BPE
BULLETIN OF POLITICAL ECONOMY
15:1 (2021): 45-68

Revisiting the role and consequences of Econophysics from a Marxian perspective

NIKOLAOS TH. CHATZARAKIS*

Abstract: The idea that economic phenomena are governed by stochasticity and uncertainty led to the extensive use of concepts and methods from the physical sciences that deal with non-deterministic patterns, giving rise to the multidisciplinary field of Econophysics. The last decade, several voices rose against it arguing that no new knowledge has been obtained and that the Econophysicists have merely 'discovered' what was already known in Economics. There also have been economists arguing that the mixture of physical models and economic ideas can still blossom and provide new insights into the study of Economics. In this paper, we attempt to reveal a different aspect of Econophysics, one that builds on its corroborative character and its role in criticizing neoclassical approach. In our view Econophysics can be used as a new enlarged version of Econometrics, as a set of methodologies to subject the economic models to logical and empirical tests. But, to do so, we argue, it is also necessary to 'release' this strict methodological research from any theoretical or ideological doctrine, including those neoclassical axioms so well incorporated in Economics. In view of this, we show that econophysical models by and large give further insights to discard the Marginalist paradigm point towards a different perception, closer to the old Classical and Marxian theories of political economy.

Keywords: Econophysics, Political Economy,

JEL classification: B12, B13, B14, B16, B41

INTRODUCTION

Econophysics is defined as an "an interdisciplinary research field, applying theories and methods originally developed by physicists in order to solve problems in economics, usually those including uncertainty or stochastic

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* Department of Economics, Aristotle University of Thessaloniki. Email: chatzarn@econ.auth.gr. The research work was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the HFRI PhD Fellowship grant (Fellowship Number: 1522)

processes and nonlinear dynamics" (Sharma *et al.* 2011: p. 2); or as "the application of the principles of physics to the study of financial markets, under the hypothesis that the economic world behaves like a collection of electrons or a group of water molecules that interact with each other." Therefore, "it has always been considered that the econophysicists, with new tools of statistical physics and the recent breakthroughs in understanding chaotic systems, are making a controversial start at tearing up some perplexing economics and reducing them to a few elegant general principles with the help of some serious mathematics borrowed from the study of disordered materials" (Savoiu and Siman 2013: p. 9).

In this sense, we can understand Econophysics as another method of treating the economy, even as a new school of economic thought that implies an entirely different conceptualization and theoretical foundation of the economic phenomena. According to Sharma *et al.* (2011: p. 2), "[t]he quantitative success of the economic sciences is disappointing when it is compared with that of physics. Its recurrent inability to predict and avert crises, including the current worldwide credit crunch is obvious", hence approaching the economic phenomena with methods and concepts developed in physics may enhance the economists' ability to measure, test, predict, and guide or avert. More broadly put by Chakrabarti *et al.* (2006), the field of Econophysics can help unify two approaches that are not entirely different, but rather have focused on different aspects on the same subject.

The term 'Econophysics' was coined by Eugene H. Stanley during a conference in Calcutta in 1995, attempting to describe the application of methods derived from Statistical Physics in order to deal with economic problems and, especially, the increasing interest of physicists to work with these problems in this manner. For almost thirty years, an increasing interest for this field led many physicists, mathematicians and engineers to engage in studies of the financial markets, either from a highly academic standpoint, or as professional analysts of the area. In either case, the results seemed promising and led to the establishment of a whole new research field, drawing initially from Statistical Physics and later from Fluid Mechanics, Nonlinear Systems, or Quantum Mechanics, those tools essential for a different approach of the usual economic problems. Addressing variables such as the stock prices as variables resulting from a physical model (*eg.* the Ising model of atoms ordered in a crystal), physicists, mathematicians and engineers suggested they can predict rises and drops and provide sufficient information to the investors so as to act accordingly with their portfolios.[1] The success seemed imminent (Chakraborti *et al.* 2011a and 2011b; Pereira *et al.* 2017; Kutner *et al.* 2019).

During the last decade and in face with the recent economic crisis, many criticisms came from both sides –Physics and Economics– against their merge. Physicists claimed to gradually become uninterested with the subject, while economists claimed that nothing essentially new was discovered concerning the foundations and frontiers of the economic science. Sharma and Khurana (2021) mention that the majority of econophysical research is currently conducted by very few researchers at specific institutions. Certainly, the discoveries of the econophysicists were many and quite remarkable, but indeed little to no new knowledge sprung. The counterarguments given *inter alia* by Buchanan (2013) bring hope that Econophysics has not died out completely but seem to restrict its use to the analysis of financial markets, mainly for professional profit-driven reasons. On the other hand, little has been said in defense of Econophysics from the standpoint of economic theory. A probable reason would be its inability to solidify and bulletproof the orthodox paradigm of Economics; another may be that axioms of this very 'orthodoxy' have been inconspicuously incorporated to most of the econophysical researches. It is most certainly a question whether modern quantitative tools can support the qualitative arguments of neoclassical theory, or whether they attempt to embody them, hence lacking their validity to test the theory.

From this realization, we are bound to question Econophysics itself, its role, purpose and consequences in the economic science. Furthermore, we are bound to examine how the neoclassical paradigm interacts with the econophysical methodologies, whether it succeeds or fails to last through these empirical tests; if not, we should also consider the paradigm that could replace it and its possible validation by the tools provided by Econophysics. In this paper, we present this twofold criticism. In the next Section, we briefly review the methods and tools that constitute Econophysics, the fundamental advantages and disadvantages it has, as well as some of its main results so far. In the Section entitled "Rise and Fall of Econophysics," we consider some unconventional results of economic research, that are either deemed econophysical or not, but can surely be parts of it; as we will see, these results are usually in a sharp contrast to the nice balanced world proposed by the neoclassical economist and more in line with heterodox Classical and Marxian views. In the subsequent Section, we deal directly with the two questions mentioned above, the exact nature, role and purpose of Econophysics, and the necessity for a paradigm shift in Economics –in a sense, forced by Econophysics. The paper concludes with a proposal to enlarge the use of Econophysics, probing perhaps to a different conceptual and theoretical point of view.

STATISTICAL PHYSICS AND THE CONCEPTUALIZATION OF MARKET MECHANISMS

The usual perception of a market –financial or otherwise– is that of the collective behaviour of many agents acting ‘randomly’, supplying and demanding commodities according to their utility –or needs– and their income restriction. It is widely believed that this perception is founded on Adam Smith’s first description of the economic phenomena; indeed, the economy is described by Smith as an area of conflicting interest, guided by the needs of the people and restricted by their income. It is, however, a perception more fitting to the description of the economy by the Marginalists, namely Stanley Jevons, Leon Walras and Alfred Marshall. The latter approached this conflict of interests as a regulating mechanism towards a static and stable equilibrium; in their views, the price and quantity for each commodity result from a balance of these conflicting forces and cannot be altered by internal mechanisms, but only from external excitations (Tsoulfidis 2010, ch. 6).

This perception was well integrated with the development of the two streams of modern Economic theory: Microeconomics and Macroeconomics. The microscopic aspect, related to the study of individuals, firms and markets, was highly influenced by the development of game theory, first by Antoine Augustin Cournot, then John von Neuman and finally by George Nash; their fundamental idea, that the conflicting interests of different ‘players’ can give rise to a stable equilibrium, either statically or dynamically, was utilized to mathematically rephrase and prove the results of Marginalism. Though not one of the original tools of analysis for Microeconomics, game theory progressed into the most distinctive one. Following this, major neoclassical economists like Paul Samuelson, John Hicks, Jan Tinbergen, Kenneth Arrow, George Stigler and others utilized mathematical tools (*eg*. analysis of difference or differential equations) to interpret the economic phenomena as if they were physical laws (*eg.* the dynamics of a pendulum) and prove the main results of both Marginalism and Keynesianism, such as the macroeconomic demand-supply equilibrium, the steady-state growth path, *etc*. (Sharma 2012). Obviously, economics was for over a century influenced by mathematics and physical sciences. However, as stated by Yakovenko (2007), Pereira *et al.* (2017) and Poitras (2018), these influences were mainly from the perspective of deterministic tools, as the ones used by Newtonian mechanics, ever since the time of Adam Smith.

In the same manner, Schinckus (2009) emphasizes that these treatments mainly ignore or reduce uncertainty, an ever-present factor in Economics, despite the fact that major economists like Knight, Keynes and Hayek, considered uncertainty as a key factor of their analysis. Notable scholars from the field of Physics, such as Adolphe Quetelet, argued from the 19th century that social and economic phenomena can be described by deterministic laws, akin to physical laws (Pereira *et al.* 2017).[2] Of course, there have been researchers like Joules Regnault, Louis Bachelier, Vincent Bronzin among others, who described price fluctuations in terms of random processes (Sharma 2012; Jovanovic and Schinckus 2013a and 2013b). However, the development of appropriate mathematical tools to treat with random processes delayed, allowing for the deterministic treatment to be established. More recently, Benoit Mandelbrot attacked these deterministic approaches, attempting a return to the stochastic processes issued by Bachelier; in his book *The Misbehavior of Markets*, Mandelbrot claimed that stock prices can be described by fractal structures, while their fluctuations are governed by a power-law (Mandelbrot and Hudson 2007).

Econophysics was seen as a response to this fundamental absence. When the first studies begun, at about 1991, the Levy distribution was used to describe the motion of stock prices (Kutner *et al.* 2019). Works by R.N. Mantegna, H.E. Stanley and others argued that non-Gaussianities emerge from the economic data, while the so-called 'extreme events' are far from rare.[3] As they put it, "[w]hen one inspects a time series of the time evolution of the price, volume, and number of transactions of a financial product, one recognizes that the time evolution is unpredictable. At first sight, one might sense a curious paradox. An important time series, such as the price of a financial good, is essentially indistinguishable from a stochastic process" (Mantegna and Stanley 1999: p. 8). Until then –and partially until now– the main belief in economics was that any erratic behaviour in the economic data can be assessed by means of the Gaussian white noise. However, these works proved quite the opposite, probing to a new insight. The Econophysics approach, as demonstrated by Chakraborti *et al.* (2006), Sinha *et al.* (2010) and Chakraborti *et al.* (2011a and 2011b) *inter alia*, focuses on analyzing data by means of tools from statistical mechanics; making no *á priori* theoretical assumption, these analyses are expected to reveal the actual function of the specific economic structure under study. People participating in this structure are considered 'particles of a gas', interacting under random mechanisms; their microscopic actions give rise to a macroscopic behaviour. Hence, the economic variables we are interested at (*eg.* the stock prices) can be compared to 'entropy', 'temperature', 'energy', or other physical variables of such a gas. As long as the main neoclassical axioms are valid, these variables should converge to the deterministic results of neoclassical theory; this is the so-called 'Efficient Market Hypothesis'. However, the afore-mentioned presence of 'extreme events' probe for the statistical significance of 'outliers' in economic activities, and hence for counterarguments to the neoclassical paradigm.[4] As a result, Econophysics is generally regarded as a heterodox and 'non-theoretical' approach.

An increasing number of articles published in *Nature*, *Physica A*, *Physical Journal B, European Journal of Physics B* and other similar journals (Jovanovic and Schinckus 2013a) proves that the interest of physicists towards this approach rose steadily during the '90s and '00s, as the ability to explore the 'outliers' and track the real evolution of (mostly financial) markets seemed tempting. For both academic and professional reasons, their attention was drawn to a statistical-mechanical description of economics. In its broader sense, this approach unifies the empirical analysis of the economic variables and the derivation of empirical insights, the simulations of economic systems modeled as gases or liquids, the simulation of economic systems treated as complex networks, and the direct draw of analogies between physical concepts (temperature, entropy, energy, *etc.*) and economic ones (prices, profits, utility, *etc.*). Yakovenko (2007) reviews the effects of these techniques when used to explore the distribution of wealth and the effects on growth, while Chakraborti *et al.* (2011a and 2011b) review the models used in financial markets research and their main results. Both studies reveal a massive empirical wealth and theoretical poverty, as econophysicists are rarely interested in the derivation of fundamental 'laws'. According to Jovanovic and Schinckus (2013b), the seek for a greater empirical realism entraps the researchers in empirical research and simulations, away from actual theory. Researchers who attempted a deeper theoretical analysis of the economy in terms of a physical system, like Richmond *et al.* (2013), ended up in tautologies about the production process, that are very well known in the economic science.[5]

It usually seems that analogies drawn between physical and economic quantities are highly dependent on the perceptions and prejudices of each researcher. The data themselves are good enough to account for the turbulent nature of the phenomena, but not to indicate any 'physical' processes behind them. The very idea behind the study of economics by means of physics seems to be the self-proof of the neoclassical assumptions. Comparing an atom in a gas to a person in a society seems logical enough, so long as clear and valid analogies can be drawn – otherwise, the whole scheme easily falls prey to mistaken and misleading perceptions. Of course, such an analogy can be drawn *ceteris paribus*, if and only if the axioms of neoclassical theory are taken for granted. Drawing back from these axioms, as first set by Jevons, Walras, Marshall and their heirs, there is a sharp contradiction between their perception and reality (Tsoulfidis 2010, ch. 6; Shaikh 2016, ch. 8). More specifically, their fundamental assumptions treat human beings as uniform passive agents,[6] whose economic function is indistinguishable, whose needs are the same though their preferences might be different, whose acts are rational and whose aim is to maximize their utility; no social characteristics (class struggle, institutional and cultural differences, gender and race) are present and influence their activities, while no irrationality may affect the general picture. Furthermore, any group of people –any firm, institution, union, or political party– reflect the same needs and aims as the individuals: they tend to maximize their utility (or their profit). Finally, these 'atoms' act freely and randomly, without any of them having greater or smaller influence in the overall picture. Under these 'rules of the game', the analogy can be drawn; eventually 'persons' and 'atoms' are similar, hence a Marshallian economy can function pretty much as a Maxwell-Botlzmann gas. But do these 'rules' indeed apply in real systems? And, furthermore, if these 'rules' are the start of the game, shouldn't they determine the end?

RISE AND FALL OF ECONOPHYSICS

Sousa and Domingos (2006) claim that 'equilibrium econophysics', that is the Econophysics approach based on 'equilibrium thermodynamics', can be used to prove the neoclassical doctrine and, on top of that, it can be formally regarded as a continuation of neoclassical economic theory; however, that seems not to be the case. Rosser (2006) argues that Econophysics are currently critical of the neoclassical orthodoxy, while Zapart (2015) claims the research conducted results to the disproof of several of the fundamental assumptions or beliefs in orthodox economic theory; Bentes (2010) and Schinckus (2010) trace so many differences in conception and treatment between Econohysics and (traditional) economics, that identify the former as an entirely different discipline. Furthermore, given the central core of neoclassical thought, the 'rules of the game' are at odds with reality (Lavoie 2008; Shaikh 2016, ch. 1; Tsoulfidis and Tsaliki 2019, ch. 6); the very idea that 'outliers' and 'extreme events' are more important than regularity, implies that the core neoclassical approach is detached from the reality of production and exchange and is permeated by preferences and therefore subjectivity in both producer and consumer behaviour. In other words, even when starting off from their assumptions, the Econophysics approach ends up contradicting them and justifying their critiques, or merely ruminating their axioms, with little further development. In fact, Econophysics seems appropriate mainly for predicting the evolution of financial markets, with several counterarguments rising even in this case (Gallegati *et al.* 2006; Rosser 2008; Gallegati 2016; Ormerod 2016), as several results are trivial or self-fulfilled (Chakraborti *et al.* 2011a and 2011b; Pereira *et al.* 2017; Kutner *et al.* 2019).

Several researchers attempt to present the Econophysics approach as universal, and hence the specific results as possible to be generalized and upreared to theory. However, the trivial and self-fulfilling results, the little new knowledge provided, and the awkward position against economic theory, make this possibility a faint one. Furthermore, other researchers seemed 'disillusioned' from the merits of Econophysics and erected questions or criticisms, referring to inherent problems of the approach. As summarized by Gallegati *et al.* (2006: p. 1), "(1) a lack of awareness of work which has been done within economics itself, (2) resistance to more rigorous and robust statistical methodology, (3) the belief that universal empirical regularities can be found in many areas of economic activity, and (4) the theoretical models which are being used to explain empirical phenomena [… are] points of particular concern". Ten years later, Gallegati (2016) but also Ormerod (2016) returned to these four points, commenting that they have not been generally resolved.[7] From the above four points, it is clear that the second is important only from a practical perspective, hence it will not concern us; as for the third point, it obviously cannot be resolved but only through the interaction with economic theory, hence through the resolution of the first and the last points. Focusing on the fourth –and most important– point, the authors observe that the economic phenomena are radically different from their physical analogues; the best example is the fundamental principle of conservation of energy that may hold for a conservative physical system (such as a pendulum or an isolated gas) but is not generally shared or has any analogue to an economic system, one that constantly produces value. Retaining the analogies in a fundamental level, we may indeed draw conclusions for the economy – we need, however, to dive deeper in the analysis of a specific market, or a specific economy, instead of ignoring any important discrepancies and ending up to grave faults.

Furthermore, they observe that most econophysical models, probably driven from the dominant neoclassical theory, conceive the economy merely as a market, as a system of exchange, and not as a system of production, exchange and distribution as a whole. Ignoring or concealing the side of commodities production and referring only to the side of commodities exchange, is a mistake of great importance, that probably occurs not due to scientific but to ideological restrictions. According to Gallegati *et al.* (2006), the incomplete knowledge of an econophysicist for the evolution of ideas within the economic theory (or theories) leads to an unawareness of the complex and usually contradicting aspects that have been formed during the last two and half centuries. For example, the central role the production process has played for the old Classical economists (mainly Smith and Ricardo) or for the heterodox economists, the emphasis that institutionalists (like Schumpeter or Veblen) placed on the turbulent diffusion of technology and innovations, the quarrel between Keynes and Hayek (and their followers) concerning the role of the state in the economy, the links between the finance sector and the production as it was conceived by Minsky and others – all these are aspects usually absent from the perception and the models of econophysicists. The latter emphasize on the analysis of a single, very specific market and try to predict particular events, rather than analyze the economy as a whole and take into account all external factors that might act upon it.

Interestingly, in two of his recent papers, Shaikh (2017 and 2020) points exactly to this subject. In an attempt to explain some famous results of Econophysics (concerning wealth distribution, wages and profits dispersion, *etc*.), Shaikh proposes a deeper understanding of the economy and the theories describing it. Instead of simply drawing analogies and proposing empirically-derived quantitative relations, he goes back to a classical conceptualization of the economy and explains the afore-mentioned relations by the unified classical theory of production, exchange and distribution of value. From this heretic point of view, most econophysicists –unlike Shaikh– appear more or less like civil engineers attempting to build a bridge without having first asked geologists for the form, composition and resilience of the soil, the physicists and chemists for the structure and endurance of the materials, the meteorologists for the rainfalls affecting the river and the banks; consequently, no matter how well the bridge is built *per se*, any external factor may always bring it down.

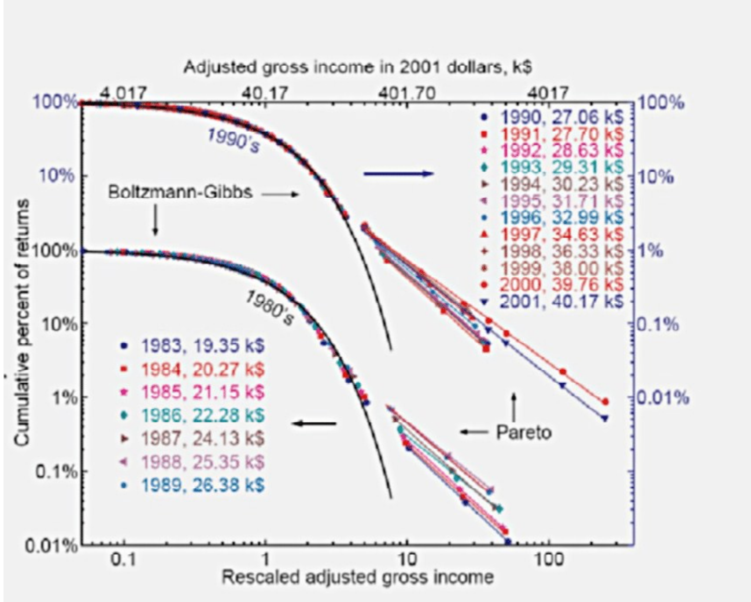
CLASSICAL AND MARXIAN ECONOMICS ON THE TEST

Going through the history of Economics, the establishers include Louis XV's physician (F. Quesnay), some moral philosophers (A. Smith and J.S. Mill), a priest (T.R. Malthus), a merchant and congressman (D. Ricardo) and many political thinkers (from D. Hume till K. Marx); consequently, the way their ideas are presented 'flirts' with the language and posture of a philosophy professor rather than of a mathematician or physicist.[8] In this sense, the establishers of economic theory weren't *á priori* opposite to any comparison of Nature and physical sciences with the economic phenomena –proposed this comparison was within reasonable reasons. Quesnay's medical training allowed him (and Marx, following his steps) to conceive the economy as a biological organism, where value and commodities outflows could be compared to the flow of blood; Smith's respect for Newton reflects on his belief that the economic phenomena can be classified and described in a similar manner as the physical phenomena; Ricardo's practical and Marx's theoretical rationalism convinced them that the economic 'laws' can be as universal as the physical ones, even though they could not (or would not) express them as such. In more recent times, the mathematical training of Kalecki, Goodwin, Tinbergen, Minsky, *etc.* guided them to the adoption of analogies between a biological, chemical or physical system and the economy.

Departing from the standard treatment of isolated markets, we may still trace cases where the Econophysics approach is used to reach safe conclusions, that concern the entire economy and are linked to aspects of economic theory –thus, resolving the first, third and fourth points set by Gallegati *et al.* (2006). Interestingly, these researches also depart from the neoclassical orthodoxy.

One of the most interesting researches in this line, but also one of the most famous and influential in the field of Econophysics, was that conducted by Drãgulescu and Yajovenko (2001), concerning the distribution of income in the developed capitalist economies.[9] They showed that incomes are not distributed homogeneously to the population, but the wealthier 1-5% of the population's income distribution differs markedly from the remaining 95-99%; while the distribution of incomes in the latter follows a typical Boltzmann-Gibbs distribution (as a typical gas in thermodynamic equilibrium), the distribution in the former follows a Pareto distribution (exponentially declining over the increase of wealth). Essentially, the top 1-5% of the population constitutes a radically different income group and hence a discrete social class from the rest, as shown in Figure 1. This result, unlike others concerning inequality and income distribution, proved that there is a functional reason for this distribution – a reason inherent to the capitalist economies, as stressed by Cotrell *et al.* (2009), Shaikh (2017 and 2020) and Thebault *et al.* (2018), that is not entirely quantitative (the size of the income) but also qualitatively (to what distribution, hence to which class each person belongs and what function does it have in the capitalist economy).

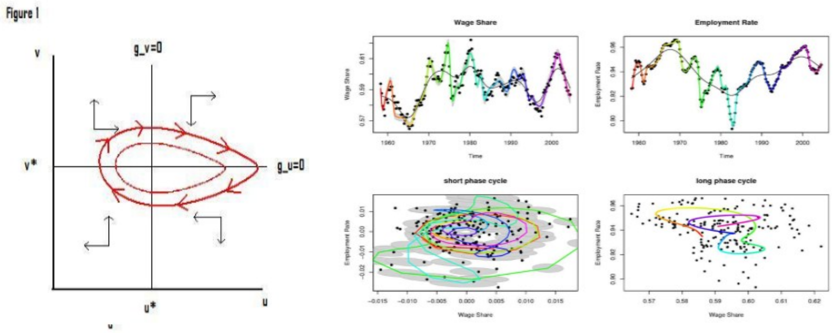
Figure 1: The income distributions in the U.S.A., during 1883-1989 (bottom curve) and 1990-2001 (top curve), from the research by Drãgulescu and Yakovekno (2001).



Of course, this was not the first heterodox research to follow an econophysical perspective. As early as the '20s and '30s, the engineering graduate Michael[3] Kalecki used to describe the capitalist economy as a dynamical system, based on the theory of mechanical oscillations –about 20 years before the same method was used by Hicks, Samuelson, Tinbergen and others. The periodic and quasi-periodic solutions of these systems was not random, as Kalecki stated, but inherent and systemic to the capitalist system; the investigation of these cycles (or quasi-cycles) in the case of investment, as affected by profits and the productive capacity of the economy, as well as Kalecki's wide knowledge of both physics and economics, allowed him to identify the causes of the Great Depression of 1929, as well as the means to escape from it.[10] When comparing him to –the also mathematically trained– Keynes on the basis of their analysis of crises and depressions, Robinson (1964: pp. 95-96) commented that Keynes "was struggling to rediscover Marx's schema. Kalecki began at that point", achieving a clearer and sounder result, much before Keynes himself.

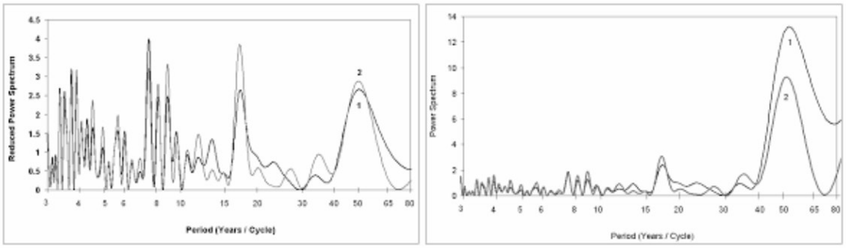
A few decades later, following a similar stream from classical and Marxian theory, Goodwin (1967) proposed a very simple dynamical system (of only two differential equations), that describes the interaction between the wage share and the employment rate of an economy, as the interaction between the population of a prey and its predator – the well-known Lotka-Volterra system, that was a cornerstone for the development of mathematicál biology. The oscillations predicted by this system were also predicted by economists such as Ricardo and Marx, as inherent fluctuations of the capitalist system; they were also proved empirically in the works of Harvie (2000), Mohun and Veneziani (2006), Flaschel *et al.* (2008), Shaikh (2016) and Stirati and Meloni (2021).[11]

Figure 2: Theoretical form (on the left) and empirical confirmation (on the right) of Goodwin's wage-employment cycles, in the short- and long-run, from the research of Flaschel *et al.* (2008), from the U.S.A. during 1958-2008.



Ironically, most continuations of Goodwin's work have a heterodox flavour, even a strong classical/Marxian basis. This view of economic fluctuations as non-circumstantial, but systematic, was proposed by several heterodox theorists (such as Marx and Schumpeter) and can actually account for their regularity by identifying their causes. For many years, this regularity –observed *inter alia* by Kondratieff and Kuznets– was not taken for granted; however, Korotayev and Tsirel (2010) attempted to prove it, by studying time-series of growth rates from the world economy for a period of over a century. Their tool was a usual one for physicists and engineers, whenever periodic behaviour was involved: the Fourier transform of the time-series, which transposes the analysis from the time- to the frequency-domain and allows the identification of those characteristic frequencies present in the time-series. Korotayev and Tsirel identified at least two periodicities, the 20-year (Kuznets cycle) and the 50-year (Kondratieff cycle), that were proved statistically significant (as depicted in Figure 3). The statistical significance of these two–especially of the larger one–matches the theoretical description provided by Schumpeter, concerning the periodic gale of innovations, and Marx, concerning the falling tendency of profitability –both mechanisms being inherent to capitalist economies

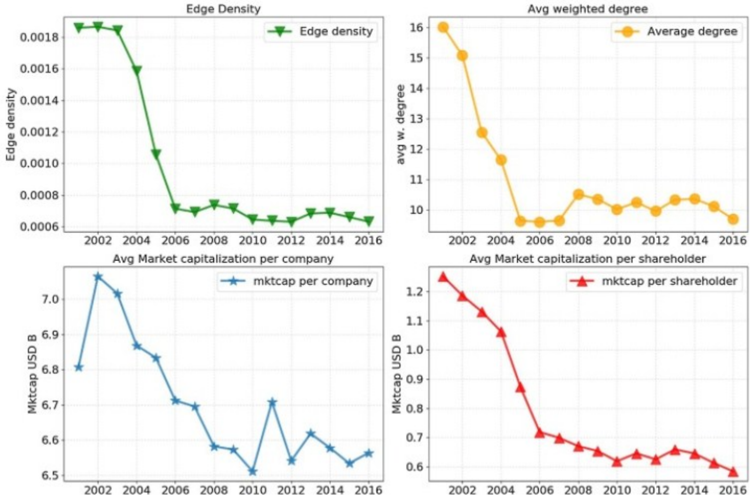
Figure 3: The periodograms of the global growth rate during 1870-2009, before (on the left) and after (on the right) the adjustment for the two world wars, as shown in Korotayev and Tsirel (2010).



The network analysis has also been put to use, most notably by Brancaccio *et al.* (2018), who analyze the process of capital centralization and conclude that the Marxian tendency towards centralization of capital during the process of accumulation is a valid description of reality and is linked with the appearance of periodic crises.[12] In this paper, they pick a list of companies from the Thomson Reuters Eikon database having more than 1 billion USD capitalization in 2016 and they create an ownership network per year for them starting from 2001; the nodes of this network are other companies (private or public), investors (funds or individuals) and even countries, while the links are the respective ownership relations, that can be attributed with a direction and two kinds of weights (the percentage of ownership, or the actual quota in 2016). Their aim is not to study merely the number of nodes (companies, funds, people, countries) or links (ownership relations), as these easily change through time, but the average network density and the average degree, that are measures of the network connectivity and retain a dynamic character. Their results indicate that between 1% and 2% of the companies under study hold cumulatively the

80% of the total net control, meaning that the degree of centralization of capital is extremely large. This degree rises sharply in 2006-2007, as a result of the financial crisis, as depicted in the measures of ownership relations (shown in Figure 4) that decrease at that time.

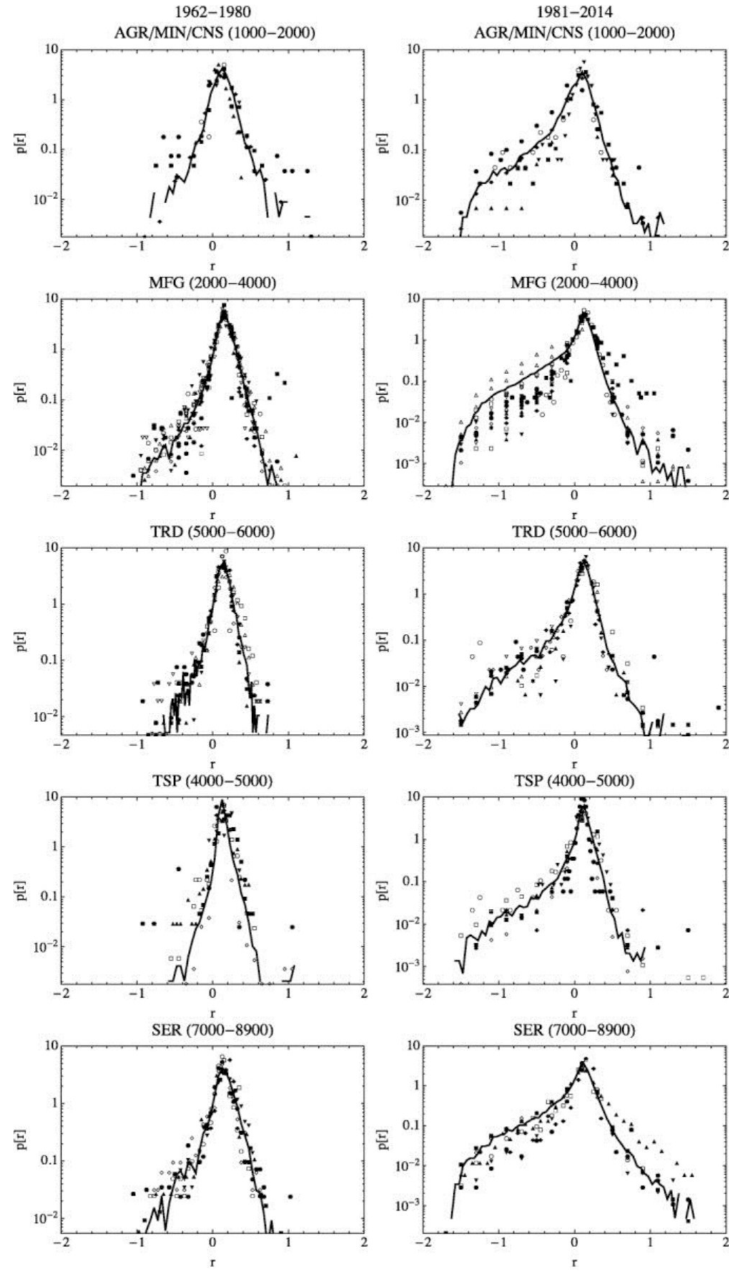
Figure 4: Some simple measures of network connectivity (edge density on the top-left panel, average weighted degree on the top-right panel, average market capitalization per company on the bottom-left panel and per shareholder on the bottom-right panel).



However, one of the most interesting researches is the one considered by many a premier of Econophysics research, found in the book *Laws of Chaos* by Farjoun and Machover (1983). These two mathematicians and political activists attempted to solve a problem of internal logical consistency within the Marxian theory, that of transforming labour values into prices of production. They felt that the solution could only be given if they avoided the usual description by means of input-output techniques –as the ones utilized by neo-Ricardian economics. However, their treatment went further enough to the formulation of an entirely different conceptualization of the Marxian theory; it provided the link between the production process (namely the labour-hours spent and the techniques used) to the sphere of exchange (the prices of commodities the consumers face), taking into account the first and fourth points of Gallegati *et al.* (2006), over twenty years prior to the statement. Farjoun and Machover realized that the fundamental variable of the economy, the rate of profit, was evolving stochastically instead of deterministically in the short-run, hence the prices of production should emerge from the labour values by means of a stochastic process, in a sound and coherent way.[13] In works of Wells (2001), Cottrell *et al.* (2009), Scharfenaker and Semieniuk (2017) and Shaikh (2020), these results have been verified, as can be seen in the tent-like distribution of rates of profit in Figure 5.

Some other interesting examples we should think of, before concluding the paper is those unifying all the above in a single scheme. Beginning with a paper by Wright (2005), we see that the entire capitalist economy can be modelled as a dynamic self-organizing model that combines the non-linear deterministic trends in the long-run with the statistical properties on the microscopic scale. As Wright (2005: p. 614) states, "[t]he aim [is] to understand the possible economic consequences of the social relations of production considered in isolation and develop a model that included money and historical time as essential elements. The theoretical motivation for the approach is grounded in Marx's distinction between the invariant social relations of production and the varying forces of production. Standard economic models typically do not pursue this distinction". In this sense, the model manages, firstly to encompass the classical/Marxian views for the capitalist economies and their subsequent realism, and secondly to apply econophysical tools to both simulate the model and compare it to empirical data; hence, the model provides an holistic perception of the economy, while it answers all points set by Gallegati *et al.* (2006). Similar models analyzing the evolution of firms-and-banks networks by means of heterogeneous-agent-based analytics and simulations have been proposed by Russo (2017) and Di Guilmi *et al.* (2020), who attempted to interpret an actual economy instead of the Marshallian view of perfect competition. Of course, their results are far from mimicking the actual evolution, they have however provided the fundamental analytical and numerical tools for the work.

Figure 5: The distributions of the rates of profit for five different sectors, during 1962-1980 (on the left) and 1981-2014 (on the right), from Scharfenaker and Semieniuk (2017).



Following Morishima's (1973) mathematical formulation of Marxian economics, a pathway has been cleared for a modernized, consistent and empirically-testable version for such approaches. Until today, several attempts have followed this stream, with some major examples found in Flaschel (2010), Shaikh (2016) and Tsoulfidis and Tsaliki (2019), providing both a theoretical framework, a mathematical formalism and empirical support for the consistence and validity of the Marxian theory as a whole; interestingly, their methods do not fall far from those of Econophysics.

CONCLUSIONS: CONSOLIDATING OR UPTURNING THE PARADIGM

Epistemologist Thomas Kuhn postulated that the physical sciences evolve through revolutions, that radically change the dominant paradigm, that is the central belief of the physical scientists for the world; hence, the transitions from Newtonian to quantum physics was not merely an extension, but a radical change in the way physicists perceived matter and energy. Science historians focusing on the social sciences, stated that the same course was not followed there (Blaug 1980). Although the main reason for this difference is that main paradigms may co-exist, the question is still valid, as social sciences –economics in particular– tend to mimic physical sciences; Lakatos observed that, despite convergence in other areas, as long as the paradigm shift is concerned, the very opposite course is followed. Essentially, the domination of economic thought by neoclassical doctrine seems to be completely unjustified, when the respective theoretical core falls prey to all sorts of criticism. Yet, this neoclassical orthodoxy constitutes the main component of economics, taught or applied (Tsoulfidis 2010).

A blind application of methods from physics, blended with an unquestioning infiltration of the neoclassical doctrines, constitutes a major part of research in contemporary Econophysics. Drawing arbitrary analogies between physical and economic phenomena, physicists, mathematicians and engineers have studied –and still study– financial markets, hoping to track patterns that would allow for prediction of the future behaviour; and indeed, this research has brought several results. However, the merits of this research are heavily founded on the afore-mentioned arbitrariness of the analogies and the latent incorporation of neoclassical doctrines in the perception of the researchers. Consequently, the true role and consequence of Econophysics is mostly shadowed. Both the non-validity of the neoclassical axioms silently infiltrating the methodology, and the unsoundness of the analogies usually drawn, has led to severe criticisms from within or from outside the field. Questions also arise concerning the validity of economic theory, when results contradict the very premises of the theoretical foundation. Econophysics, having no *á priori* need to rely on theory, is able to falsify the dominant paradigm of economics; however, econophysicists rarely attack it and usually accept it and rely on it, without realizing that they mess theory and ideology with mathematical and statistical techniques.

Reconsidering the first and fourth point of Gallegati *et al.*'s (2006) critique, we observe that the self-proclaimed neutrality of Econophysics is as much an advantage as a disadvantage. Applying econophysical tools blindly, without any serious consideration of economic theory, might bring up a lot of valuable results for the professional profiteers in the stock market, but will restrict the theoretical and empirical research in a futile discourse over unimportant details. On the other hand, applying econophysical tools after a consolidated economic paradigm, one that is justified by both theoretical and empirical arguments, allows for an improvement on theoretical research. Following the research by Goodwin, Morishima, Farjoun and Machover, Drãgulescu and Yakovenko, Korotayev and Tsirel, Flashcel, Shaikh, Tsoulfidis and Tsaliki and many others, we see there are chances of incorporating econophysical tools and methods in clear economic research. Econophysicists such as Rosser (2006), Menon (2012) and Gallegati (2016) seem to chart a similar way.

What is important though is to clarify what the role and purpose of Econophysics is – in other words, what Econophysics actually is. Unlike Bentes (2010) and Schinckus (2010), who treat Econophysics as an entirely different discipline, it is the writer's belief that Econophysics is another methodological field for applying and empirically testing economic ideas, perhaps a new and enlarged version of econometrics or mathematical economics. It may provide tools and methodologies that have been unapproachable so far, to solidify or disproof theoretical arguments. However, one needs to respect the fear of many economists for the intrusion of quantitative methods (Mirowski 1991 and 1992); at the same time, one should also consider the opposite suspicion, that questionably and/or invalid theoretical principles should not infiltrate the mathematical and statistical tools used to prove them. The point is not whether to apply or not such methods, but not to uprear them to a cornerstone of some discipline. Consequently, Econophysics should be 'freed' from any theoretical or ideological dresses and allowed to be incorporated to the technical armoury of economics. This would, first of all help to improve the empirical tests and practical uses of economics. But, it may also lead to a long-expected paradigm shift in the very core of the latter. Most results so far seem to indicate that Econophysics might be just the right tool from the armoury that would allow for a deeper empirical understanding of the capitalist economy and probe for solid theoretical ideas to be tested and replace the current unsound core of Economics.

Acknowledgements

I wish to thank without implication professors Lefteris Tsoulfidis and Persefoni Tsaliki, for helpful discussions and comments on the draft, and the anonymous referee for helping out to consolidate the main argument of the paper.

Notes

1. Similarly, the research field of Sociophysics was later developed, addressing issues of Sociology in a similar manner, through appropriate physical models (Chakrabarti et al. 2006).
2. It is noteworthy that some of the founders of sociology, such as Henri de Saint-Simon and Auguste Comte were influenced by Quetelet's ideas of 'social physics'.
3. Their book in 1999 provides one of the first introductions to the discipline, as well as a good account of research till that time.
4. Interestingly, even heterodox economists such as Lavoie (2008) have admitted that there is a "large number of empirical studies that seem to "verify" neoclassical theory, in particular when fitting Cobb-Douglas production functions" and attempted to explain why this happens – and why it is not a valid argument in favour of the neoclassical doctrine. Although his arguments about empiricism and internal inconsistencies in neoclassical economics stand, it is worth pointing that Econophysics has shown the path for an empirical refutation of it.
5. In the book by Richmond et al. (2013), a serious attempt is made to relate neoclassical economic theory with the theory of thermodynamics, assuming that the unobserved collective action of people in an economy gives rise to observed macroeconomic variables (total output, capital, labour, circulation of money, etc.) in the same manner the unobserved collective motion of particles in a gas gives rise to observed macroscopic quantities of the gas (temperature, energy, etc.). This description seems a modernized and corrected version of Nicholas Georgescu-Roegen's attempt, without any of his fallacies. Nevertheless, it fails to produce any new knowledge, but merely restates the well-known introductory principles of neoclassical economics.
6. Oddly enough, the Greek word for 'persons' and 'atoms' is the same one.
7. Buchanan (2013) defended the use of Econophysics, however he has not responded to Gallegati's et al. (2006) criticism, that does not concern the

validity of the tools, but of the conception of Econophysics. This is what makes their critique so important: it does not criticize the use of mathematical or physical tools or their validity, but the means by which they are applied.

8. Remembering professors of Classical Political Economy saying that "classical economists thought like mathematicians, but expressed their thought like philosophers", I must draw attention to sir Isaac Newton's Principia Mathematics Philosophiae Naturalis, where very little mathematical relations are present. Another interesting detail here is the use of 'invisible hand' by Smith, which–aside from competition–was also used to describe the force of gravity in the context of Celestial Mechanics.
9. For further discussion in the methods and results of this research, see Yakovenko (2007).
10. The first volume of his collected works (Kalecki 1990) covers the papers and books of that period. Until today, papers such as Krawiec and Szydlowski (1999) consider his ideas in terms of the dynamical systems analysis.
11. Further developments, incorporating Marxian, Schumpeterian and Kaleckian elements, can be found inter alia in Glombowski and Krüger (1987), Goodwin (1990), Flaschel (2008 and 2010), Sasaki (2013) and Shaikh (2016).
12. We should mention that a similar research was conducted by Vitali et al. (2011), and as Brancaccio et al. (2018) themselves state, the methodologies are almost identical. The fundamental differences are the database and the fact that Vitali et al. do not extend their analysis to more than one years, hence they are unable to draw the same conclusions for the long-run tendency of the capitalist system.
13. Some years earlier, (the mathematically-trained) Morishima (1973) and Bródy (1974), as well as (engineer-trained) Shaikh (1977) had solved the deterministic version of the 'transformation problem'–under specific conditions–utilizing a procedure known as Jacobi iteration. The majority of modern authors, like Flaschel (2010), Shaikh (2016), and Tsoulfidis and Tsaliki (2019) favour this analysis, without entirely discarding Farjoun and Machover; in fact, Farjoun and Machover's stochastic conception is shared by them in their discussion of competition.

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