Self-organization in Agricultural Sectors and the Relevance of Complex Systems Approaches for Applied Economics

Christian Noell
Associated Professor of Economics
Food and Resource Economics Institute
Royal Agricultural University (KVL)
Rolighesvej 25, DK-1958 Frederiksberg C, Denmark
email cno@kvl.dk, phone +45-3528-2267, mobile +45-2613-9106

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"Anything that must have a specific shape or form can easily be ruined forever. That is why I want my art to be formless."
Masaaki Hatsumi
(Hayes and Hatsumi, 2003)

Abstract

The paper attempts to highlight the question, if modern complex systems theory can be a relevant and useful tool for agricultural economics and other applied economic disciplines and how. Focus is on the consequences of self-organization, an emergent property of large systems with many components. The proposition is made that economic systems are indeed self-organizing systems and some explorative data analysis, that is a test for power law distributions in the sectors economic changes, is carried out on Danish agricultural sectors, particularly the pork sector (chapter 2). The results suggest that power law distributions exist in the analyzed sectors, which is seen as an indication of self-organization in the sectors under investigation and specifically for “self-organized criticality” (chapter 3). If economic systems in fact turn out to be self-organizing, should they not also have similar systems characteristics as other complex systems like attractors, fractal structures, synchronity and other higher emergent system properties? What would be the consequences for the way economic systems, their internal dynamics and external regulation are understood in general economics and particularly in applied economics? The read thread through this paper is an attempt to highlight these questions systematically in a first overview. In chapter 4 we will turn away from the pork sector example and extend our view to other properties of complex systems and to the “nature” of complex systems in general. In chapter 5 different systems concepts from Boulding´s hierarchy of systems (“clockwork”-, “control”-, “open”-systems) are connected to different economic theories by the question how complexity is dealt with in economic disciplines. In chapter 6 ten “lessons learnt” are suggested about how complex systems theory could be made useful in applied economics disciplines and how it could change the way real world economic systems are perceived, analyzed and regulated. The paper is a short version of a current working paper of the author (Noell 2006).

2 Introduction

Some years ago I came across the book “How nature works”, written by the Danish theoretical physicist and systems theorist Per Bak (Bak 1997). He drew a radically new picture of how large systems in nature as well as in human society develop over time. I was stunned by his claims e.g. that external shock is only of limited importance for systems dynamics, and that self-organization of those systems leads to a non-linear (in the sense of disproportional) response to external shock. He furthermore concluded that a self-organizing system can, seen form “outside”, can react seemingly randomly to external shock. After the first stunning disbelief I started to wonder if his theory about systems dynamics would also apply to economic sectors, whole economies or any other network of economic agents. Later in the book Bak showed in collaboration with others (Bak, Chen, Sheinkman & Woodford 1993) that indeed also in economics systems evidence of complexity caused by processes of self-organization could be found. I started to do an explorative data analysis on economic data by myself in the same way as Bak and others did before (e.g. Sheinkman & Woodford 1994). My next thought was that if economic systems in fact turn out to be self-organizing, should they not have similar systems characteristics as other complex systems? What would be the consequences for the way economic systems, their internal dynamics and external regulation are understood in general economics and particularly in applied economics? The read thread through this paper is an attempt to highlight these questions systematically and in more detail. In **chapter 2** some results of a data analysis of the Danish pork and other sectors are presented and first links to complex systems theory are made. In **chapter 3** these findings will be discussed specifically in the light of the theory of “self-organized criticality (SOC). In **chapter 4** we will turn away from the pork sector example and extend our view to other properties of complex systems and to the “nature” of complex systems in general. In **chapter 5** different systems concepts (“clockwork”-, “control”-, “open”-systems) are connected to different economic theories by the question how complexity is dealt with in economic disciplines. In **chapter 6** some conclusions are drawn about how complex systems

theory could be made useful in applied economics disciplines and how it could change the way real world economic systems are perceived, analyzed and regulated.

3 Measuring power law distributions in Danish agricultural sub-sectors

Per Bak`s main proposition is that changes in characteristic properties of large systems can indicate the presence of self-organization processes, if the changes are “power law” distributed. Those power law distributions (or Levy distributions, a special form of exponential probability distributions) can relatively easily be determined, given sufficient data and an appropriate indicator variable are available. Thus, if we follow Bak in that self-organization is the cause of complexity in systems then testing for power law distributions is a powerful analytical tool. Since Bak further claims that self-organization is a general property of systems as such, that is independent of the kind of system, power law testing can also be applied to economic systems. In the remainder of the chapter a case study on the Danish pork sector will presented and discussed.

3.1 Quantitative analysis for power law distributions

The analysis is based on Bak´s proposition that economic systems are self-organizing systems. Consequentially the first proposition for the explorative analysis is:

Proposition 1: *The Danish pork sector is a self-organizing system*

If we assume that changes of the aggregate monetary production value over time are indicating the inner development of the pork sector, then we can formulate the second proposition as follows:

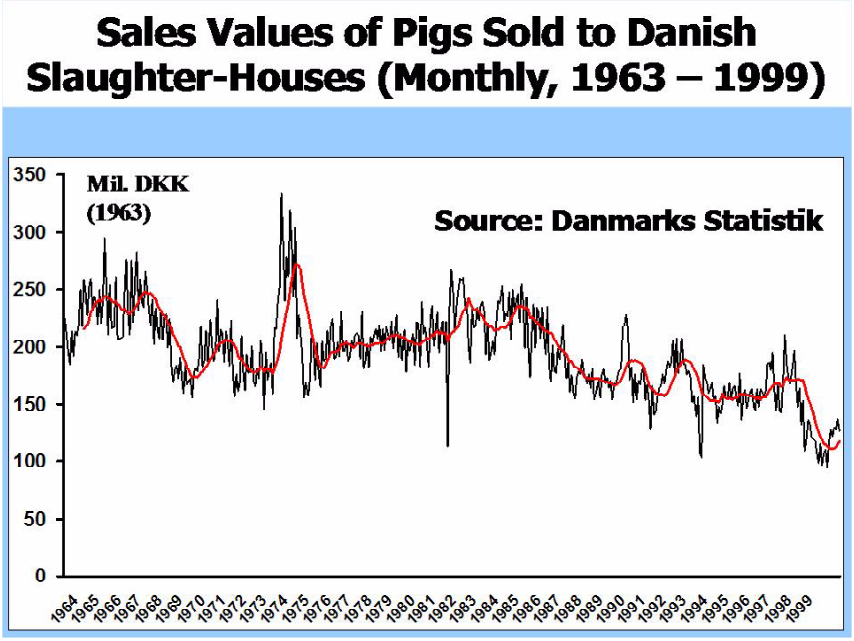
Proposition 2: *The aggregate monetary production is a suitable indicator to test the Danish pork sector for self-organization.*

From the second proposition immediately follows the third:

Proposition 3: *Changes of the aggregate monetary production value over time of the Danish pork sector are power law distributed.*

Power law distributions are linear functions of an indicator variable and the frequencies of its measured values on a double-logarithmical scale. Thus, the graph of a power law distributed

variable is a straight line with a negative slope. As a test for the existence of PLDs in agriculture a linear regression analysis was carried out on various sub-sectors of Danish agriculture based on official statistical data on average monthly producer prices (P; corrected for monthly rates of inflation) and monthly (t) production volumes (Y) from 1963 to 1999 (Danmarks Statistik, 1963 – 1999). In **graph 1** the data are visualized for the sales values of pigs sold to Danish slaughter-houses.



Graph 1: Sales values (black graph) and moving average (red graph) of sales values of kg pigs sold to Danish slaughterhouses from 1963 to 1999 (prices corrected for inflation).

The absolute values of fluctuations were transformed into relative measures by a 12-months moving average. Purpose was to reduce possible biases in the classification of the sizes of fluctuations in the calculations for every product. A test variable (Z) was calculated as follows:

$$Z_t = 100 * | P_t Y_t - P_{t+1} Y_{t+1} | / S_{i=1...12} (P_{t-i} Y_{t-i} / 12)$$

The results were then broken down into discrete frequency distributions. Class width was uniformly set to 5% (j = 1..20) of the respective maximum Z-value. Each class was represented in the regression analysis by the logarithm of its average Z-value (Zav_j) and the logarithm of the class frequency (n_j):

$$Z_j = \ln(Zav_j),\ F_j = \ln(n_j)$$

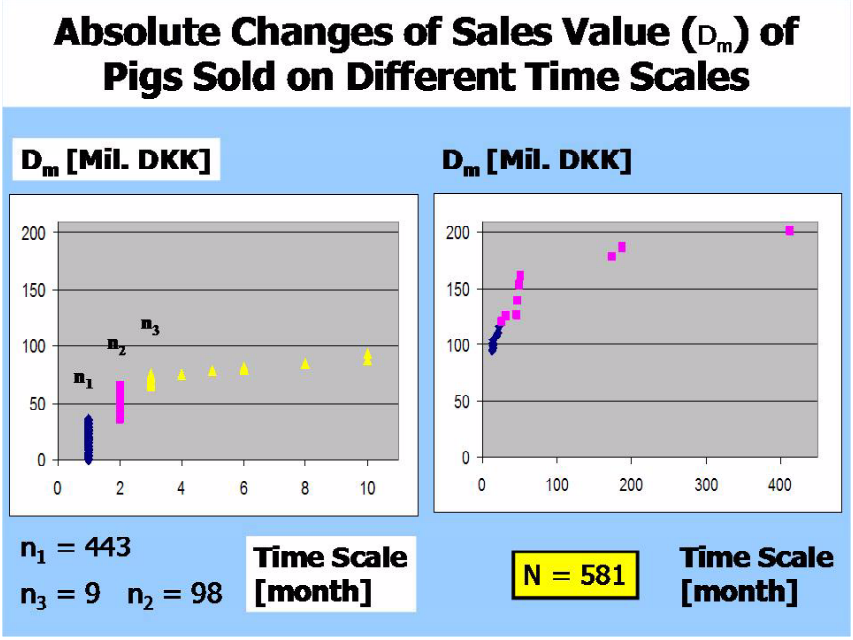
The regression functions for all ten sub-sectors under investigation show a high variety of slopes (b) between –0.5 and –1.5 (see **table 1**). Most of the Pearson´s correlation coefficients (see **table 1**) are below -0.9, for milk, beef of cows, beef of steers they are below -0.95, and for pork the correlation coefficient is even below -0.975, which brings the statistical relations close to functional relations.

Table 1: Correlation coefficients as evidence for discrete power law distributions in the changes of production values of selected sub-sectors of Danish agriculture

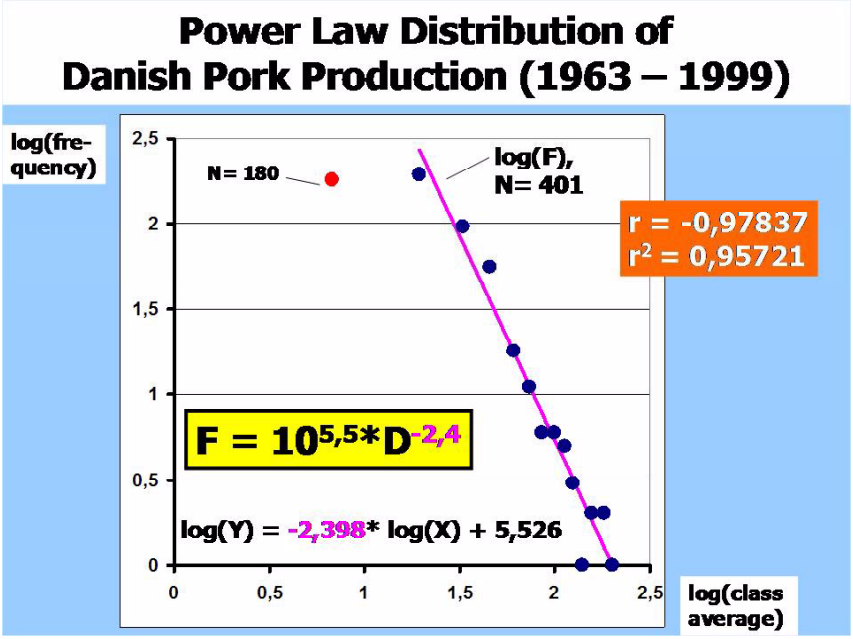
Product	**Intercept m**	**Slope b**	**Corre-lation r**	**R [%]**
Pork	-1.13	0.92	**-0.973**	95
Beef (cows)	-1.16	0.87	**-0.957**	92
Beef (bulls)	-1.02	1.14	**-0.955**	91
Milk	-1.37	0.47	**-0.951**	90
Barley	-1.12	0.64	**-0.943**	89
Potatoes	.1.30	1.59	**-0.940**	88
Eggs	-1.68	0.92	**-0.926**	86
Wheat	-1.33	0.57	**-0.925**	86
Butter	-1.25	0.74	**-0.925**	86
“young bulls”	-0.61	0.79	**-0.925**	85
Fresh Cheese	-1.22	0.68	**-0.915**	84
Beef (heifers)	-0.58	1.01	**-0.881**	78
Beef (total)	-0.71	0.68	**-0.840**	71

It can be concluded from these results that there is quantitative evidence for power law distributions in the economic systems under investigation. In **graph 2** changes of the production values for pork are plotted for all time scales. The maximum change has increased from 45 MDKK to 200 MDKK, which means that the power spectrum has almost doubled. Furthermore very small changes were excluded from the analysis, because their number is largely overestimated due to the restriction to monthly data. Weekly or even daily data would further spread out the power spectrum. The results of the extended analysis are given in **graph 3**. Note that now a $\log_{10}$-logarithmical scale is used. Pearson´s correlation coefficient has marginally improved and the power spectrum reaches from 1.25 to 2.3. **Graph 3** also illustrates what is meant by the “scale free” structure of self-organized systems,

because all changes over all time horizons fit into the same power law distribution. Thus, following the argumentation of Bak (1997) and Mandelbrot (2004) the time structure of the development of production values of pork production – and probably most of the other sub-sectors – seems to be fractal.



Graph 2: Absolute changes in the sales value of pigs sold to Danish slaughterhouses on different time scales. The measurement period varied from 1 to 432 months.



Graph 3: Discrete power law distribution and regression function for the pork sector if changes of the production values on all time scales are considered and very small changes are removed from the analysis.

3.2 Does the Danish pork sector show self-organized criticality?

The consistency of the above results further supports the conclusions that the measured fluctuations of agricultural production reflect the existence of processes of self-organization in Danish agriculture. E.g., the decade long discussion about the existence or nonexistence of "pork cycles" could find a relatively easy theoretical explanation if we look at the phenomenon from the SOC perspective. The frequently occurring increase of pork production (capacity) from a certain point of time on followed by a relatively sharp decrease fits very well the idea of threshold dominated internal dynamics of the sector as well as the irregularity of its occurrence. Regular business cycles would be very unlikely in a business sector with complex business dynamics, while irregular ups and downs of the business activity would be typical for the state of dynamic equilibrium. It would also explain why policy measures, price changes and price regulations sometimes have a strong effect on the sectors even if they are small and sometimes they do not have any effect, even if they are big. Substantial changes in the sector organization only occur, if the sector or parts of it are in a critical state. New investments as well as disinvestments in pork production are very much depending on profit expectations. Decisions to invest or disinvest are very often tied to certain profitability thresholds: the majority of farms will not react, unless their profit expectations have reached a certain level or range. Since pork farms are operating under comparable economic conditions, their individual threshold levels are not only lying in relatively narrow ranges but are also communicated quite intensively. If the perspective of self-organized criticality is extended to the fractal structure of the development of the pork sector small scale threshold effects would overlap and grow together to larger scale threshold effects based on the same organizational principles. In other words, dynamic equilibria in the business activities would lead to dynamic equilibria in the investment activity and the production of the sector. Processes of technological and organizational innovations in the pork production, changes of the pork farm structure, development of financial crisis in the sector, external investment activities and even food crisis and their emergence could be reasonably explained by the theory of self-organized criticality.

3.3 Power law distributions in economic systems

Since Thomas Schelling's Segregation Model (Schelling, 1978) processes of self-organization in economic structures have received growing attention. Also classical models of economic organization as the von Thuenen-Mills model or Christaller's Central Place theory show certain attributes of self-organizing systems. Paul R. Krugman developed an explicit model of self-organization in economics (Krugman, 1996), that also had a significant impact on research in spatial economics (see e.g. Masihisa, Krugmann and Venables, 1999). In theoretical economics Scheinkmann and Woodford (1994) explicitly connected SOC to the occurrence of PLD in their research model of economic fluctuations. They found that fluctuation in aggregate economic activity can result from many small, independent shocks to individual sectors because those shocks fail to cancel out each other in the aggregate due local interaction of the economics agents and other reasons. Power law distributions (PLD) of the quantitative behavior of economic systems (mostly price fluctuations) have been investigated by Mandelbrot (1963) and many others since. PLD are found in almost every sufficiently complex real world social system. Benoit Mandelbrot was among the first to discover PLD in price changes of Cotton and other agricultural commodities, but he did not further investigate the underlying causes. In recent economic literature evidence of PLD in all parts of the economy has been presented: *"They* [power law distributions] *are indicative of correlated, cooperative phenomena between groups of interacting agents at the microscopic level."* (Ormerod and Mounfield, 2001, p. 573). PLD of business sizes were investigated by D`Hulst and Rodgers (2001); Ormerod (2002) identified them in US business cycles, Ormerod and Mounfield (2002) in European business cycles while Ponzi and Aizawa (2000) report about PLD in financial market models; various other authors have found them in stock markets.

Furthermore economic systems can be identified as "slowly driven, interaction-dominated threshold systems" (SDIDTS, the second necessary condition for SOC, see chapter 3). Economic activity is to a very large extent, if not completely, interaction dominated and

changes occur in general slowly enough (and fast enough) that meta-stable structures can evolve and a separation of time scales can occur.

4 The mechanism of complexity: Self-organized criticality (SOC)

Self-organised criticality (Bak, Tang and Wiesenfeld 1987) is a specific characteristic of a certain type of complex system. Per Bak (Bak 1997) proposed an idealised model of a sand pile as a visual aid to demonstrate this phenomenon that has also been observed in economic systems (Ormerod and Mounfields 2002, 2001; Ormerod 2002; D´Hulst and Rodgers 2001; Ponzi and Aizawa 2000). SOC is generally accepted in complex systems theory nowadays, and has shown its usefulness in many scientific and practical areas (Bak, 1997; Jensen 1998). “Self-organised criticality is so far the only known general mechanism to generate complexity.” (Bak 1997, p. 2). Self-organized criticality implies that changes to, or reactions by, a system or its parts only occur if certain quantifiable characteristics of individual system components have threshold levels that can trigger an action. In the system component every incoming external impulse is converted into an increase in the value of the characteristic instead of an immediate response (Jensen 1998). When the threshold level is reached, the system component sends out impulses to other system components and the environment, while the state of the system characteristic that has triggered the action is reset accordingly. If a system consists of a number of components of that type and if those components are connected, then they are able to interact. In the course of interaction “change impulses” are transported throughout the system and the individual system components build up each others threshold levels and finally trigger each other into action. In the state of criticality the interaction among different system components is so intense that a local event is able to spread out to encompass the whole system, or at least large parts of it, much the same as a domino-effect or chain-reaction. The size of the avalanche-like system reaction depends on the degree to which the system components have locally, or as a whole, reached their threshold levels. There are many different states that a local part of the system can assume where impacts of different magnitudes do not lead to an immediate reaction, but

to an increase in the local readiness to react. These states are called meta-stable. When a system has locally reached the threshold level the state is called marginally stable. In the latter case, a small perturbation can trigger a wide range of responses. For the mathematical details about the state of self-organized criticality the interested reader might refer e.g. to excellent discussion in Jensen (1998). Only a certain type of complex systems is able to evolve into a state of self-organized criticality (Jensen, 1998, p.126 ff.)**:** slowly driven, interaction–dominated threshold systems so called SDIDT systems. As Jensen further points out in his constructive definition of SOC, finally it is the separation of time scales of causes and effects that makes self-organized criticality possible, due to the fact that the threshold effect impacting on a system in a "relaxed" state does not lead to a direct reaction, but contributes to the build up of the "critical" state of alertness. After some time the critical state relaxes and the build up of a critical reaction potential begins again. If the system is influenced too often and/or too heavily or is relaxing too fast the process of avalanching cannot build up. An agreed upon definition of SOC and a formal mathematical description for the development of SOC in complex systems, have not yet been developed due to the immense mathematical difficulty that sharp threshold processes impose. Nevertheless, a system is very likely to show self-organized criticality if the following sufficient and two necessary conditions are fulfilled:

1) The statistical properties of a system's behavioral variables exhibit a power law distribution (**sufficient condition**).
2) Basic conditions (threshold levels, meta-stability, marginal stability) and processes (building up and relaxation of threshold levels, avalanche like system changes) that constitute a state of SOC can be identified (**first necessary condition**).
3) A system can be identified as a SDIDTS that is a slowly driven, interaction–dominated threshold system (**second necessary condition**).

5 Characteristics of the complex nature of "open" systems

5.1 Basic properties

Complex systems are **open** in the sense that they constantly exchange energy, matter and information with other systems. They are **dissipative structures** that produce **order** and because of this they can exist far away from **thermodynamic equilibria**. Either the **number of system elements** is large or the **variety of relations** is high. Even a system of two elements can show complex behavior if the elements are complex systems themselves, as is the case with human beings. Due to their characteristic "openness" the **boundaries** of complex systems are **difficult to determine**. If we talk about "firms", "markets", "industries", "sectors", "supply chains", "regions" and the like as systems, we always have to set boundaries and make decisions about what to include in a particular system and what not. To a certain extent the delimitation of any system is an issue of human perception and purpose. The relationships of system elements are **short-ranged**. Thus, **neighborhood** relations rather than **total connectivity** of system elements constitute complex systems. The relationships among the system elements contain **negative and positive feed back** loops. Positive feed back is regarded as being a particularly important feature of structural development. The relationships among the system elements, as well as between the system and other systems are **non-linear**. Small causes can result in large effects and vice versa, the size of a cause and the size of an effect may be completely uncorrelated. Complex systems have a **history** and their further development is highly sensitive to the **state** they are in. Even the smallest changes can result in large deviations of future states from those in the past or present. Complex systems are **nested** (embedded) and develop **hierarchies** of system levels also called "**hyperstructures**". E.g. buyers and sellers form markets and markets form economies, while the buyers and sellers themselves can be people or organizations formed by people.

5.2 Advanced properties

While self-organized criticality is the driving force of complexity, the results of self-organization in a system are "emergent properties". Depending on the physical characteristics of a complex system and its context, typical emergent properties on high

hierarchical levels can occur that have a significant impact on systems behavior. There is an immanent tendency to **synchronization** of states and phase changes among system components and in nested systems (Strogatz 2003). Complex systems **adapt** structure and behavior to each other. Due to **redundant** structures complex systems are insensitive to damage. Highly developed systems develop the capability to repair themselves and (beyond the "open" systems level) have reproduction metabolisms. Complex systems do not have the tendency to develop into single, or even static, equilibrium states. Instead they possess many possible **attractors** or equilibrium states. An attractor can be a point, a regular path, a complex series of states or an infinite sequence (strange attractor). The repetition of very simple development rules on successive levels of systems development can lead to very complex so called **fractal** structures. **Criticality** is a state of a system at which its properties can suddenly change (threshold effect). Complex systems are said to self-organize into critical states of higher reactivity, go through phase changes, "relax" into a less reactive state and then start again to develop into a critical state and so on.

6 Complex systems and economics

There is no doubt that economic systems are complex. Prominent economists such as Adam Smith, Thorstein Veblen, John Commons, Alfred Marshall, Maynard Keynes, Friedrich von Hayek, Herbert Simon, Nicholas Georgescu Roegen, Kenneth Boulding, Oliver Williamson, Paul Krugman, Thomas Schelling, to name but a few, have pointed this out throughout the history of economic thought. Whenever a number of economic agents interact with each other, e.g. in an auction, at a stock exchange, in product markets, in industries or in whole economies, the overall outcome of the interaction is difficult to understand, predict or influence. The greater the number of agents involved, the more intense their interactions are and the longer they last, the greater the number of side effects, feed back reactions and unintended consequences becomes that have an influence on future outcomes. The characteristics and interactions of the individual agents (producers, traders, consumers, policy makers, institutions) organize and shape over time a stable but not static structure that

behaves according to constantly evolving and changing rules. In terms of modern system theory we say that under such circumstances system elements (economic agents in our case), their interactions and the forces of self-organization form a complex system. Complex systems do not only include the characteristics of simpler systems, but also characteristics of higher organization that clearly differentiate complex systems from non-complex systems. In Kenneth Boulding`s famous *hierarchy of systems* (Boulding, 1956) complexity starts to appear on the level of "open" systems (4th level out of 9). Below this level in the hierarchy are "framework" systems (1st level), "clockwork" systems (2nd level) and "control" systems (3rd level). Hierarchy levels with higher complexity than "open" systems are named "genetic" systems (5th level), "animal" (6th level), "human" (7th level), "social organization" (8th level) and finally "transcendental" (9th level), which represents the most complex and comprehensive systems level of all. For a contemporary in depth discussion of the systems characteristics associated with the different levels of Boulding´s hierarchy see a.o. Hatch (1997). Most of modern economic theory is based on the idea of second-level "clockwork" systems with some extensions (e.g. game theory and agency theory) to third-level "control" systems, which is the realm of modern management theory. Only fairly recent developments in institutional economics, evolutionary economics, ecological economics and particularly in organization theory are beginning to conceptualize and research economic and other social systems with fourth-level "open" systems approaches. It is evident that disciples of all economic disciplines are very aware of the immense complexity of economic life and the world in which it is embedded. Differences are apparent within the strategies suggested to cope with this complexity, which have only provided very general insights into economic phenomena of low complexity or to very specific insights into economic phenomena of medium complexity. Although these differences appear to be huge at first glance, and in direct contradiction with regards to neo-classical economics and institutional economics, they are not large compared to the degree to which any economic discipline is able to approximate the true complexity of "social organization" (as the eighth level of Boulding`s hierarchy of systems). Furthermore, it

should be kept in mind that even the most advanced research in natural sciences has only just started to explore fifth-level “genetic” systems. Higher degrees of complexity that would affect social systems have not even been discovered yet. Thus, however sophisticated economic theories might appear, they are still only extremely vague approximations of real world economic life and the differences between neo-classical and institutional economics are subtle in this context. Ultimately it boils down to a trade off between “complexity” and “generality” in the theoretical approaches adopted with comparable explanatory and predictive power.

7 What can we learn for applied economics?

The following ten “lessons learned” for applied economics research conclude our discussion: **(1) Self-organization** is a driving force of economic systems of equal significance to political or other external controls, as well as the activities of individuals or groups of economic agents. **(2) Complex systems theory** does not suggest that the use of standard economic theory should be overcome or abandoned in applied economics but supplemented and further developed by new dynamic approaches. **(3)** Complex systems theory is at the **core** of institutional economics and particularly evolutionary economics. Game theory also offers an analytical access to the simpler forms of complexity. **(4)** Complex systems theory predicts that the state of economic systems does not converge to overall static equilibria but to **dynamic equilibria,** probably due to the not yet fully explored effects of self-organized criticality. **(5)** Complex systems theory predicts that there is a substantial amount of **complex structure** in economic systems. A good deal of the perceived randomness and seemingly impenetrable complexity of economic systems and their development can be explained by concepts of attractors, fractal structures, threshold processes, synchronicity and other **emergent properties** of complex systems. **(6)** Due to the dynamic stability of SDIDTS (slowly developing interaction dominated threshold systems) **basic characteristics of overall and long term behavior and development** of economic systems are relatively easy to identify and to predict by empirical analyses, e.g. theory-based emergent properties like

self-organized criticality. **(7)** The nature of complex systems implies, and confirms real world experience, that behavior and the development of economic systems are very difficult – if not impossible – to **predict in detail and over long time horizons**. **(8)** Economic systems are difficult to **control** due to their emergent property of non-linear response to external shocks and influences. Policy makers, as well as top management, have to customize and time their policies to the development, existence and relaxation of **critical states** in the economy and businesses respectively. **(9)** Complex systems theory opens up new perspectives to real world economic systems. **Long standing research questions** could – as demonstrated in chapter 5 for the pork cycle – be approached in new ways and **new properties** of economic systems could be identified. **(10)** In the use of **Agent Based Modeling** approaches and other simulation techniques that allow interaction, the occurrence of self-organization and complex spatial and time structures has to be expected.

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