Economic Thought 5.2: 29-43, 2016

Complexity Modelling in Economics: the State of the Art

Bruna Bruno, Marisa Faggini, and Anna Parziale, University of Salerno, Italy
brbruno@unisa.it, mfaggini@unisa.it, aparziale@unisa.it

Abstract

The economic crisis happening across the world over the last few years describes a range of interdependencies and interactions, and has 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. As such, it is increasingly recognised that economic phenomena cannot be exclusively investigated as being derived from deterministic, predictable and mechanistic dynamics. Instead, a new approach is required by which history-dependence, organic and ever-evolving processes are also accounted for. As this view implies new challenges and opportunities for policy, we will focus our attention on innovative components of Complexity Theory for the study of economics and the evaluation of public policies.

Keywords: complex systems, economics, public policies

1. Introduction

The economic crisis happening across the world over the last few years describes a range of interdependencies and interactions, and highlights 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 neoclassical economic theory, overlooks the dependencies and interconnections between different elements and their influence on macroeconomic behaviour, and it too often fails as an analytical approach (Morin, 1992). Its goal is to reduce the overall behaviour of a system to a number of essential elements and then to study these parts separately – the system can then be analysed in every detail. The reconstructed behaviour of this system is obtained by simply re-aggregating its components (the principle of overlap). The focus of the 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 sciences went through the 20th century developing and perfecting a model based on 19th-century hard sciences. Due to an increasing body of experiential knowledge using science in the quest for precise answers, it is now agreed that such certainty is illusory in the field of economic theory.

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, economics, engineering, and computer science oriented to overcome the simplifications and idealisations that have led to unrealistic models in these sciences.

The goal of complexity theory 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. No more aggregates reduced to the analysis of single, representative, individual parts, ignoring by construction any form of heterogeneity and interaction – instead the aggregate emerging from the local interactions of agents. From this point of view the system is different from the sum of its parts.

The behaviours of complex systems depend on the interactions (often with retroactive character) among parts, and not so much (or not only) from the characteristics of the parts themselves; the behaviour of the single parts themselves does not give us an explanation of the behaviour of the 'whole'. 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 can imply markedly different outputs. For this reason our understanding of the behaviour of a system at a certain point might be valid only for a very small space around this point.

In economics, complexity theory challenges 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 does not work anymore by simplifying, linearising and dividing, but by 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 who rely on viewing 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 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 – aimed at evolution and change, rather than only in the 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 the 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-organisation, 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 for managing economic crises, we will focus our attention on innovative components of complexity theory.

The paper is structured as follows. Section 2 discusses the distinguishing characteristics of complex systems, and section 3 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.

2. 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, i.e., 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). Complex systems generate unpredictable dynamics which enable their elements to transform in ways that are surprising – through adaptation, mutation, transformation, and so on.

Deconstructing a complex system into individual components destroys the system's 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 emerging properties from the organised interactions of its entities and hence the reductionist method of traditional science does not work. And *vice versa*, if the system is 'complicated' – we *can* apply it.[2]

[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).

[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, 2009).

We can summarise the set of features that are widely associated with complex systems in this way (Cilliers et al., 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. Nonlinearity means that the superposition principle[3] does not work. 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. So, small causes can have large effects and *vice versa*. This is a precondition for complexity.
  -Feedback loops. A part of a system receives feedback when the way its neighbours interact with it at a later time depends upon how it interacts with them at an earlier time. This is a mechanism by which change in a variable will result in either amplification (positive feedback) or a dampening (negative feedback) of that change. An example[4] of a positive feedback loop could be between income and consumption. The bigger the income *per capita* in an economy, the more people consume. This will produce a further increase in their *per capita* income, and so on. 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-organisation. A system that is characterised and acts through many adapting elements is called self-organising. These participating elements establish an organisational structure that does not require any central coordination. Self-organising systems will adapt themselves continuously in autonomous ways, so as to better cope with various internal and external perturbations. The generated organisation results from internal constraints and mechanisms, which are based on local interactions between its components. The Invisible Hand of Adam Smith could be a typical example of self-organisation in economics.

- **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 levels 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 characterisation. All that can be said is that such systems have the potential for generating new behaviours. Markets are a well-known example of emergence. A market exists as long as buyers and sellers exist and they exchange goods and money. 'Markets' are related to the activity of buying and selling and can be neither explained by the properties of buyers or sellers, nor by the characteristics of trade (Noell, 2007).

---

[3] 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 (Ladyman, Lambert and Wiesner, 2012, p. 4).
[4] As suggested importantly by Ron Wallace, feedback has been functionally explored in a wide variety of systems ranging from molecular signalling pathways to monopolistic economies (Albert et al., 2000).

- **Open systems**. Open systems refer to systems that interact with other systems or the outside environment, whereas closed systems refer to systems having relatively little interaction with other systems or the outside environment. Complex systems are thermodynamically open systems. The interactions make it 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**. 'Path dependence can mean just that: Where we are today is a result of what has happened in the past. For example, the statement "we saved and invested last year and therefore we have assets today" might be more fashionably expressed as, "the capital stock is path dependent"' (Margolis and Liebowitz, 1998). 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.

- **Power laws.** A power law implies that small occurrences are extremely common, whereas large instances are rare. Many man-made and naturally occurring phenomena, including city sizes, incomes, word frequencies and earthquake magnitudes, are distributed according to a power-law distribution. Complex systems are sometimes characterised by probability distributions that are best described, instead of by a normal distribution, by a power law. This slowly decreasing mathematical function can predict, probabilistically, future states of even highly complex systems. There is good evidence for the presence of power-law distributions in many economic variables, such as returns, order flow, volume and liquidity.

Summing up, complex systems are dynamic, nonlinear systems with multiple equilibria, evolving in time and space, which self-organise from local interactions and are strongly characterised by historical dependencies, complex dynamics, thresholds and multiple equilibria (Carpenter et al., 1999; Levin, 1999).

As a result, main methodologies applied in complexity are quite different from those used in traditional science. They include agent-based modelling (otherwise known as 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-organised criticality and synergetics.

3. Complexity Modelling in Economics

For a long time, scientific models were built starting from the consideration that causal mechanisms of natural phenomena were linear and characterised by the superposition principle. In this sense, effects are proportional to causes, small inputs produce proportionally small outputs, and the whole simply equals the sum of its parts. Thus, it is possible to divide a complicated system into simpler constitutive parts, separately analyse each component and, finally 'reconstruct' the behaviour of the system by re-aggregating its components.

This reductionist approach too often overlooks the dependencies or interconnections among elements and their influence upon macroeconomic behaviour. Its focus is not to study the unfolding patterns its agents create, but rather to simplify its questions to make them manageable and user-friendly. Unfortunately, these principles, imposed by the Cartesian paradigm of simplification, have created a separation between reality and its formal representation.

In economics, the neoclassical theory based on this principle describes 'smart people in unbelievably simple situations', while the real world involves 'simple people [coping] with incredibly complex situations' (Beinhocker, 2012, p. 52).

In fact, 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 a representative agent: an agent that has complete information and acts with rationality when making choices and his choices are aimed to optimize his 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 calculation. He has time and ability to weigh every choice against every other choice and, finally, he is 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 rational choice imperative: given a set of alternatives, choose the best.

This process of choice postulates utility values associated with possible perfectly foreseen states of the world 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 maximise 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 reaches the same conclusion, only Gaussian deviation from the norm is allowed and they cancel each other out in the average. It is not important that the direct relation of each individual with another is only seen through the 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 optimisation problem is an individual demand curve, used as the exact specification of the aggregate deduced by simply summing up the behaviour of agents that compose a market or an economy. Therefore, the result of decision problems of the representative economic unit is obtained *sic et simpliciter* by aggregating quantities.

There are not significant differences between micro and macro levels: the dynamics of the 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 with each other and, put simply, are not rational in a conventional sense. Therefore we end up with totally unrealistic hypotheses because they don't reflect real individual behaviour (Robles, 2007) or the complexity of human decision making (Shapiro and Green, 1994). As observed by 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 …' (Friedman, 1953, p.14).

This affirms the theory of rational expectations, with the assumption that agents also have, implicitly, the knowledge of the model from which the consequences of their actions descend. This will give the economic actors much more knowledge than econometricians building the model have access to (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 deviate from the average do not cancel each other, but they could reinforce each other. Each individual can reach only a partial knowledge that is focussed around his/her own 'world' (local information) and react to external shocks in different ways (local rationality).

While it could be the case that the assumption of rational behaviour 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. Under appropriate conditions, they evolve non-optimal but highly effective heuristics for operating in complex environments. There is no assurance that, when faced with novel environments, individuals will shift efficiently to new heuristics.

These interactions not only influence macro patterns but also create increasingly complex networks that allow them to compensate for having limited information and facing formidable information processing costs. In the Walrasian economy, agents do not interact at all.

Rational agents operate in equilibrium markets 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 endogenise 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 interdependencies between agents are typically restricted in various ways that generally involve direct interdependencies, as opposed to the interdependencies that are implicit in market transactions. Changes in outcomes are seen as movements in equilibria and not as natural progressions in a dynamic process.

From this dominant mechanical world view the scientific community is moved towards a view of the world as interconnected: where variation cannot be ignored, where new behaviours can emerge, where change is not predictable and understandable in simple, single-dimension relationships. In recent years this alternative view is named complexity theory: the scientific framework devoted to study complex systems.

Undergoing an incursion in time, we can trace the notion of complex system to Aristotle who said, 'The whole is greater than the sum of its parts', but in economics the roots (Terna, 2015) of the complexity view can be found in two seminal papers – by Anderson (1972) and Rosenblueth and Wiener (1945).

In particular, from Anderson's pioneering paper,[5] 'More is different', economists at Santa Fe Institute, Stanford, MIT 'have focused on creating a new kind of scientific research community based on the complexity science' (Naciri and Tkiouat, 2015). The result in economics has been born of a long-term research programme of complexity economics that 'is not an adjunct to standard economic theory, but theory at a more general, out of equilibrium level' (Arthur, 1999). From here numerous contributions to complexity economics have occurred in different research areas (Beinocher, 2006).

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; 2015).

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 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, life and creation.

The relevance of complexity does not deny the value of equilibrium models. Equilibrium may well remain at the core of economic theory. However, even the most casual observer recognises 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 can be hard to identify if the system settles there (Bouchaud, 2008). To overcome the limitations of orthodox theory, what was done was to relax restrictive assumptions and introduce more realistic behaviours – 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.

Complexity theory seeks explanations of how the economy works by additionally requiring 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. No more an aggregate reduced to the analysis of a single, representative, individual, ignoring by construction any form of heterogeneity and interaction, but instead the aggregate emerging from the local interactions of agents. The economy considered as a complex system, emphasises a bottom-up, agent-based approach to model the economic systems made by interconnected layers populated by more and more complicated agents (people, families, firms, banks, central banks, international institutions, multinationals…).

[5] 'The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.(…) The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other' (Anderson, 1972, p.393).

3.1 Managing Complex Systems

Understanding of complex systems is possible only if we build appropriate models.

A model represents an attempt to link seemingly related phenomena logically into a theoretically coherent framework. This framework is based on an underlying theory that allows one to analyse a range of relationships, providing a causal structure with, or without, a feedback mechanism. More importantly, however, a scientific model is built by making restrictions on observable relationships.

The specification of a causal mechanism and reductionism on potential relationships are the distinguishing characteristics of a model (Faggini, 2009).

The study of economic systems has traditionally been based on three types of models: visual models, mathematical models, and empirical models.

- Visual models are simply pictures of an abstract economy. Nevertheless most visual models are visual extensions of mathematical models.
- Mathematical or theoretical models consist of a set of mathematical equations that provide a useful description of how an economy works.
- Empirical models are mathematical models designed to be used with data. They are used to verify the qualitative predictions of theoretical models and convert these predictions to numerical outcomes by using statistical and econometric techniques.

Development in the field of computer science allowed building a fourth type of model: computational models.

Computational methods are used to replicate and understand market dynamics emerging from the interaction of heterogeneous agents, and to develop models that have predictive power for complex market dynamics. They are based on simulation, i.e., a set of instructions, rules, equations or constraints by which to show the interaction of numerous variables, including hidden feedback and secondary effects, that are not so apparent in purely mathematical or visual models. For this reason they are considered to be the natural way to manage the complexity of economic systems.

Even if, in this class of model, we also have simplified mathematical models[6] that try to abstract the most important qualitative elements into a solvable framework, there is one method that is particular to the study of complex systems and has largely been developed and applied in this field – agent-based modelling. Traditionally, agent-based models (ABM) are used for studying phenomena from biology, such as social insects and immune systems. Here, simple agents interact locally with simple rules, merely responding predictably to environmental cues, and not necessarily striving for an overall goal. Nevertheless, we observe a synergy which leads to a higher-level whole with much more intricate behaviour than the component agents. The field of Artificial Life produced a number of models based on simple agent rules capable of producing a higher-level identity, such as the flocking behaviour of birds, which were called 'swarms' or Agent Based Models (ABM).

Agent-based models or 'agent-based computational economics'[7] (Boero et al., 2015) and 'multi-agent systems' have been used to model very different kinds of complex systems, from the simulation of socio-economic systems to the elaboration of scenarios for logistics optimisation, from biological systems to urban planning. The goal of ABM is to separately and

[6] The tools used in such studies include dynamical systems theory, information theory, cellular automata, networks, computational complexity theory, and numerical methods like Montecarlo simulation, integration methods, linear algebra and spectral methods.

[7] http://www2.econ.iastate.edu/tesfatsi/ace.htm

individually simulate the agents and their interactions, allowing the emergent behaviours of the system to appear naturally (Dosi et al., 2010; Gallegati et al., 2010). These models investigate how aggregate outcomes arise from the micro-processes of interactions among many agents.

4. 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 towards individual choice – not considering that preferences and behaviours are socially constructed under various social and economic influences.

Policy recommendations are based on the optimisation 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-characterised 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 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.

As 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. Policymakers 'would have to content themselves with constantly observing and, where possible, influencing a system over which they have much less control than one has been led to think' (Kirman, 2016). They should aim to find and exploit desirable attractors; identify and avoid dangerous tipping points; and recognise when a system is in a critical self-organising state.

Policy needs to be suitably tailored to specific problems and has to take into account that a policy instrument launched today might not necessarily work tomorrow. The economic system is constantly evolving in unpredictable ways.

Of course, 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 in the relevant networks – of who might influence whom and when – the more chance a policy has of succeeding. Much of this knowledge is held at decentralised levels. Decentralisation may 'work', because it is a 'patching algorithm' – a means of solving public policy problems defined over a most complex 'social welfare landscape' (Faggini and 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 level of governance[8] finds solutions as a result of interdependencies with each other level, the result can be high overall welfare. Conversely, if the different levels of governance are disconnected, the result is a lower level of overall welfare.

The existence of multiple interdependencies means that a lot of these independent actions at system level can be handled using computational methods to approach search problems. The main idea is that if the best solutions are selected in many iterations, the algorithm will converge to a single, very powerful solution. Taking into account that no unique solution exists, 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 themselves continually to environmental 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). We must develop institutions that are able to influence rather than command – where this influence is not devoted to directing the economic system towards a particular direction as that system itself[9] may not necessarily be evolving in efficient state.

[8] Relations across levels of government have changed over the last two decades. Decentralisation has made local and regional governments more powerful in formulating and delivering policy. This change from a centralised and 'vertical' system has made governance more complex by involving a wider range of stakeholders at different levels. As a result, both horizontal and vertical relationships are increasingly important. Understanding this complex network of relationships, as well as developing effective collaboration between levels of government, is critical to enable efficient policy making and service delivery.

[9] We would make neither statements nor predictions as we do today, but would rather make probabilistic statements about the trajectories that the economy might follow. The difference with our current

In this sense complexity economics neglects political economy if, with this term, we mean how a government with limited resources tries to satisfy the needs and desires of its citizens. Here government interventions are devoted to reducing or eliminating some form of market failure in order to re-stablish the conditions of Pareto optimality. However, to the extent we are dealing with a complex economy the policies should not be expected to achieve specific outcomes.

> 'We have to rethink the way in which economic policy is conceived and enacted… […] Far from advancing toward a precise analytical model capable of being used for forecasting, and thus of guiding economic policy, the nature and ambitions of economic policy would have to change' (Kirman, 2016).

The first necessary step is the modification of expectations arising from policies (i.e. pairings of goals and rules/instruments) by shifting emphasis from static optimisation under constraints to adaptability. We must search for the right policy that *reacts* to the evolution of the system rather than *pushing* it in a desired direction. To this end, an important contribution could be offered by ABMs that could allow enable us to 'test' the outcomes of policy interventions.

Of course 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.

5. Conclusions

Traditional economics is built upon 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 can no longer be neglected by economic theory and need 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-behaved theory of perfectly rational agents rather than to venture into trying to model the infinite number of ways agents can be irrational.

Because complexity theory implies new challenges and opportunities for policy and for managing economic crises, economics should focus attention on its innovative components for the study of economic phenomena and the implementation of public policies. In particular as economic systems consist of locally interacting agents who are all continuously pursuing advantageous opportunities, such an economy may very well be studied in the framework of complex adaptive system theory (see Anderson et al., 1988).

Complexity theory goes well beyond traditional policy and economic instruments. Attention is focused on dynamic connections and evolution, not just on fixed structure. The decision making process under complexity involves policymakers having to go beyond strict

approach is that these trajectories would not be 'equilibrium' paths and their evolution would be largely endogenous.

and traditional determinism if they wish to act efficiently. 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 policy implementation will depend critically on the nature of the interdependencies. 'Economics can do better, it's time to move on' (Beinhocker, 2006, p. 23).

Acknowledgements

We are grateful to Brian O'Boyle, Pietro Terna, and Ron Wallace for their extensive and helpful comments on the *Economic Thought* Open Peer Discussion forum.

References

Albert, R., Jeong, H., Barabasi A.-L. (2000) 'Error and attack tolerance of complex networks.' *Nature* 406 (6794), pp. 378-382.

Anderson, P. W. (1972) 'More is different.' *Science*, 177, pp. 393-396

Anderson, P.W., Arrow, K.J., Pines, D. (1988).The Economy as an Evolving Complex System. The Proceedings of the Evolutionary Paths of the Global Economy Workshop, September 1987, Santa Fe, New Mexico (Vol. V, Santa Fe Institute Studies in the Sciences of Complexity). Redwood City, CA: Addison-Wesley

Arthur W.B. (1999) 'Complexity and the Economy.' *Science*, 284, pp. 107-109.

Arthur W.B. (2013) 'Complexity Economics: A Different Framework for Economic Thought.' SFI Working Paper 2013-04-01.

Arthur W.B. (2015) *Complexity and the Economy.* Oxford: Oxford University Press.

Beinhocker E. (2006) *The Origins of Wealth: Evolution, Complexity, and the Radical Remaking of Economics*. Boston, Massachusetts: Harvard Business Press.

Beinhocker E. (2012) 'New economics, policy and politics.' In Dolphin T., Nash D., (eds) *Complex new world: Translating new economic thinking into public policy*. London: IPPR.

Boero, R., Morini, M., Sonnessa, M., Terna, P. (2015) *Agent-based Models of the Economy From Theories to Applications*. London, UK: Palgrave Macmillan.

Bouchaud J. (2008) 'Economics needs a scientific revolution.' *Nature,* 455(7217), 1181.

Carpenter, S., Brock, W., and Hanson, P. (1999) 'Ecological and social dynamics in simple models of ecosystem management.' *Conservation Ecology*, 3(2) 4. [online] URL: http://www.consecol.org/vol3/iss2/art4/

Cilliers, P., Biggs, H. C., Blignaut, S., Choles, A. G., Hofmeyr, J. S., Jewitt, G. P. W., Roux, D. J. (2013) 'Complexity, modelling, and natural resource management.' *Ecology and Society* 18(3): 1. http://dx.doi.org/10.5751/ES-05382-180301

Cilliers, P. (1998) *Complexity and postmodernism. Understanding complex systems.* London: Routledge.

Dosi, G., Fagiolo, G., and Roventini, A. (2010) 'Schumpeter Meeting Keynes: A Policy-Friendly Model of Endogenous Growth and Business Cycles.' *Journal Of Economic Dynamics & Control*, 34(9) pp. 1748-1767.

Durlauf, S. (1997) 'What should policymakers know about economic complexity?' *The Washington Quarterly*, 21, pp. 57–165.

Durlauf S. (2011) 'Complexity, Economics, and Public Policy.' Working paper. Madison: University of Wisconsin.

Faggini, M., Parziale, A. (2011) 'Fitness landscape and tax planning: NK model for fiscal federalism.' MPRA Paper.

Friedman, M. (1953) *Essays in Positive Economics*. Chicago: University of Chicago Press.

Gallegati M., Kirman A. (2012) 'Reconstructing economics: Agent based models and complexity.' *Complexity Economics* 1, pp. 5–31.

Gallegati, M., Delli Gatti, D., Gaffeo, E., Cirillo, P. and Desiderio, S. (2010) *Macroeconomics from the bottom-up.* Berlin: Springer.

Gilbert N., Bullock, S. (2014) 'Complexity at the social science interface.' doi: 10.1002/cplx.21550.

Goldstein, J. (1999) 'Emergence as a construct: history and issues.' *Emergence* 1(1) pp. 49–72.

Horgan, J., (1997) *The End of Science: Facing the Limits of Knowledge in the Twilight of the Scientific Age*. New York: Broadway Books.

Jones, H. (2011) *Taking responsibility for complexity: How implementation can achieve results in the face of complex problems?* London: Overseas Development Institute.

Kay, J. (2012) 'Foreword.' In Dolphin, T., Nash, D. (eds) *Complex new world: Translating new economic thinking into public policy*. London: IPPR.

Kirman, A. (2016) 'Complexity and Economic Policy: A Paradigm Shift or a Change in Perspective? A Review Essay on David Colander and Roland *Kupers's Complexity and the Art of Public Policy*.' *Journal of Economic Literature*, 54(2) pp. 534-72.

Ladyman, J., Lambert, J., Wiesner, K. (2012) *What is a Complex System?* University of Bristol: Bristol. Available at: http://www.maths.bristol.ac.uk/~enxkw/Publications_files/What%20is%20complexity.pdf.

Levin, S. A., (1999) *Fragile Dominion: Complexity and the Commons*. Reading, MA: Perseus Books.

Manson, S. (2001) 'Simplifying complexity: a review of complexity theory.' *Geoform*, 32, pp. 405-14.

Margolis, S. E., Liebowitz S. J. (1998) *Path Dependence, New Palgrave Dictionary of Economics and the Law.* London: MacMillan. http://wwwpub.utdallas.edu/~liebowit/palgrave/palpd.html

Morin, E. (1992) 'From the concept of system to the paradigm of complexity.' *Journal of Social and Evolutionary Systems*, 15(4), pp. 371-385.

Naciri, N., Tkiouat, M. (2015) 'Complex System Theory Development.' *International Journal of Latest Research in Science and Technology*, 4, pp. 93-103.

Nelson, R. (2002) *Economics as Religion.* University Park, Pennsylvania: Pennsylvania State University Press.

Noell, C. (2007) 'A look into the nature of complex systems and beyond "Stonehenge" economics: coping with complexity or ignoring it in applied economics?' *Agricultural Economics* 37, pp. 219–235.

OECD Global Science Forum (2009), 'Report on applications of Complexity Science for Public Policy: New Tools for Finding Unanticipated Consequences and Unrealized Opportunities.' www.oecd.org/sti/gsf

Orrell, D. (2010) *Economyths: Ten Ways Economics Gets It Wrong*. London: Icon Books.

Robles, J.M. (2007) 'Bounded Rationality: A Realistic Approach to the Decision Process in a Social Environment.' *Theoria*, 16(1) pp. 41–48.

Rosenblueth, A., Wiener, N. (1945) 'The Role of Models in Science.' *Philosophy of Science*, 12(4), pp. 316-321.

Sargent, T. J. (1993) *Bounded Rationality in Macroeconomics*. Oxford, UK: Clarendon Press.

Schön, D. (1973) *Beyond the Stable State*. Canada: The Norton Library.

Shapiro, I., Green, D. (1994) *Pathologies of Rational Choice Theory: A Critique of Applications in Political Science*. New Haven: Yale University Press.

Terna, P. (2015) 'From Complexity to Agent and their Model.' In Boero, R., M. Morini, M. Sonnessa, and P. Terna (eds), *Agent-based Models of the Economy – From Theories to Applications*. London: Palgrave Macmillan.

SUGGESTED CITATION:

Bruno, B., Faggini, M. and Parziale, A. (2016) 'Complexity Modelling in Economics: the State of Art.' *Economic Thought*, 5.2, pp. 29-43. http://www.worldeconomicsassociation.org/files/journals/economicthought/WEA-ET-5-2-Bruno-et-al.pdf