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Econophysics as a New School of Economic Thought: Twenty Years of Research

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In 2015, the science known as econophysics, which has been developing very quickly in latest years, celebrated its 20th anniversary. Perhaps a 20-year period is too short to evaluate the importance and achievements of econophysics, but the broad scope of research and significance of certain results encouraged me to undertake such an attempt. If societies appreciate efforts by econophysicists, perhaps we will be able to avoid next economic crises and related losses. Econophysics is a transdisciplinary science based on the observation that physical objects and economic objects can share a common theory. Since logical homologies are its foundation, it is an example of the well-known isomorphism principle formulated by Ludwig von Bertalanffy. The emergence of interdisciplinary fields of knowledge is consistent with the paradigm of general systems theory. The development of a given field of knowledge is most often measured by its ability to formulate new knowledge about reality. Progress in research can be spoken of both when the application of traditional methods leads to the discovery of new facts and when new scientific laws are discovered using new methods. Econophysics is an attempt to develop economics through the transfer of research methods and techniques from physics to economics. We are therefore dealing here with a second possibility. The methods of physics most often applied in economics include the theory of stochastic processes, cellular automata and nonlinear dynamics. This study presents the most important existing achievements of econophysics and the attempts to reconcile them with traditional economic knowledge. The accomplishment of a paradigmatic correspondence between econophysics and economics, both in the local and in the global sense, is a prerequisite for using the achievements of the former in economic policy.

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1. Introduction

An alarming phenomenon related to econophysics is its distinctiveness from the mainstream economics, although both sciences share the same subject of research. It seems quite strange, since physics has long been a source of inspiration for economists. Unquestionably, in the second half of the 19th century, physics significantly accelerated the development of economics by providing a necessary methodological framework. A gap between economics and physics emerged in the first half of the 20th century, when fundamental elements of neoclassical theory were formulated. There was unquestionable progress, but since that time, economics has been gradually becoming a deductive science. More and more frequently, idealized assumptions have not matched real economic relations, which — as a result of the progressive civilization of mankind — have become increasingly more complex. As a result, the predictive power of economic models did not allow the accurate prediction of threats related to changes in market conditions, which was clearly demonstrated by the global financial crisis. In such conditions, econophysics, a science of a different nature, inductive, based on observations, using methods hardly known in economics, entered the game. Initially, it could be perceived as a certain anomaly, a dead end, particularly from the point of view of economists. However, the emergence of econophysics is consistent with modern trends in science, initiated in 1930s by general system theory. Initially, the subjects of its interest included selected, key economic issues mainly concerning the functioning of financial markets or some macroeconomic issues. This resulted from the existence of appropriately large sets of data in these fields, which was a preliminary condition for appropriate use of the methods of physics.

After twenty years of its existence, econophysics significantly extended its scope of research and nowadays deals with practically the majority of contemporary economic issues. Although it does not fully correspond to Kuhn's scheme of scientific revolutions, his dilemma concerns every transdisciplinary science. Nevertheless, Kuhn's perspective, after certain modifications, including introduction of the notion of a transdisciplinary matrix, provides for evaluation of the previous achievements of econophysics and determining the conditions of its integration with economics. However, we can talk about the success of econophysics as a science and the proper application of its achievements when it creates an impact on the course of actual economic processes. Econophysicists will satisfy those conditions when their models result in accurate predictions and can be used by economists as useful tools for leading an economic policy. A methodological barrier is another issue, but in a longer term, it can be overcome by the introduction of appropriate changes into systems of education. Therefore, integration of econophysics and economics will be determined not only by theoretical premises, but practical ones.

2. Directions in the development of science: from the Kuhnian paradigm and disciplinary matrix to the transdisciplinary matrix and econophysics

The paradigm in Kuhnian understanding means the notional and theoretical bases of a given science [1]. The problem with the application of this term results from the fact that it has multiple meanings. A term that is very close in meaning is the notion of a research community, which is created by a set of persons practising a given science [2]. The paradigm can be understood in the global sense, taking into consideration all factors that determine the ease of communication within the research community and the unanimity of its members in professional matters. In order to avoid ambiguity, I suggest replacing this understanding of Kuhn's paradigm with a new notion — the disciplinary matrix [3]. This is a property common to all researchers representing a given science, which they use as a platform for understanding. It conditions the existence of a scientific community. It is composed of four elements determining the cognitive activity of the community: symbolic generalizations, metaphysical, ontological elements and models, values and exemplars [4]. If — according to Kuhn's suggestion — the notion of a paradigm is narrowed to exemplars, then the term will be used in the local sense.

The notional grid outlined above was used by Kuhn to describe the developmental processes of science. Knowledge is created by hierarchically-constructed research communities, which focus on precisely specified research tasks. Insofar as the unanimity in professional issues determines the ease of communication inside such groups, the flow of information between the communities is hindered and often leads to fundamental incompatibility of views. In other words, research communities are like islands scattered across the sea, with its inhabitants living in relative isolation.

Such a description of scientific development does not fit the reality of modern times. Increasingly often, science faces such challenges that cannot be met by traditional, hierarchical communities. This has resulted in the need to search for new methods of acquiring knowledge and solving scientific problems. For this reason, the general systems theory, initiated in 1937 by the Austrian biologist and theoretician Ludwig von Bertalanffy, has entered the sphere of interest of representatives of different types of sciences [5]. The essence of the general system theory is the isomorphic principle, which postulates the existence of structural similarities between objects described by various types of sciences. The concept underlying the isomorphic principle is not related to analogies, which are only superficial similarities of phenomena and processes, but to logical homologies. We deal with the latter when factors affecting given phenomena or processes are varied, while formal laws governing the dynamics of apparently different objects are identical. The discovery of homology significantly facilitates research, since it accelerates obtaining the final explanation for phenomena. The notion of system, assigned a relatively broad meaning, enables the transfer of models from one discipline to the other.

It should also be emphasized that the increasingly popular use of general system theory in science has brought about significant transformations in the structure of research communities. They gradually lose their hierarchical character and their organization becomes horizontal [6]. Not only the subject of research, but also the methodology applied can be a factor forming the research community and bringing together researchers. Thus, the research community can be established by representatives of various types of sciences. While examining specific phenomena, their theories do not have to be developed from scratch, but the results of other sciences can be applied.

Modern general system theory is based on four components: cybernetics, catastrophe theory, deterministic chaos and sciences of complexity [7, 8]. This methodological foundation is used in multiple fields of sciences, therefore — with reference to the Kuhnian tradition — I suggest calling it the transdisciplinary matrix. Since its sources are in the natural sciences, mainly physics, the application of methods of physics in economics has been termed econophysics. The origins of this science are conventionally dated back to 1995, when physicist Stanley proposed this term at the second Statphys–Kolkata conference [9].

Mantegna and Stanley understand econophysics as the activity of physicists who attempt to solve economic problems by applying methods that have been previously verified in various branches of physics [10]. However, such a view on the subject seems too narrow, as it assumes a cognitive activity only on behalf of physicists. Perhaps several years ago, when the participation of economists in this activity was low and most results were published in physical journals, such an opinion would be justified. Nevertheless, it is not correct today. An increasing number of economists can apply methods and techniques originating from physics to solve economic problems. It seems that the transdisciplinary matrix has become a basis for permanent cooperation between representatives of both sciences, which is certainly favourable for the development of theory and practice of management. There has been an increase in the number of interdisciplinary journals publishing research papers in econophysics. Additionally, the complexity concept can increasingly frequently be found in purely economic journals. Colander et al. emphasize that, as a result of work by a growing number of researchers, nonlinear dynamics, including the theory of deterministic chaos and sciences of complexity, is slowly changing the image of the main trend in economics [11].

3. Bidirectional relations between economics and physics

Econophysics is most often understood as initiating progress in economics by using physics. However, as there are many examples of reverse relations, those sciences seem interrelated. The first power law was discovered at the end of the 19th century by an Italian economist, Vilfredo Pareto, examining the distribution of income within various societies [12, 13]. Fractal distributions were applied in natural sciences much later, owing to works by Lévy and Mandelbrot [14–17]. At this point, the concept of a random walk, developed by Bachelier and applied in the option pricing model as early as 1900, should be also mentioned [18]. This idea emerged in physics only five years later, owing to Einstein [19].

The history of the emergence of chaos theory is very informative. The sensitivity of nonlinear dynamic systems to initial conditions was discovered in 1890 by Poincaré, who examined the so-called restricted three-body problem [20]. In natural history, this problem came back as late as in 1963, when Edward Lorenz examined the model of the Earth atmosphere using numerical methods [21]. However, a Swedish economist, Palander, had come up against this phenomenon back in the 1930s while analysing duopoly and oligopoly models [22, 23]. Similar observations were made at the beginning of the 1950s while examining Goodwin's business cycle model [24].

For an economist, one of the most important fields of physics is thermodynamics. The proposal to reach operationally meaningful theorems put forward by Samuelson, treating the values of the equilibrium of economic variables as a solution to a certain problem by finding extreme points, provides a model example of the transfer of thermodynamic principles to economics [25]. This allows the introduction of an economic equivalent of the correspondence principle in establishing relationships between comparative statics and comparative dynamics: dynamic evaluation of equilibrium stability allows formulating useful conclusions regarding statics, while observation of static systems is useful from the point of view of dynamics. This means reasoning in categories of principle of correspondence known in physics, which claims that the quantum description of a system can, in a boundary case, be reduced to a classical description.

In turn, Georgescu-Roegen proved that the need to explain phenomena of a purely economic background concerning the efficiency of steam engines provided the real source of thermodynamics [26]. This author refers to thermodynamics using the term "physics of economic values". He also claims that the second law of thermodynamics, expressing the entropy principle, is the most economic of all laws of physics. Economic processes consist in transformation of low entropy into high entropy; therefore, low entropy is a necessary condition for utility of a given good. Rarity of goods results from constantly reducing low entropy resources in the human environment. Unfortunately, as production processes reduce low entropy resources, the basic feature of economic phenomena is their irreversibility. Consequently, economic streams do not form a closed system — as conventional economics, based on closed systems, claims — but they flow unidirectionally.

4. Aleatory moment

Econophysics is considered a relatively young scientific discipline. However, it is worth noting that its foundations were laid in 1958 by a Polish researcher — Rawita Gawroński — who perceived the need to supplement the methodology of economics by some ideas derived from physics, including the theory of stochastic processes, which he named *an aleatory moment* [27]. He criticised traditional economics based on 19th century physics, where there was no place to capture uncertainty in human behaviour. In his opinion, a broad introduction of methods of physics to economics would result in revision of the content of economic assumptions, which is actually being observed today. He saw the rationality of such a transfer in that both sciences share the same subject, determined by an observable part of phenomena based on a specific number of parameters.

Another advantage resulting from the application of methods of physics consists — in Gawroński's opinion — in making economic considerations more specific. He emphasized that psychological loads of the researcher significantly impacted the practice of science. They result from a specific world view, traditionalism, political orientation, impact of the environment, or even their own temperament. Such a load on an economic theoretician is certainly heavier than in the case of a physicist. Therefore, it seems to be a logical conclusion to assume that broader application of the methods of physics will help economists to reject unnecessary ideological baggage, thus increasing the transparency of reasoning and taking researchers closer to the truth.

The remarks by Gawroński are today as relevant as they were in 1958. This can be observed in the significant differences which exist between the mainstream economics and econophysics. It is not a secret that economists typically build their models on the basis of empirically unverified assumptions, which usually are treated like religious dogmas [28]. The mainstream economics is, to a large extent, a deductive science, since it uses mathematical modelling based on axiomatic foundations. On the other hand, econophysics is an inductive science out of its nature; it has an empirical character, is based on observations and discovers relationships between them by the application of mathematical tools and logic. Econophysics does not attempt to adjust observations to a priori models, but examines the mechanisms of the operation of real economic systems [29]. This has caused the expected integration of economics and econophysics to be delayed, with the result that they are considered two separate sciences [30, 31]. This is the reason why econophysics still continues to have a marginal effect on economics [32]. The success in this regard depends largely on the method of training new generations of econophysicists [33]. Certain signs of progress can be seen in economic practice. As Ouellette observes, econophysicists or representatives of similar professions, more and more frequently are offered lucrative positions in financial institutions, thus displacing classically educated economists [34]. Over time, such phenomena should force certain changes in mainstream economics.

The diagnosis of Gawroński concerning the relation of economics to reality was dramatically confirmed during the global financial crisis. Mainstream economics was not able to predict the downturn, resulting in huge losses suffered by business entities. Closer relations of econophysics with reality could considerably improve accuracy of business forecasts, if they are perceived in time. Therefore, the perspectives of econophysics are optimistic, although it is a science that is just emerging [35].

Gawroński provided the first programme of econophysics formulated in a modern way. This opinion is confirmed by his conclusions concerning uncertainty, anticoincidence, partial attainability of static equilibrium, impossibility of separating neighbouring systems, limited nature of the principle of determinism, game theory, entropy and passage of systems to chaos, which he understood as the state of partial or total disorder, or a relation of the observer towards the object. He also perceived collective facts, which he understood as a reflection of all human activities. All of this proves the fact that he predicted the emergence of such concepts as chaos theory and complexity theory.

5. Econophysical nature of microeconomics

Modern microeconomics is a science for which 19th century physics has become the model of knowledge. As proven by Ekelund and Hébert, the emergence of microeconomics was, to a significant extent, the effect of the work of French engineers [36]. In the mid-19th century, the French corps of state civil engineers, led by Dupuit, started in France. The members of the corps, while implementing various technical projects, learned to solve accompanying economic problems through the application of mathematical methods. This proved that microeconomics in the form known today emerged long before 1870. Their 40 years of engineering work aimed at understanding and determining the value calculation method, became the source of utility theory and the demand model.

The ideas initiated by French engineers were continued in 1870s by Walras, Jevons and Menger, although it was Marshall who proposed a coherent form of neoclassical microeconomics [37]. Neoclassicists, aiming at improving the academic status of this science, incorporated into it mathematical ideas and apparatus from the leading science of those times — thermodynamics. Basic equations of physics of the mid-19th century were translated into the language of economics in 1892 by Fisher [38]. Material points were converted into business entities, force was renamed as marginal utility, while net energy was used to define gain. The most important scientific notion of that time was a closed system, which aimed at achieving thermodynamic equilibrium. Not surprisingly, closed systems quickly become popular in economics. They affected economic thinking in the 20th century, producing many elegant mathematical models of general equilibrium and the rational expectations hypothesis.

The problem with neoclassical microeconomics is that it does not fit reality. This is caused by the increasing complexity of real economic processes, resulting from the progress of civilisation. In this situation, it seems to be a good solution to treat markets and economies as complex adaptive systems and to apply the achievements of complexity theory. Complex adaptive systems are open dynamic systems, composed of mutually interacting agents and demonstrate emergence [39]. This direction in the development of economics has much to do with econophysics and it has even received its own name — complexity economics [40].

6. Main directions in the development of econophysics

Before proceeding to further considerations, it is worth summarizing previous findings concerning the relationship between economics and physics. Economics, from its very beginning, was strongly related to physics, which provided it with the main source of inspiration and development. One can even risk the statement that economics in the early stages of its development was identified with what we refer today to as econophysics. Therefore, the beginnings of econophysics should be dated back to the mid-19th century, and they may reach even further in the past. At the beginning of the 20th century, the developmental paths of economics and physics began to split, the consequence of which are the disproportions observed today. If it had not been for this division, we would perhaps have been able to avoid many unnecessary crises. In this context, it seems justified to divide econophysics into an old and new science, as proposed by Rasekhi and Shahrazi [41]. The criterion of division depends on who initiated the application of the methods of physics in economics. In old econophysics, these were economists, while in the new econophysics these were physicists. Therefore, the old econophysics covers mainly the achievements of neoclassical economics and is associated with such economists as Walras, Jevons, Menger, Fisher, Marshall, Samuelson, and Georgescu-Roegen. The new econophysics dates back to 1995, but its precursors include Pareto, Bachelier, Lévy, Mandelbrot, Palander and Rawita Gawroński. The new econophysics will be the subject of discussions in the further parts of this work.

What are the physicists undertaking the research in economics driven by and what are the aims of economists currently using the methods of physics? One can agree with the opinion that almost every researcher has its own attitude to the issue and selects problems subjectively following his or her personal preferences. Consequently, it seems that significant differences must exist as regards views concerning issues that are worth dealing with and methods that should be used. Indeed, there are a large number of very detailed results, and econophysicists have recognized many paths of economics, but there is still no general and commonly accepted basis that would link everything into a coherent research program.

Econophysics can be systematized in two ways. If we start with its definition, indicating that the aim of its research is of an economic nature and physics provides the methodology, then we can group research results according to classical rules consistent with economics textbooks [42]. The systematics can be also carried out on the basis of methodological premises, as often suggested by physicists [43, 44].

In econophysics, just like in another transdisciplinary fields, there is a blend of two, not always consistent currents, which consists in a clash of current hierarchies, demanding an immediate solution to economic problems with available methodology. Examples of such problems could be inequalities in the distribution of national income, unemployment or poverty. Therefore, econophysics is a science of a complex nature and as such, can itself be the subject of complexity theory research. Consequently, the occurrence of collective phenomena could be expected within its framework. Indeed, the view presented reveals clear signs of self-organization and crystallization of main ideas.

As studies show, econophysicists have good knowledge of current economic problems and have at their disposal methods permitting their deeper examination. Security markets and foreign exchange markets are particular areas of interest for econophysicists. They generate relatively long time series, which is a basic condition for effective application of methods of physics. Those issues are extensively discussed in the literature [45, 46]. The sphere of interests of researchers also includes many other issues, such as the reasons behind business cycle fluctuations, economic growth factors, income distribution, issues of economic equilibrium, property markets, hyperinflation mechanisms, and the evolution of enterprises.

A broad front of empirical research is accompanied by quite rapid progress in theory. This research is of a bidirectional nature. On the one hand, what is tested is logical coherence and correctness of traditional economic models, while on the other, an opportunity emerges for the development of innovative, original theories. Some applications of methods of physics have resulted in surprising outcomes which may be regarded as new laws of economics. This leads to the need to reject or modify many dogmas that do not hold when confronting reality. Traditional assumptions made in economic modelling, such as linearity or convergence to equilibrium, are inadequate to describe developing markets and economies.

7. Development of econophysics in the world and in Poland

For preparing a division into world and Polish econophysics the criterion of affiliation provided by research authors was used. While presenting the achievements of Polish researchers, the focus was on achievements presented in symposia organized since 2004 by the Section of Physics in Economy and Social Sciences, which makes a part of the Polish Physical Society. Eight such symposia have been held so far. The results of the research were published in *Acta Physica Polonica A* and *Acta Physica Polonica B*. A review of the crucial directions in econophysical research covers the basic research trends in the world and in Poland and reveals a series of interesting facts.

- Modern econophysics was initiated by physicists, who perceived the possibility of solving economic problems using methods applied in natural sciences. From the very beginning, the development of this science was based on international cooperation and — using Kuhn's language — scientific communities formed by physicists, including Polish physicists.
- Attempts by a Polish researcher, Rawita Gawroński, who tried in 1958 to arouse the interest of the scientific community of Polish economists in the application of methods of physics in research on markets and economies, were entirely ignored. Nobody remembers his work today and he is not referred to.
- A regularity which can quite clearly be observed both in world econophysics and in Polish econophysics, consists in determining the aim of research through methodology. A review of literature demonstrates that most research concerns financial markets and some macroeconomic issues, which is understandable as it results from access to appropriately large databases. The reasons for creating those databases were based on an economic background, since the events important from the point of view of monetary and fiscal policy are recorded. Thus, econophysics found its place immediately in the centre of the mainstream economics.
- Generally, there are no differences between the paradigm of the world econophysics and the paradigm of the Polish econophysics. There is also a paradigmatic correspondence between econophysics and the mainstream economics, but only in a local sense, i.e. as regards specimens.
- There is no paradigmatic correspondence between econophysics and the mainstream economics in the global sense. Spontaneously developing econophysics has forced a change of a disciplinary matrix into a transdisciplinary matrix, but it seems that the process occurs in a slightly different way in the world and in Poland.
- The analysis of authors' affiliations proves significant transformations in the structure of scientific communities identifying with economics. Pursuant to the science development model proposed by Kuhn, scientific communities have a hierarchical

structure. The higher level group is made of all naturalists, while on the lower level we have physicists, chemists, astronomers or zoologists. There are also communities on even lower levels. A similar hierarchy exists in social sciences. However, if we take into account econophysics or sociophysics, then it turns out that they are created both by the representatives of natural and social sciences. Therefore, the transdisciplinary nature results in the transformation of groups of a hierarchical structure and development of new organisations of flat structures. Thus, a research community related to economics gathers representatives of many various disciplines of science.

- The tendency to transform scientific communities from hierarchical organisations into flat ones is occurring in both worldwide and in Poland. In the world, this process seems to run without significant disruptions, while in Poland, it is clearly hindered in view of the reasons mentioned by Rawita Gawroński.
- The data also reveal another surprising phenomenon that does not fit the scheme of scientific revolutions developed by Kuhn. Transformations occurring in hierarchical scientific organizations lead not only to distinguishing groups of a flat structure, but also to changes in the existing traditional communities and their relations with newly-emerged communities. This concerns scientific relations and the principles of cooperation between researchers joining the new group with persons remaining in the old community. This phenomenon refers, to a greater extent, to traditional organizations related to economics. It consists in hindered scientific communication of economists who move to a new group with persons who remain in the hierarchical organization. Also in this case, the assessment by Rawita Gawroński provides a good explanation.
- The academic level of works published in the most prestigious international journals and Polish journals is equally high, which means that Polish econophysics belong to the leading group of the world science.
- It seems that the successes of econophysics in subsequent years will be related to its usefulness for economic policy. Without emphasizing its application aspect and proving its usefulness in transforming economic processes, it would be difficult for econophysics to gain advantage over classical economists. This general tendency concerns both world and Polish econophysics.

8. Major achievements of econophysics

In the empirical trend, a flagship achievement of econophysics is questioning the efficient-market hypothesis. Andersen and Sornette present quite strong evidence for this case [47]. While examining the dynamics of security markets, which are complex adaptive systems, they discovered an endogenous mechanism for the emergence of characteristic pockets of predictability. In such periods, a significant degree of organization of agents and their strategy can be observed, which brings to mind herding regimes. Predictions are then unusually accurate: 100% accuracy was achieved for the period of 3 days. Processes of self-organization in the behaviour of agents are proven by the dynamics of the major world stock exchange indices. Research shows that the role of exogenous shocks in the development of financial markets can be lower than predicted by the standard theory of economics.

A promising research trend that has been developed within econophysics is the application of numerical methods, so popular in nonlinear dynamics, for testing the existing, nonlinear economic models. Those methods also facilitate a search for new, theoretical methods for describing economic phenomena, since they permit overcoming impediments resulting from the linearity assumption. The lack of analytical solutions, typical for nonlinear models, is no longer a restriction, as their place is increasingly often taken by numerical results.

9. Conventional nonlinear economic models as a basis for integration of economics and econophysics

Despite the postulated distinctiveness between economics and econophysics, they have many elements in common and the integration of those sciences should start exactly with those elements. Where are these common elements? To a lesser extent, they will be empirically-based, since as it was mentioned earlier, mainstream economics is of a deductive nature, while econophysics is inductive. Therefore, common elements should be sought in the sphere of theory. As economists related to econophysics demonstrate, economics is not an empty box, but it contains many valuable achievements, not always known to econophysicists [48]. The achievements of conventional microeconomics and macroeconomics include various nonlinear models formulated by economists, the properties of which were not fully known for a long period. They were revealed only through the applications of nonlinear dynamics [49]. Therefore, the use of the methods of physics to demonstrate unexpected properties of conventional models that are well-known to the society of economists is a natural, and the easiest, way to integrate economics and econophysics.

In the period when the linearity principle dominated economics, models directly referred to reality. When a given linear model proved imprecise, it was replaced with another, more complicated linear model. From the present perspective — knowing that the world is of a nonlinear nature — it can be claimed that this was not an effective path of scientific progress. The degree of approximation of the research results to reality can be determined only with the use of a nonlinear, more precise model. Since most nonlinear models have no analytical solutions, object trajectories are calculated using numerical methods. The results take the form of numbers, and more precisely, they are time series, sometimes very long. Therefore, it turns out that even more precise nonlinear models do not have direct references to the real world. There must exist an immediate level between the theory and the practice — calculations and numbers obtained in this way [50]. The existence of this level facilitates carrying out empirical research, since the theory indicates the type of structures which should be expected to be observed in a time series.

One of the basic issues in classical microeconomics is the stability of a Cournot-Nash equilibrium. A cognitive archetype used in analyses conducted within this field are — as mentioned above — static, linear closed systems, tending towards thermodynamic equilibrium. Selfish aspirations of agents, used for demonstrating equilibrium stability, have been incorporated into this pattern of scientific knowledge. Aspirations of entrepreneurs to maximise profits make the market system reach a stable Cournot-Nash equilibrium state, which is determined by the intersection of linear reaction functions. Reasoning of this type is taught as standard in microeconomics [51]. However, numerical explorations of simple, standard, nonlinear oligopoly models have proven that Cournot-Nash equilibrium points are stable only over the shortest periods. These are periods in which variables (production values) change and parameters (marginal costs) remain constant. Pursuant to the convention adopted in economics, in short periods various types of costs may change, including marginal costs. Fixed costs are the only volume that is unchanging over those periods. The postulate of profit maximisation makes entrepreneurs reduce marginal costs. This results in the drifting of markets along short-term states towards states of higher complexity. States far from equilibrium are natural market states. This is in contradiction to the basics of traditional microeconomics. Selfish aspirations of agents do not guarantee the stability of market equilibrium.

Explanation of the issue of the equilibrium stability in an oligopoly requires taking into account the nonlinear nature of reaction curves. Numerical results indicate that the dynamics of market structures are subject to the operation of the new law, which I named the *law of progressive complexity* [52]. According to this law, most economic systems naturally tend towards the state referred to as the edge of chaos, the complexity of which is much higher than the complexity of equilibrium states. The edge of chaos should be understood as an intermediate state, which occurs between ordered behaviour and chaotic behaviour [53, 54]. In this state, market systems demonstrate the highest efficiency in information processing, which enables them to operate efficiently in a changing environment, while maintaining an appropriate structure. In such cases, it can be claimed that such systems have reached an optimum level of complexity. It cannot be too low or too high. Poor adaptation abilities are a feature demonstrated by systems with both a low degree of complexity and a high degree of complexity.

The idea of the edge of chaos supplements the traditional approach, indicating that markets almost automatically strive towards a state of equilibrium. The same economic forces that ensure equilibrium in the short term are also the source of complex dynamics in the long term. Numerical explorations have proven that a change in control parameters results in passage of the objects through a series of equilibrium positions. The movement across equilibrium states usually ends at the bifurcation point. At this place, a sudden quality change occurs concerning the nature of the model solution. Further dynamic changes most frequently lead to the emergence of complex behaviours in the form of a deterministic chaos. The ones most frequently occurring in explorations of complexity forming scenarios include infinite cascades of period-doubling bifurcations.

All of this proves that the law of progressive complexity is to some extent universal, as it operates in a similar manner both in market structures and in macroeconomic systems [55]. This complies with one of the basic ideas of the complexity economics referring to the phenomenon of emergence, which negates the need to distinguish the micro and macro level. According to this idea, macro images are an emergent result of interactions and behaviours occurring on the micro level.

There are several sources of complexity in macroeconomic systems. From the point of view of nonlinear dynamics, they do not significantly differ from those found in micro systems. The most frequent include: chaotic attractors and repellers, the coexistence of attractors, sensitive dependence on parameters, catastrophes of complexity, final state sensitivity and the effects of fractal basin boundaries or chaotic saddles. Each of these sources of complexity can be responsible for creating a specific edge of chaos. The emergence of complexities in national economies results from mutual interactions occurring between the natural activity of business entities and the monetary and fiscal policy run by the state. Households, enterprises and other entities try to achieve their own economic objectives and plans. This activity is rational in the sense that it usually means maximization of utility, profit or another variable. In turn, the state tries to implement desirable social objectives, by introducing economic policy. The results of these mutual interactions depend on the examined period. In a short term, behaviours tending towards equilibrium often dominate, while in the long term, the same forces may generate complexity. The transfer to the edge of chaos can initially take place along a certain path of moving equilibrium, but the occurrence of bifurcations can be expected sooner or later.

Reaching the edge of chaos by the national economy can have three results, depending on the institutional structure of the system itself. The first case occurs when the examined object turns out to be a complex adaptive system. In such systems, an occurrence of emergent phenomena can be expected, which takes the form of ordered collective phenomena. The occurrence of emergent phenomena requires previous manifestation of complexity, which most often results from the operation of the law of progressive complexity. Since collective phenomena are related to a temporary reduction of complexity, complex adaptive systems have the ability to automatically rebound off the edge of chaos. A certain form of self-organization can be observed in their functioning, of a quasi-intelligent type, which allows them not only to survive, but also to grow and develop. The operation of these systems is regulated, on the one hand, by the law of progressive complexity and, on the other hand — by the emergence principle. The second case occurs when the objects do not reveal emergent properties after crossing the edge of chaos, but the level of their complexity grows, exceeding the critical level determined by the complexity catastrophe. Consequently, adaptive abilities of the system disappear, which causes the risk of its disintegration. An example of such an economic system are socialist economics. The third case concerns an object caught in an interchangeability trap between complexity and instability. In objects of this type, economic policy aimed at reducing complexity leads to an increase in instability and vice versa, while activities aimed at reducing instability increase complexity. In such conditions, the economy fluctuates between the complexity catastrophe and the instability catastrophe, while costs of complexity tend to grow when the system approaches any of those levels. An example of such an object is economy subject to transformation processes, where a chaotic attractor occurs in the form of a chaotic hysteresis [56].

10. Developmental potential of econophysics

The need to revamp economics is particularly important now, in the period of global financial crisis. Replacement of traditional economics by econophysics provides an interesting attempt to stimulate scientific progress in soft sciences [57]. However, this solution has several weaknesses, which have been analysed in depth by Rosser [58, 59]. First of all, econophysicists attribute a much higher degree of originality and innovativeness to their work than it deserves, which results most often from their unsatisfactory acknowledgment of the former achievements of economics. Secondly, econophysicists do not use a statistical methodology that is sophisticated enough in comparison to econometrics. Thirdly, econophysicists search the data for universal empirical regularities, which probably do not exist. Fourthly, the theoretical models they use are problematic and subject to multiple limitations. In Rosser's opinion, the first three arguments are predominantly justified. The first problem will disappear in time, as econophysicists tend to have better knowledge of relevant literature; additionally, they also work together with economists. Evidence for the existence of universalities in data is very scant, particularly as regards the distribution of income and wealth. As a matter of fact, econophysicists rarely apply sophisticated statistical tests to confirm the empirical ubiquity of scaling phenomena in economic data. The situation is different as regards the fourth argument, since it is only partially justified. It can be applied to the majority of econophysical models, which most often are pure exchange models. However, it is not applied in economic theories based on statistical mechanics. In the opinion of Rosser, a transfer of ideas from statistical mechanics to economics permits the establishment of models allowing production, yet they must be formulated on the basis of information entropy. To achieve this, the advice of Samuelson, who observed that the mathematical structure of classical thermodynamics was connected by isomorphisms with theoretical economics, should be followed [60].

The weaknesses of econophysics are often – in the opinion of physicists – magnified by economists [61]. McCauley, when referring to Rosser's arguments, in particular to the first and the fourth ones, points out the weaknesses of the neoclassical production models. In his assessment, they do not differ in any particular matter from neoclassical models of exchange, since, as in the case of the former, their empirical bases are unsatisfactory or do not exist at all. Therefore, econophysicists will not gain any advantage from reading standard economics texts and should ignore them. It may be claimed that this opinion is certainly exaggerated, since economics provides many unquestionable achievements. McCauley also emphasizes that in his group, the research starts from preparing market histograms, upon which an empirical model is deduced without assuming any a priori mathematical models. It is in his response to the second accusation of Rosser that McCauley criticizes the nature of rigorous and robust statistical methodology in economics. Econometricians assume the correctness of a model accepted in advance with a certain number of unknown parameters, and they then try to match it by force to a non-stationary time series by the best choice of parameters. However, nonlinear dynamics indicates that by matching any infinite precision model — stochastic or deterministic — to inherently finite precision data, it is not possible to avoid non-uniqueness [62]. Thus, econometricians, as McCauley claims, mislead themselves and others, believing that their models can be useful in understanding economic processes. Referring to the third argument, the author claims that it is partially right and provides conditions in which the universality of scaling exponents in finance cannot be expected.

The discussion presented above is not unusual; on the contrary, it is a necessary factor for the future integration of economics with econophysics. Nevertheless, it cannot be expected that econophysics will replace economics or that a significant part of economics can be absorbed by physics [63]. Unquestionably, econophysics are often right in criticising economics, but this relation is also true in the other direction. Quite serious charges, which can hardly be questioned, are also formulated against econophysics. Econophysical models do not usually contain age variables, which means that they consider immortal agents, which last forever, just like atoms. Whereas in economics, it is obvious that changes of income and wealth are a function of multiple agents, which is taken into account in overlapping generations models [64]. Additionally, the charges put forward by Roehner, who claims that econophysicists examining financial markets omit the role of big players, such as big banks, international financial institutions, big corporations, big investment funds, influential media corporations or powerful government organizations, are also justified [65]. Ignoring the role of those macro-players certainly makes it difficult, or even impossible, to examine many financial, economic and social phenomena. For comparison, in physics, this would mean elimination of external forces, which would result in isolation of all systems from the environment and focusing only on endogenous interactions. Not all econophysicists are aware of the true nature of financial markets and the fight for money taking place behind the scenes of economic life [66–67]. It should be presumed that in spite of the above reservations, econophysics will play a significant role in the transformation of economics. Unquestionably, the transdisciplinary matrix presented above will provide a basic element in this integrated approach.

11. Conclusions

Since econophysics has been dealing with financial markets from the moment of its emergence, it has also been involved with the most critical issues in economics [68–70]. Financial markets rule all other markets, exerting a global effect on them. For this reason, all economic events occurring in those markets are recorded. Without this, it would be not possible to conduct any economic policy. The task of econophysics is to gain an impact on economic processes, which cannot be achieved without convincing economists that econophysical models have better predictive abilities and demonstrate better understanding of reality than previous economic models. This slightly resembles an attempt to persuade a rich man to voluntarily share his wealth, when he does not feel like doing so. Nevertheless, the growing development potential of econophysics provides a factor promoting this task. For the last 20 years, econophysics has been constantly broadening the scope of its interests and has introduced new methods into its arsenal. The latest ideas include the use of quantum mechanics to explain the nature of a business cycle and research in the history of economic thought, involving the analysis of economic source texts on the basis of key word frequency [71, 72]. It has become a very fast developing science.

Before integrating econophysics with economics, the later should be evaluated. If the status of the economics is good then, in principle, we will have nothing to do and econophysics will not be necessary. However, in the opinion of Zhang, the current status of economics, and in particular, the science of finance, resembles thermodynamics before Boltzmann or even Carnot: many observations defy theoretical explanations and, additionally, there is no uniform basis for modelling [73]. It is hard not to agree with this theory. Most probably, a series of economic phenomena can be grasped and properly interpreted only with the use of entirely new terms and appropriate language, which shows that economics textbooks should be soon rewritten. However, it cannot be done without econophysics. Perhaps, as Rosser foresees, the final success of econophysics will come when this science disappears as a result of its integration with economics [74]. Such a status would mean a full paradigmatic correspondence between them, namely, both in the local and the global sense. However, it does not seem to be possible. Transdisciplinary sciences usually develop much faster, at least not slower than their basic — source sciences. Biophysics has not disappeared, indeed, it is alive and well. It should be rather expected that econophysics will preserve a certain distinctness, at least due to the fact that the methodology of physics seems to be richer than the methodology of mainstream economics.

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