last century, was dominated by the notion that science would yield answers of the simplest kind to a wide range of applicable problems. In particular the science went through the twentieth century developing and perfecting a model based on nineteenth-century hard sciences. Due to an increasing body of experiential knowledge of using science in the quest for exact answers to important problems and the growing realization that such certainty is illusory this idea has gradually dissolving.

During the last two decades a new field of interdisciplinary research, named "science of complexity, or complexity theory" emerged from the interplay of physics, mathematics, biology, economy, engineering, and computer science oriented to overcome the simplifications and idealizations that have led to unrealistic models in these sciences.

Its goal is to explain in a multidisciplinary way how complex and adaptive behaviour can arise in systems composed of large numbers of relatively simple components, with no central control, and with complicated interactions. Not more aggregate reduced to the analysis of a single, representative, individual, ignoring by construction any form of heterogeneity and interaction, but the aggregate emerging from the local interactions of agents. From this point of view the system is different from the sum of the parts.

The behaviours of complex systems depend on the interaction (often with retroactive character) among parts and not so much (or not only) from the characteristics of the parts themselves; the behaviour itself of single parts does not give explanation of the whole behaviour. Even if all the simpler constitutive parts are analysed and a complete and exhaustive understanding of their operation is reached, we are not able to understand the system as a whole.

Moreover these systems can show structural instability: small modifications could imply final results strongly different. For this our understanding of the behaviour of a system in a certain point could be valid only for a very small space around this point.

In economics Complexity Theory challenges its fundamental orthodox assumptions (equilibrium, representative agents, rational choices), and seeks to move beyond them, emphasising the power of networks, feedback mechanisms and the heterogeneity of individuals.

It works not more by simplifying, linearizing and dividing, but observing the relevance of interrelationships among the components of systems - as well as their relationships with the environment and vice versa - in determining collective behaviours.

Economic scientists relying on seeing the social system as a static system—with linear relationships, equilibrium, and connections that fit relatively simple equations have to turn to new economic theories in order to understand how the economy really works and how governments might manage the economic system more effectively. So it is time to explore new ways of managing our economy oriented at evolution and change rather than only at pursuit of competition, efficiency, and growth.

This new approach is not just an extension of standard economics but a different way of seeing the economy as a system where actions and strategies constantly evolve, where time becomes important, where structures constantly form and re-form, where phenomena appear that are not visible to standard equilibrium analysis, and where a meso-layer between the micro and the macro becomes important (Arthur, 2013).

Static equilibrium and perfect rationality, ignorance of innovation, downplaying of institutions, and assumption of zero-sum market transactions are assumptions relaxed in favour of “an economy made up of millions of overlapping activities, in which individuals, businesses and other institutions are highly connected and constantly interact, where preferences change and markets shift in unpredictable ways. It is a description that is immediately more recognisable in reality” (Kay, 2012). Its main concepts include emergence, adaptation, self-organization, patterns, agents, networks, wholeness, interdependent interactions among divergent yet connected parts, learning and memory, change and evolution, holism and synergy (Manson 2001).

This paper starts from the premise that there is a lot wrong with conventional economics and that insights from new economic thinking need to be taken seriously. The idea is to investigate economic phenomena not as derived from deterministic, predictable and mechanistic dynamics, but as history-dependent, organic and

always evolving processes. Because this view implies new challenges and opportunities for policy and managing economic crises, we will focus the attention on innovative components of Complexity Theory.
The paper is so structured. The first section discusses the distinguishing characteristics of complex systems, and the second unpacks the implications of applications of Complexity to Economics. The latter shows how the insights and methods of complexity science can be applied to assist policymakers.

Section 1-Complexity Theory: more is different

Both macro and micro events, from predictions of the general performance of the economy to more local issues such as climate change, sustainability, demographic change and migration, transnational governance, and security, among others, seem beyond our understanding and control.

The issues involved in each of these areas transcend disciplinary boundaries and making progress will require a significant interdisciplinary effort and a paradigm change in scientific thinking (Gilbert and Bullock 2014).

Complexity theory is a highly interdisciplinary research programme that encompasses a broad range of theories, empirical work, and methods involving not only economists, but psychologists, anthropologists, sociologists, historians, physicists, biologists, mathematicians, computer scientists, and others across the social and physical sciences.

Beyond this, however, it is difficult to be much more precise, as the notion of Complexity is itself extremely equivocal[1] and open to debate. For this reason, it is not possible to give an exact definition of what is meant by "Complexity."

To some, complexity theory is merely the study of branches of different sciences, each with its own examples of complex systems, while others argue that there is a single natural phenomenon called 'complexity', which is found in a variety of systems, and which can be the subject of a single scientific theory or approach.

Nevertheless both positions seem to agree about the object of study of Complexity, that's, complex systems.
A complex system is composed of many parts that interact with and adapt to each other and, in so doing, affect their own individual environments and, hence, their own futures. The combined system-level behaviour arises from the interactions of parts that are, in turn, influenced by the overall state of the system.
Therefore Complexity is a characteristic of a system and arises because of the interaction among the components of a system (Cilliers 1998); it is not so much the properties of the individual components, but their relationships with each other that shape complex behaviour. The properties of the system emerge as a result of these interactions; they are not contained within individual elements (Durlauf 2011). **C**omplex systems generate dynamics unpredictable which enables their elements to transform in ways that are surprising, through adaptation, mutation, transformation, and so on.

Decomposing a complex system into individual components destroys the system properties. Thus, complex systems, such as the brain, living organisms, social systems, ecological systems, and social–ecological systems, must be studied as global systems. In this sense we are unable to mathematically derive the complex

[1] The MIT physicist Seth Lloyd provided over 45 definitions, indicating just how much disagreement there is on what is meant by complexity (Horgan 1997, pp. 303, f11).

emerging properties from the organised interactions of its entities and hence the reductionist method of traditional science does not work. Vice versa if the system is complicated we can applied it[2].

We can summarised the set of features that are widely associated with complex systems in this way (Cilliers 2013):

- **Large number of components**. Complex systems usually consist of a large number of components that influence and are influenced by others. The individual elements of a system are influenced directly by the behaviour of the system as a whole, and at the same time their interactions lead to the emergent behaviour at the aggregate level of the system. These dynamic interactions are characterised by three properties:
  -Nonlinearity: small causes can have large effects and vice versa. This is a precondition for complexity. A system is linear if one can add any two solutions to the equations that describe it and obtain another, and multiply any solution by any factor and obtain another. Nonlinearity means that this superposition principle does not apply. This implies that while linear thinking is based on the belief that the whole is only the sum of its parts the nonlinearity refers to the fact that the whole is more than its parts.
  -Feedback loops. The effect of any activity can feed back onto itself, sometimes directly, sometimes after intervening stages. A part of a system receives feedback when the way its neighbours interact with it at a later time depends on how it interacts with them at an earlier time. Feedback can be positive (enhancing, stimulating, reinforcing) or negative (detracting, inhibiting, counterbalancing). The interplay between the two feedbacks is just one of the few examples of a self-perpetuating process that complex systems possess (Orrell 2010).
  -Self-organization. A system that is characterized and acts through many adapting elements is called self-organizing because no entity control it and creates it. Self-organizing systems, continuously will adapt itself in autonomous way so as to better cope with various internal and external perturbations.
- **Emergence.** Emergence relates to the dynamic nature of interactions between components in a system (Gallegati and Kirman 2012). The dynamic character of emergent phenomena is not a property of a pre-established, given whole, but arises and becomes apparent as a complex system evolves over time (Goldstein 1999). Emergent properties could be defined as properties that occur at a different level of aggregation rather than the description of the components of the system. In any event, the hallmark of this kind of complexity is novelty and surprise which cannot be anticipated through any prior characterization. All that can be said is that such systems have the potential for generating new behaviours.
- **Open systems**. Complex systems are thermodynamically open systems. The interactions make difficult to determine the border of a complex system, so we need to understand the system's complete environment before we can understand the system, remembering the environment itself is complex.
- **Path dependence**. Because they change with time, complex systems have histories. Not only do they evolve through time, but their past is co-responsible for their present behaviour. Any analysis of a complex system that ignores the dimension of time is incomplete, at most a synchronic snapshot of a diachronic process.

[2] A car composed of thousands of parts whose interactions obey precise, simple, known and unchanging cause-and-effect rules is a complicated system. For this it can be well understood using normal engineering analyses. An ensemble of cars travelling down a highway, by contrast, is a complex system. Drivers interact and mutually adjust their behaviours based on diverse factors such as perceptions, expectations, habits, even emotions (OECD Global Science Forum, Report 2009)

- **Power Laws.** Complex systems are sometimes characterized by probability distributions that are best described, instead of normal distribution, by a power law. This slowly decreasing mathematical function can predict, probabilistically, future states of even highly complex systems.

Synthesizing complex systems are dynamic nonlinear systems with multiple equilibriums, evolving in time and space, which self-organize from local interactions and characterized by historical dependencies, complex dynamics, thresholds and multiple basins of attraction (Carpenter et al. 1999, Levin 1999).
As consequence the methods applied in complexity studies are quite different from those used in traditional science. They include: agent--based modelling (otherwise known as generative computer simulation), cellular automata, catastrophe theory, complex adaptive systems, data mining, dynamical systems theory (otherwise known as chaos theory), fractal geometry, genetic algorithms, neural networking (otherwise known as distributed artificial intelligence), power law, scale-free networks, self-organized criticality, synergetic.

Section 2- Complexity modelling in Economics

In order to abstract from heterogeneity, which allows the application of rigorous calculus to economics to gain deep insights embedded in a formal elegant framework, the explanation of human behaviour is brought back to that of representative agent: an agent that has complete information and acts with rationality when making choices and her choices are aimed to optimization of her utility or profit.

This agent must present perfect knowledge and complete information. On the base of such an information and knowledge, he must be able to make every sort of necessary complex calculations. He has time and ability to weigh every choice against every other choice and finally he is a fully aware of all possible choices. Further, individual preferences are taken to be given a priori, rather than constructed and revised through on-going social processes: they are primitive, consistent, and immutable. He operates according to the choice imperative: given a set of alternatives, choose the best.

This process of choice postulates utility values associated with possible states of the world perfectly foreseen in which situations with higher utilities are preferred to those with lower ones. Those preferences are defined over outcomes, known and fixed, so that decision makers maximize their net benefits by ordering and choosing the alternative that yields the highest level of benefits. Possible differences regard only quantitative and not qualitative levels.

Complete information implies that each individual reach the same conclusion, only Gaussian deviation from the norm is allowed and they cancel each other in the average. It is not important the direct relation of each individual with others as individuals is only in relation with the market through the money that compensates for every deviation from the norm.

The behaviour of all the agents together is treated as corresponding to that of an average or representative individual. In this way aggregate quantities and their relationships are derived directly from the analysis of the micro-behaviour of this representative agent. The solution of this optimization problem is an individual demand curve used as the exact specification of the aggregate deduced just summing up the behaviour of agents that compose a market or an economy. Therefore the result of decision problem of the representative economic unit is the results of aggregate quantities.

There are not significant differences between micro and macro levels: the dynamics of this latter is just the summation of dynamics of the former. The behaviour of an economic group is adequately represented by that of a group whose members have the identical characteristics of the average of the group.

But these assumptions are inadequate to describe a world in which agents use inductive rules of thumb to make decisions, they have incomplete information, they are subject to errors and biases, they learn to adapt over time, they are heterogeneous, they interact one another, in a few words are not rational in a conventional sense. Hypothesis totally unrealistic because they don't reflect real individual behaviour (Robles 2007) nor the complexity of human decision making (Shapiro and Green 1994). As assumes Friedman "*Truly important and significant hypotheses will be found to have «assumptions» that are wildly inaccurate descriptive representations of reality, and, in general, the more significant the theory, the more unrealistic the assumption …"*[3]. This affirms the theory of rational expectations, with the assumption that agents have, implicitly, also the knowledge of the model from which descend the consequences of their actions. This will give the economic actors much more knowledge than econometric that builds the model (Sargent 1993).

Economic agents cannot obtain perfect knowledge of the global consequences of their actions; they are not able to equate costs and benefits of knowledge; behaviours that deviating from the average does not cancel each other, but they could reinforce each other. Each individual can reach only a partial knowledge that is focussed around its "world" (local information) and react to external shocks in different ways (local rationality).

While it could be the case that the assumption of rational behavior is credible for a small subset of people, it is certainly the case that not all agents are equally rational, as is implicit in conventional theoretical models. In the real world agents are bounded rational. This typically means that the belief formation process of each agent can be described as a simple function of certain past data available to each agent. Individual beliefs are rational in the sense that given an agent's information set, the agent's beliefs correspond to the probability statements that describe the environment under study. In a complex system, these interactions not only influence macro patterns but also create increasingly complex networks.

Rational agents operate in equilibrium market where crises can only be triggered by acute exogenous disturbances, such as hurricanes, earthquakes or political upheavals, but certainly not precipitated by the market itself. If one tried to endogenize some of those elements into economic models, it would become clear that they produce systemic instabilities, which are fundamentally incompatible with a system in equilibrium. In this framework the interdependences between agents are typically restricted in various ways that generally involve direct interdependences as opposed to the interdependences that are implicit in market transactions. Changes in outcomes are seen as movements in equilibria and not as natural progressions in a dynamic process.

Complexity economics builds from the proposition that the economy is not necessarily in equilibrium: economic agents (firms, consumers, investors) constantly change their actions and strategies in response to the outcome they mutually create. This further changes the outcome, which requires them to adjust afresh. Agents thus live in a world where their beliefs and strategies are constantly being "tested" for survival within an outcome or "ecology" these beliefs and strategies together create (Arthur, 2013).

Under equilibrium by definition there is no scope for improvement or further adjustment, no scope for exploration, no scope for creation, no scope for transitory phenomena, so anything in the economy that takes

[3] Friedman. (1953), p.14.

adjustment -adaptation, innovation, structural change, history itself- must be bypassed or dropped from theory. The result may be a beautiful structure, but it is one that lacks authenticity, aliveness, and creation.
The relevance of Complexity does not deny the value of equilibrium models. Equilibrium may well remain at the core of Economic disciplines. However, even the most casual observer recognizes that most markets, political systems, and social systems do not sit at rest but are constantly in flux. We have to focus on the constant dis-equilibrium or continuously shifting micro-equilibrium points rather than a pre-defined equilibrium point. Even if an equilibrium state exists in theory it may be totally irrelevant in practice. The equilibration time is far too long, as Keynes noted, in the long run we are all dead- and therefore often irrelevant to understanding what is going on and it is hard to identify if the system settles there (Bouchaud 2008). To overcome the limitations of orthodox theory what has been done was to relax restrictive assumptions, introducing more realistic behaviour, heterogeneity, institutional effects, dynamics, endogenous innovation and so on. Nevertheless much of this work introduces just one element of realism to an otherwise standard model without abandoning the core idea that the economy is an equilibrium system.

The Complexity theory seeks explanations of how the economy works that have empirical validity. To accept human behaviour, imperfect institutions, and the complex interactions and dynamics of the economy as they really are rather than what an idealised model says they should be. Not more aggregate reduced to the analysis of a single, representative, individual, ignoring by construction any form of heterogeneity and interaction, but the aggregate emerging from the local interactions of agents.

Section 3-Public Policies in Economic Complex Systems

The aim of policy until now has been to regulate economic systems mechanistically toward desirable outcomes, by manipulating positive/negative incentives addressed to individual choice not considering that preferences and behavior are socially constructed under various social and economic influences.

Policy recommendations are based on optimization of some measure of societal preferences reflected in an objective function, often a form of efficiency, using models that are essentially mechanic and deterministic.
The aim is to produce a ranking of alternative strategies identifying the optimum one and assuming the decision-maker has a well characterized system model and can represent uncertainty with probability distributions over the input parameters to that model.

Moreover because the economy is viewed as naturally being in a state of efficiency, interventions are justified by market failures: the need to create some public good, or the need to avoid some negative spillover effects or externalities.

When the crisis came, the serious limitations of existing economic models immediately became apparent. Policy-makers during the crisis found the available models of limited help because they failed to predict it and seemed incapable of explaining what was happening to the economy.

The approach of conventional policy has been theoretically built-in by the influence of mainstream economic theory and this has been one of the most serious reasons for recent policy failures. The principal cause of this failure was not the size of the state or the magnitude of the action or resources involved but the theory and methodology used for policy design and implementation.

If policymakers had better models, they might have been able to run more and different policy scenarios and gained different insights into the crisis. Politics and judgment will always play a key role in major policy decisions – but better models can help the policymakers to anticipate and understand key patterns that involve or concern humans, thus enabling wiser decisions about policy interventions.

The vision of the economy as a complex system provides a completely different policy perspective yielding new ways of designing and implementing policies, and in particular suggesting that a more integrated and holistic policy approach towards economic systems can produce better results. It focuses attention on dynamic connections and evolution, not just on designing and building fixed institutions, laws, regulations and other traditional policy instruments.

Because cause and effect in complex systems are distributed, intermingled and not directly controllable, policymakers need to become more comfortable with strategies that aim to influence rather than control: finding and exploiting desirable attractors; identifying and avoiding dangerous tipping points; and recognising when a system is in a critical self-organizing state.

Policy needs to be suitably tailored to specific problems and has to take into account that a policy instrument launched today might not always work tomorrow because the economic system is constantly evolving in unpredictable ways. This does not mean that we are operating in the dark, that the success or otherwise of a policy is merely a matter of chance.

The more knowledge we have of how people are connected on the relevant network, of who might influence whom and when, the more chance a policy has of succeeding. Much of this knowledge is held at decentralised levels. Decentralization may "work," because it is a "patching algorithm," a means for solving public policy problems defined over a most complex "social welfare landscape" (Faggini, Parziale MPRA 2011).

Decentralisation can help shorten the feedback loops that inform decision-making, so actors can respond more quickly to developments (Jones 2011). If every single different levels of governance find solutions as a result of interdependences whith each other level, the result can be a high overall welfare. Conversely, if the different levels of governance are disconnected, even finding best single solution, the result is a lower level of overall welfare. The existence of interdependencies provides that a lot of these independent actions of system levels can be handled using genetic algorithms to approach search problems. The main idea is that if the best solutions are selected in many iterations, the algorithm would converge to a single very powerful solution. Taking into account the existence of no unique solution, the research can be done through a searching algorithm on a fitness landscape, a dynamic landscape in which complex systems move searching for optimum conditions and adapt continually themselves to environment's changes imposed by policymakers.

Policymakers should plan their interventions on the basis of seeking to shape the 'fitness landscape' and altering the behaviour of economic system, rather than the current approach which, in crude terms, identifies a problem and aims to solve it through one or two incentive-based policies arising from an empirically defective framework.

Of course, this does not take away the importance of overarching policy goals, clearly defined strategy or even national policy instruments, but rather points to the need for a richer policy framework that bridges the divide between national strategic priorities and the grassroots realities that policy is attempting to influence.

Policy therefore needs to be dynamic. Rather than thinking of policy as a fixed set of rules or institutions engineered to address a particular set of issues, we should think of policy as an adapting portfolio of experiments that helps shape the evolution of the economy over time (Beinhocker 2012).

When dealing with complex problems it is not enough to keep intervening to modify institutions; rather, 'we must invent and develop institutions which are "learning systems"', which are 'capable of bringing about their own continuing transformation (Schön 1973). According with the growing recognition that policymaking systems are complex and that they are involved in a co-evolutionary dance with other complex systems we need to modify our expectations of what policies can realistically achieve. A first necessary step is the modification of expectations arising from policies (i.e. pairings of goals and rules/instruments) by shifting emphasis from static optimization under constraints to adaptability. Policies should not be expected to achieve specific outcomes. Not all areas of government activity are complex, and for those areas that are not, a more traditional, directive approach is likely to be best. But these areas are often not where the most pressing challenges lie. The insights from complexity can help where other approaches are failing, and here there is a strong case for governments using them.

Conclusions

Traditional economics is built on very strong assumptions that quickly become axioms. These concepts are so strong that they supersede any empirical observation (Nelson 2002). While the other disciplines like physics have learned to be suspicious of axioms this change has not yet taken hold in economics, where ideas have solidified into dogmas.

The increasing complexity and interconnectedness of economic systems cannot be anymore neglected by Economic Theory and needs a paradigm change in economic thinking. It is time for economists to explore entirely new approaches and combine equilibrium methods with new approaches. It is time to investigate economic phenomena not as derived from deterministic, predictable and mechanistic dynamics, but as history-dependent, organic and always evolving processes. Of course, it is all easier said than done, and the task looks so formidable that some economists argue that it is better to stick with the implausible but well corseted theory of perfectly rational agents rather than to venture into modelling the infinite number of ways agents can be irrational.

Because Complexity Theory implies new challenges and opportunities for policy and managing economic crises, economics should focus the attention on its innovative components for the study of economics phenomena and the implementation of public policies.

Complexity Theory goes further traditional policy and economics instruments. The attention is focused on dynamic connections and evolution, not just on fixed structure. Decision making process under complexity involves that policymakers have to go beyond strict and traditional determinism if they wish to efficiently act. In complex systems prediction and control are generally made possible by identifying the cause-and-effect relation and then controlling the causes so policymakers need to focus attention not only on control but also on strategies that aim to influence. The effects of different policies may be highly nonlinear, rendering history a poor guide to evaluating policy effectiveness (Durlauf 1997) because policies implementation will depend critically on the nature of the interdependences.

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