COMPLEX Final Scientific Report, Volume 2
Non-linearities and System-Flips

Edited by Nick Winder and Hans Liljenström

With contributions from the COMPLEX Consortium
http://owsgip.itc.utwente.nl/projects/complex/

COMPLEX (EU Project n°: 308601) is a 48-month project. We began collecting material for this report in Month 38 and started editing it together in Month 40. This report is a snapshot of the project taken in its final year. Please check the COMPLEX website for updates, executive summaries and information about project legacy.

C O M P L E X
Knowledge Based Climate Mitigation Systems for a Low Carbon Economy

Published by Sigtunastiftelsen, Sigtuna, Sweden
Human Nature Series
Editors: Nick Winder and Hans Liljenström
Graphic design: Regina Clevehorn, Sigtunastiftelsen
Printed by Kopieringshörnan I Uppsala AB, Uppsala 2016
ISBN: 978-91-976048-2-6
www.sigtunastiftelsen.se

6. Socio-Ecological Systems

Iñaki Arto, Iñigo Capellán-Pérez, Tatiana Filatova, Mikel González-Eguinob, Klaus Hasselmann, Dmitry Kovalevsky, Anil Markandya, Saeed M Moghayer, and Meron Belai Tariku

Ecosystems often do not respond smoothly to gradual change (Gunderson & Pritchard, 2002), The nature and extent of the feedbacks can produce a change of direction of the trajectory of the system itself (Walker, 2004). Biodiversity changes and ecosystem processes are likely to cause nonlinearity, particularly when thresholds of ecosystem resilience are exceeded (Chapin *et al*. 2000).

The most basic models of ecosystem dynamics in general and of population ecology in particular are substantially nonlinear. For instance, a model of population growth of organisms under limiting environmental constraints proposed by Verhulst in the 19th century (the logistic growth equation) has an S-curve as a solution, and the predator-prey Lotka-Volterra model (dated back to 1920s) describing the population dynamics in an ecosystem consisting of two interacting species is an interesting example of a conservative nonlinear system exhibiting periodic, strongly non-linear oscillations (Lorenz, 1993; de Vries, 2013).

Nonlinear dynamics in socio-economic systems

Economic systems, like many natural systems, are complex systems with non-linear dynamics, interactions and feedbacks loops. Among first studies of complexity in economic systems are Schumpeter and Hayek, and Simon. Indeed, with the recent explosion of interest in nonlinear dynamical systems, in mathematics as well as in applied sciences the fact that simple deterministic nonlinear systems exhibit bifurcation routes to chaos and strange attractors, with 'random looking' dynamical behaviour, has received much attention in economics (see for example Brock & Hommes, 1997, 1998). The complex economic modelling paradigm was mainly developed by economists as well as natural scientists and computer scientists within multidisciplinary fields of research.

'Tipping points', 'thresholds', 'regime shifts', and 'irreversibility' — all are terms that describe the flip of a complex dynamical system from one steady state or equilibrium to another alternative state or equilibrium, the so-called catastrophic shift. Catastrophic changes in the overall state of a system can ultimately derive from how it is organized — from feedback mechanisms within it, and from linkages that are latent and often unrecognized. The change may be initiated by some exogenous shocks. Once set in motion, however, such changes can become explosive and afterwards will typically exhibit some form of hysteresis, such that recovery is much slower than the collapse. In extreme cases, the changes may be irreversible. For financial institutions, the Wall Street Crash of 1929 and the Great Depression are examples of such a shift.

In mathematical terms, this means that the system can undergo a catastrophic shift that is a small changes in certain parameter values of a nonlinear dynamical system can cause equilibria to appear or collide or disappear, or to become stable or unstable. This could lead abrupt and sudden changes of the behavior of the system or mathematically speaking can cause dramatic changes in geometrical qualitative structure of the system. It can be said that catastrophe theory is a special case of bifurcation theory, part of the study of nonlinear dynamical systems (cf. Kuznetsov, 2004). Bifurcation theory is widely argued to have been developed first by the great French mathematician, Henri Poincaré, as part of his qualitative analysis of systems of nonlinear differential equations (1880-1890). The other principal figure in this field was, Christopher Zeeman (1977), who was responsible for coining the term catastrophe theory.

The economic dynamics is mainly concerned with modelling fluctuations in economic and financial systems, such as prices, output growth, unemployment, interest and exchange rates (see for example Brock & Hommes, 1998). These dynamics can be also concerned with modelling coupled natural-socio-economic systems such as ecological-economic and climate-economic models (cf. Wagener, 2003; Moghayer & Wagener, 2008). Regarding the main source of economic fluctuations there are two main conflicting views. The linear, stable view in which it is argued that these fluctuations are driven by random exogenous shocks to consumer preferences, technology, firm's earning, dividend, etc. This view, which dates back 1930's by Frisch, Slutsky, and Tinbergen, does not offer an economic explanation to those fluctuations, but rather exogenous forces to linear stable economic systems. In the nonlinear view, however, the economy may be unstable and even in the absence of external shocks, fluctuations in economic variables can arise.

Earlier studies of non-linearity in economic dynamics were conducted by Goodwin, Hicks, and Kaldor who developed non-linear, endogenous business cycle models in the 1940's and 1950's. However, this view was criticized especially with regards to the law of motion in these models that are considered ad-hoc and that the agent's behavior was considered irrational. The latter was triggered by the rational expectations revolutions in 1960's and 1970's (cf. Muth (1961)). New classical economists developed alternatives within general equilibrium framework, characterized by optimizing behaviour of consumers and firms, market clearing for all goods in each period and all agents having rational expectations. An example of such models is Dynamic Stochastic General Equilibrium Models (Clarida *et al.*, 1999), which is currently a dominating tool for policy analysis.

Zeeman (1974) was among the first application of critical transition theory or catastrophe theory in economics to study nonlinear economic dynamics. This paper models bubbles and crashes in stock markets. Debreu (1970) set the stage for doing so in regard to general equilibrium theory with his distinction between regular and critical economies, the latter containing equilibria that are singularities. Discontinuous structural transformations of general equilibria in response to slow and continuous variation of control variables can occur at such equilibria. Analysis of this possible phenomenon was carried out using catastrophe theory. Bonanno (1987) studied a model of monopoly in which there were non-monotonic marginal revenue curves due to market segmentation. Multiple equilibria can arise with smoothly shifting cost curves, which he analyzed using catastrophe theory. Beside these theoretical contribution, there have been a few empirical studies of catastrophic changes in economics. Fischer and Jammernegg (1986) was among few efforts to empirically estimate a catastrophe theory model in economics that was of a model of inflationary hysteresis involving a presumably shifting Phillips Curve.

Large numbers of economic models with critical transition can be seen in the urban and regional economics among them are Mees (1975), Wilson (1976), Dendrinos (1979), and Beckmann and Puu (1985). A good example in transport economics is Andersson (1986) that modeled "logistical revolutions" in interurban transportation and communications relations and patterns as a function of long run technological change using a fold catastrophe. In finance, Krugman's (1984) of multiple equilibria in the demand for foreign currencies could rather easily be put into such a framework following along the lines of the Varian (1979) approach can be seen as application of catastrophe theory. Many models are now studied of multiple equilibria in foreign exchange rate models, with many of these taken very seriously given the numerous foreign exchange crises that have occurred in recent years.

Another important application of catastrophe theory or critical transition can be seen in the ecologic-economic systems focusing on the abrupt changes in biological populations and the state of ecosystems, including collapses to extinction as a result of interaction with human activities. Indeed, whenever human activity influences the state of an ecosystem, usually through some form of pollution that is a by-product of some kind of production activity, the difficult problem arises of assessing the relative interests of producers affecting the ecosystem and producers and consumers enjoying it.

In the next section, a recent research on the economics of lakes will be reviewed, presenting the results in critical transition and catastrophe theory and bifurcation form. The aim of this section is two-fold: first, to provide and illustration example of all the terms and definitions discussed in the previous sections; second, to provide a prototype example of a stylized non-linear coupled economic- environmental model that exhibits non-linearities, thresholds and irreversibility in the presence of environmental tipping points[1].

[1] The presented model and results are based on a recent research program carried out by Saeed Moghayer (authour of this report), and Florian Wagener in the Center for Nonlinear Dynamics in Economics and Finance at the University of Amsterdam (cf. Moghayer, 2012).