EVOLUTIONARY ECONOMICS AND SIMULATION

WITOLD KWAŚNICKI

1. Introduction

Development of simulation approach to study social processes is strongly correlated to progress in computer technology. The increasing computational power of modern computers and increasing possibilities of graphic representation allows simulation with more adequate metaphors and analogies to real processes. One of the leading branches of economic analysis applying the simulation approach is evolutionary economics, but even within this field of research the importance of simulation is not uniform. The following section of the article deals with the use of the simulation approach in analysing and understanding real phenomena. Problems of model testing and validation are also described in this section. In the third section a short analysis of the role played by simulation in evolutionary economics is presented. A variety of simulation approaches to analysing economic development are presented in the fourth section. Two main streams of models, namely those rooted in Schumpeterians tradition and the agent- based approach, are characterized. Working out a so-called common platform (i.e., software which would be able to model economic development and can be used both by economists skilled in computer programming and those not familiar with it) is being pursued at the moment. In the last section three propositions about such common platform are briefly discussed.

2. The specificity of the simulation approach

A simulation study requires well-designed methods of model development, validation and verification. A model of a real phenomenon is always a simplified, idealized and approximate representation of the process.[1] Any theoretical system

[1] There are four basic reasons for model construction and analysis: (1) understanding and explanation of a given phenomena, (2) forecasting (prediction of future development) or retroprognosis (retrodictions), (3) supporting decision making to achieve well defined goals, and (4) design for

is a kind of abstraction describing in very specific way relations between some selected abstract entities. This kind of system can be treated as a model representing selected aspects of reality only when there exists homeomorphism between real objects and abstract objects. Therefore it can be said that each model consists of three fundamental elements: the set of abstract entities, the relations between them and homeomorphism allowing proper interpretation of abstract entities in terms of real phenomena. As Henri Poincaré (1952, p. xxiv) wrote in *Science and Hypothesis*: "The aim of science is not things themselves, but the relations between things; outside those relations there is no reality knowable."

The model representation depends on the aims of our inquiry and on all constraints related to the process. Exactness and validity of a model of a technical (engineering) system is reached mainly through so-called identification. Having collected records of real process behaviour for given input $u(t)$ and output $y^m(t)$ the modeller tries to adjust the models behaviour to reality either by selecting the proper (optimal) values of the model's parameters or by changing the model's structure. In a schematic form the process of model adjustment is represented in Figure 1. This kind of adjustment is sometimes called 'a behaviour replication test', whose main aim is to compare the model behaviour with the behaviour of the system being modelled. Where historical time series data (or the results of a real system's development in the factory or laboratory) are available, the model must be capable of producing similar data. That is, for the same initial conditions and inputs, the model's behaviour should parallel the historical data. An important question is how closely the model's behaviour should match the historical data, since historical data are less than perfect and, sometimes, far from being perfect. If historical data are very poor or nonexistent, the test may be one of reasonableness and we ought to use another validation tests (see below). In most cases a specific criterion of the model's exactness is employed, such as mean-square error. For an assumed criterion the model adjusting process can be done analytically or through simulation, applying one of the well-known optimization algorithms. This 'technical' approach through model parameter identification is not fully applicable to socio- economic models. First of all, in most socio-economic phenomena we are not able to select a class of suitable models (linear models are frequently not applicable). Contrary to engineering systems, there is no possibility of making repeated experiments with socio-economic systems. It is much easier to disaggregate whole engineering systems into a number of smaller subsystems which can be analysed separately. Socio-economic systems are highly interrelated, and disaggregation into semi-isolated subsystems is frequently impossible. In engineering systems optimization (related to search for better – or the best – performance of given system, optimal control of engineering processes or limited resources) is the primary aim of modelling (and simulation) efforts. It seems that in the social sciences

optimal performance of a system.

and in economics the main aims of models building are: better understanding of mechanisms of development of observed phenomena (processes), building different, alternative scenarios of development of given socio-economic systems, and education of the decision-maker through ’imprinting’ proper intuitions. This last aim is achieved through interactive applications of simulation models to test decisions made by managers and analysing the reaction of the model.

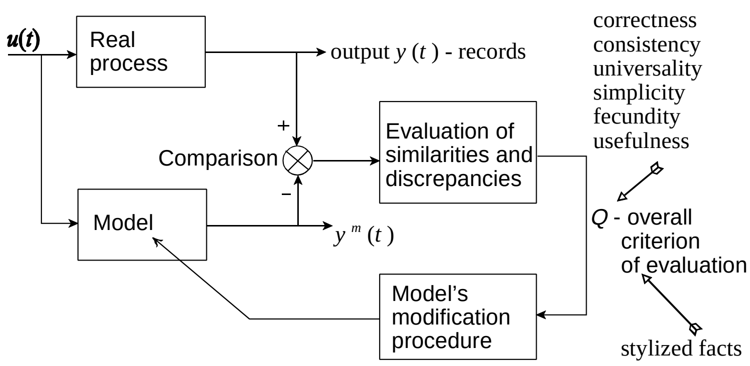


Figure 1. Model and reality.

Evaluation of socio-economic models thus must proceed in a different way than engineering ones. In contrast, this ’engineering’ vision of socio-economic processes prevails in orthodox economics. For orthodox economists make assumptions, similar to those made in classical physics and engineering, on the possibility of: (1) isolating a specific sphere of socio-economic reality, (2) specifying all relations of phenomena within the sphere with the external environment, and (3) building a model which describes all important phenomena observed within the chosen sphere, with all essential influences of the external environment included. On the basis of such a model some optimal control, or optimal path of development, is calculated. Such a mechanistic approach to socio-economic processes turned out to be wrong and misleading. A lot of decisions made by policymakers on the basis of such models caused strong social and economic tensions, especially visible in the 1970s, that is, during the period of radical structural changes of the economies of industrialized countries.

In socio-economic processes, the clear isolation of well-defined spheres of reality, the specification of important relations with the external environment, the building of relevant mathematical models and optimizing the choice of suitable policies are almost impossible. Questions concerning optimal decisions in a long-term perspective and in periods of structural change lose their significance. Far more important become the questions about the mechanisms of long-term development and on the possibilities of controlling the economic process to reach a satisfaction (not optimal) course of development. These kinds of questions form the root of the evolutionary approach, not only in economics. Acceptance of an evolutionary perspective in dealing with a socio-economic system almost naturally enforces a specific way of subtly controlling the development of social systems, not through imposing optimal values of relevant parameters but through creating favourable conditions for suitable development.

The different nature of engineering and socio-economic systems also causes differences in the possibility of testing and validating of developed models. As it was mentioned, in engineering systems it is possible to compare numerical data (records of development of real systems) with numerical output of a model. In socio-economic system collection of reliable set of proper data (records) is frequently impossible. Therefore, validation of socio-economic models is frequently done on the base of so-called stylized facts. As Nicholas Kaldor (1961) wrote:

> Any theory must necessary be based on abstraction; but the type of abstraction chosen cannot be decided in a vacuum: it must be appropriate to characteristic features of economic process as recorded by experience. Hence the theorist, in choosing a particular theoretical approach, ought to start off with a summary of facts which he regards as relevant to his problem. Since facts, as recorded by statisticians, are always subject to numerous snags and qualifications, and for that reason are incapable of being accurately summarized, the theorist, in my view, should be free to start off with a 'stylized' view of facts – i.e., concentrate on broad tendencies, ignoring individual details, and proceed on the 'as if' method, i.e. construct a hypothesis that could account for these 'stylized facts' without necessarily committing himself to the historical accuracy, or sufficiency, of the facts or tendencies thus summarized.

The list of these 'stylized facts' is indeed very long, and naturally different for different systems. They can range from the microeconomic evidence concerning for example dynamic increasing returns in learning activities or the persistence of particular sets of problem-solving routines within business firms, to industry-level evidence on entry, exit and log-normal- distributions in firm sizes.

Facing the problem of choosing between alternative models we do not evaluate any single assumption, law, or conclusion which is part of each model. In fact we try to build sub-criteria and try to evaluate each alternative model applying these sub-criteria. In the next step of our evaluation process, subjective weights are attached to each sub-criterion and on the basis of the general index thus constructed the whole model is evaluated. This general index helps us to find a final answer to the general question: which model do we prefer? It seems that the most important and the most popular sub-criteria are:

1. *correctness* – consequences of the model ought to be very close to the results of experiments and/or observations;
2. *consistency* – the model ought to be consistent not only internally but also with other commonly accepted theories used to describe similar or related phenomena;
3. *universality* – consequences of the model ought not to be confined to individual cases, as intended at the initial stages of the model development;
4. *simplicity* – the model ought to create order in the formerly isolated phenomena; some evaluations based on individual feelings of harmony and beauty are also taken into account in this partial evaluation;
5. *fecundity* – the model ought to throw new light on well-known phenomena; it ought to be the generator of new discoveries;
6. *usefulness* – this practical criterion dominates frequently in sciences, being very close to engineering and industry.

As it was mentioned, the evaluation is highly subjective and it is difficult to generalize but it seems to me that the advantages of orthodox models are their simplicity and usefulness, but evolutionary models ought to be estimated for their universality, higher consistency and all above for their fecundity. Correctness seems to be a neutral sub-criterion in a sense that currently orthodox models better describe macroeconomic phenomena but at the micro level evolutionary models are much more correct.

It is good to have one, a general indicator (hopefully as a scalar) allowing for evaluation of exactness of the model and its validity. In engineering system a mean-square criterion is used, and sometimes it is possible to construct such a criterion for socio-economic systems. But in most cases only a highly subjective overall criterion is used based on selected stylized facts and at least some the six sub-criterions mentioned above. This specificity of socio-economic system is indicated in Figure 1 by mentioning stylized facts and subjective sub-criteria. Even if we are able to collect quantitative data and we try to minimize the identification criterion (i.e., the distance between the model's behaviour and real data) we have very rarely the situation as clear as in Figure 2. In a case of a minor share of stochastic factors it is possible to adjust the model's behaviour to collected records simply 'filtering' noise over an observed trend.

Very frequently we have a situation when considered processes are highly stochastic. Even when we are able to collect relevant data it is often very difficult to identify trends simply because stochastic factors dominate (Figure 3). The

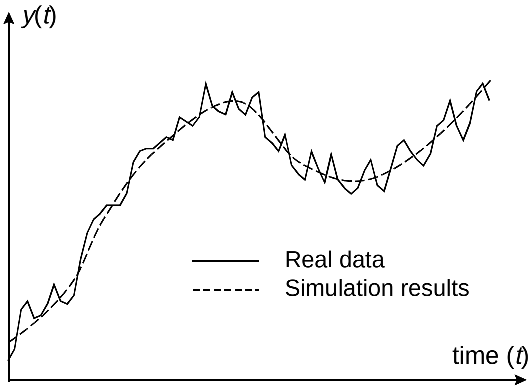


Figure 2. Trends and reality.

question arises how to evaluate similarities if both variables are realizations of essentially the same stochastic process. A fundamental question is how to evaluate and how to decide when a model leads to satisfactory results and is acceptable for further research? It is much easier to evaluate a model if the stochastic process is stationary and ergodic. There are well-know stochastic tests to evaluate the level of similarities between different realizations of the same process, as, e.g. variance analysis and confidence intervals. Unfortunately most real processes (especially those of the socio-economic sphere) are non stationary ones and it is very difficult to work out effective tests of their evaluation.

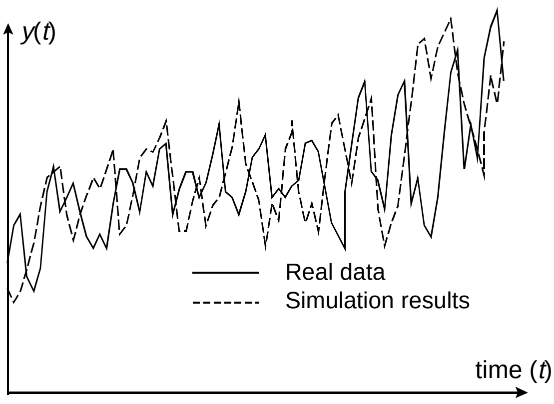


Figure 3. Stochasticity and reality.

An inventive approach to model validation can be found in Law and Kelton (1982, p. 341). They describe the application the Turing Test to evaluate the level of similarity between simulation results and real system. People with a deep knowledge of a given system are asked if the results presented correspond to the phenomena which they knew from their experience. They do not know if the results are real or simulated. The experts do not evaluate in dichotomous categories of 'good'-'bad' (or yes-no) but are asked to present rather detailed analyses and point out what in their opinion is correct and acceptable and what is dubious or incorrect. There are two virtues of such an approach. First, the opinions can be used to improve the model, and second, they can evaluate the degree of similarity between model and reality. This approach was applied in the ISEM model describing in *US Air Force Manpower and Personnel System*. The model was built to work out alternative policies of employment in the US Air Force. The Turing Test procedure was applied a number of times. The final model was very promising and was implemented in practice.

Another effective 'classical' approach to model validity is spectral analysis. This technique allows for a comparison of model behaviour and real data without tedious and time-consuming simulation experiments. In the evolutionary framework it has been applied, e.g., by Silverberg and Verspagen (1995) where they compare the power spectrum of GNP per capita resulting from their simulations to the log distance of six countries to the USA-frontier of per capita GNP and to the power spectrum of the coefficient of variation of per capita GNP in six OECD countries. Similarly Silverberg and Lehnert (1993) analyse time series for technical change and growth generated by their simulations by means of spectral analysis, in order to decompose them into harmonic oscillations of various frequencies. The result is a downward sloping linear curve in a plot of the log of spectral density vs. the log of the frequency of the oscillations and it is interpreted by Silverberg and Lehnert to be a form of long or Kondratiev waves which are neither strictly periodic nor a random walk. Spectral analysis allows to evaluate average level of models' behaviour and the persistence of observed mode of behaviour. It allows also to build confidence intervals. Figure 4 illustrates that possibility for a typical power spectrum of selected characteristics of economic development (e.g. stock prices). In the same figure the estimated trend and intervals with assumed 95% probability of confidence are also presented.

An advantage of spectral analysis is that there is no necessity of repeating simulation experiments tens or hundreds of times for the same initial conditions to compare the model's behaviour with reality. A disadvantage of this approach is that to apply it properly it is necessary to have long time series with hundreds or even thousands of elements.

There are no fully valid models because all models are approximations of the

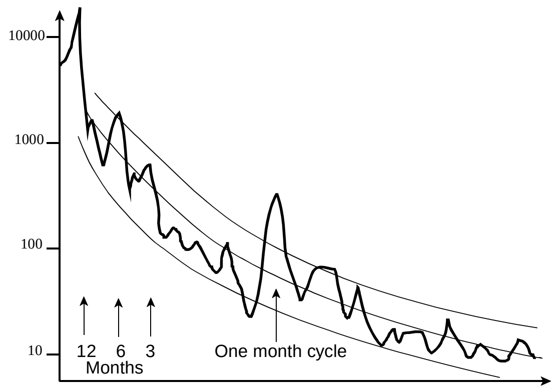


Figure 4. Power spectrum – stock prices.

system, being modelled. William E. Deming noticed that “All models are wrong. Some models are useful.” Does the model serve the purpose for which it was intended? Is it helpful? Therefore, the developer’s or user’s purposes must be taken into account in evaluating a model’s validity. Much depends on the purpose for which the model is developed for example, the choice of the level of detail used in the model. Difficulties with having inadequate model to a given situation can be illustrated by the following example. This example is interesting because in that case rather simple, rude approach turned to be more advantageous then a very sophisticated and sensitive one. In the beginning of 1958 very sensitive Geiger counters of energetically charged particles were carried by the USA Explorer satellites. The aim of this experiment was to measure the concentration of charged particles. About 1000 kilometres above the Earth the counters indicated that abruptly the number of particles dropped down to the null level. Some of the researchers were puzzled but in the end most of them have accepted the results. But one researcher, namely James A. Van Allen, astonishingly proposed to launch not very sensitive counters but quite contrary very rough and nonsensitive once. It was a right proposition. It turned out that null reading during the first Explorer mission was because the number of particles was so intense that sensitive counter simple were not able to count them. Through this way the first, so-called Van Allen, radiation belt was discovered. In December 1958 a second belt, at a distance of about two to three Earth radii from the Earth’s surface, was discovered by Van Allen’s group.

There are no general rules for proper selection of appropriate level of detail, demarcation of boundaries between a model and its environment, and similar considerations. It is still the ”art” aspect of simulation model development. The usefulness of any analytical model or simulation model ultimately lies in the subjective view of the model builder and its user.

The basic test of a model's validity is that all important factors in the real system exerting an influence on the behaviour of the system must appear in the model. Further, all factors in the model must have a counterpart in the real system (homeomorphism). The development of the simulation approach in the last decades indicates an important shift from traditional statistical tests toward more qualitative and subjective tests belonging to two main classes: model structure tests and model behaviour tests. Among the first class the most popular and important are the model parameter tests and the extreme conditions test. The second class encompasses behavioural replication, anomalous behaviour, sensitivity, prediction, family member and boundary tests.

Model parameter tests can be considered as a basic test. All the time we ought to be sure that the assumed values of all parameters of the model are plausible, reasonable and consistent with whatever supporting data might exist. Extreme condition tests show the ability of a model to function properly under extreme conditions. Positive results of these tests support significantly increase confidence in model. It was Francis Bacon who emphasized the importance of active experiment with the main objective of compelling Nature to manifest its properties in conditions never, or rarely, observed in natural processes. It is worth mentioning this kind of test because testing extreme conditions may easily be overlooked, especially in the early stages of model development. Neglecting this testing may degrade model performance under both normal conditions and when the model is used to answer questions falling outside the operating regions emphasized in early development.

While making simulations and testing the model (e.g., extreme condition or behavioural replication tests) we ought to look for anomalous behaviour of the model. Tests of anomalous behaviour may contribute convincingly to establishing model validity.

Small, reasonable changes in a model's parameter values should not normally produce radical behavioural changes. From this point of view, most social systems, but certainly not all, are stable. Positive results of behaviour sensitivity test increase confidence in the model but, on the other hand, simulation models are often used to search for parameters values that can effect behavioural changes. Therefore, we ought to be very cautious in using that test for models' validation purposes.

Confidence in the model is also reinforced if the model not only replicates long-term historical behaviour but also allows for prediction of system development. A special instance of prediction is retroprognosis-real data from periods of the far past are used to identify the model's parameters and then simulation results for the years following the identification period are compared to the subsequent development.

2.1. SIMULATION AND OTHER APPROACHES

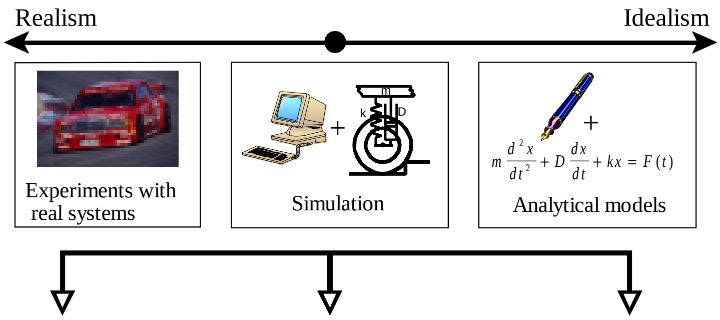
Three techniques of models building and development are presented in Figure 5. The left side of this spectrum is represented by research made on real (physical) objects (e.g. testing new design of a car driving on different kinds of surfaces). The other side of the whole spectrum are mathematical (analytical) models, e.g., working out a set of differential equations to describe a car suspension system and solving analytically. The third alternative, namely simulation, is placed somewhere between these two extremes. In deriving simulation model, the system (e.g., a suspension system) is partitioned into elementary subsystems (springs, shock absorbers, torsion bars, stabilizers, etc., in economics they can be firms, consumers, banks, markets, etc.). The next step is to build sub-models for those subsystems and to connect them to form a model for the whole system. To be closer to reality the sub-models are usually nonlinear ones and therefore the simulation models are normally unsolvable analytically. It is very difficult to made experiments on real objects in socio-economic sciences, although some preliminary steps toward that direction are made through so-called experimental economics, where in laboratory conditions situations very close to reality are created. Most investigations in economics are covered by the two other techniques. To show advantages and disadvantages of these three techniques let us use a very simple example, namely the problem stated more than 250 years ago, in 1733, by Goerge Louis Leclerc (later better known as Comte de Buffon). He stated the following problem: if we have straight, thin needle of the length l and we toss that needle on the table on which parallel lines are drawn, providing the distance d between those lines is greater or equal l, what is probability that the needle does not cross any line?

One of possible way to find the answer for that question is to build mathematical model and calculate the probability from obtained equation. Applying standard principles of probability calculus it is possible to proof that the probability that needle does not cross any line is equal to:

$$P = 1 - \frac{2\,l}{\pi\,d}$$

Assuming that the distance between lines equals the needle length ($l = d$), we can calculate that probability P is equal to 0.3634.

The second possibility is to make experiments with a real needle and a real table. Therefore it is necessary to prepare a table, draw parallel lines and tossing the needle on it and counting number of successes. In fact these experiment was done by E.E. Bassett from University of Kent. He has used a tailor needle and draw lines of the distance d equal to the needle length. Results of the two series of experiments are following: (i) 390 trials and 254 crossings and (ii) 960 trials and 638 crossings. The estimated value of probability in the first Basset experiment is 0.3487 and in the second 0.3354. The aim of Basset experiment was to estimate



Advantages

- realism - final verification	- imitative realism - study of nonexisting systems - time passing control - criterion elasticity - controllability and repeatability of experiments - limited mathematical skills - relative low costs - use of expert knowledge	- generality of results - optimal solutions

Disadvantages

- system has to exit - improper time scale - constrained values of control parameters - limited number of possible experiments	- lack of generality of results - large number of experiments required - optimization problems - long duration of simulation studies - simulation misusing	- far reaching simplifications - sophisticated mathematics

Figure 5. Three techniques of real processes study.

value of π (through so called Monte Carlo approach). Applying theoretical equation for probability P it is possible to calculate estimated value of π by solving the above equation and expressing π as the function of P. The estimated values of π are 3.0709 and 3.009, respectively in both experiments. Comparing it with real value 3.1416, we can conclude that the estimation is not very accurate. To improve it the number of trials ought to be much larger, but as we can expect it is a rather tedious and time- consuming process.

The third possibility is to use computer simulation approach. It is not real system experiment nor shuffling mathematical symbols. Essence of simulation is working on substitutes, a kind of imitation of that what is going on in reality. There is wide spectrum of possible imitation of reality. To emulate shopping we can imitate a process of clients' arriving to a shop by tossing a coin and e.g., assuming that client arrives when reverse occurs twice in a row (i.e. probability is equal to 0.25). That seems to be rather inconvenient. Naturally it is easier to use a computer to generate random values with assumed probability distribution. To facilitate imitation of the Buffon problem we can write a computer program. In fact it is not very complicated one and it is possible to write it relatively quickly. The program consists of approximately 40 lines of text and it took around half an hour to write it and to make experiments. Following the conditions of Basset in the first series of 390 tosses I have got the estimated probability equal to 0.3410 (and estimated value of $\pi = 3.0350$) and in the second experiment of 960 tossing $P = 0.3833$ and $\pi = 3.2432$. To improve estimation it is necessary to toss a needle much longer, e.g. for 100 000 tossing the estimated value of P is equal to 0.3626 ($\pi = 3.1377$) and for ten times greater number of trials (i.e. 10^6) we are much closer to theoretical value, namely $P = 0.3633$ and $\pi = 3.1412$. Advantage of simulation approach lays not only in the speed of running the program to get required results (e.g., simulation lasts around 30 seconds to estimate the probability for 100 000 trials). It is very easy to change initial conditions of simulation. To change length of the needle is enough to provide new value of the initial parameter. In principle, for the written computer program which simulates our problem it does not matter if the length of the needle is greater or smaller then the distance between lines. It is still simple changing the value of a relevant parameter. But it occurs that for theoretical consideration the assumption that the needle length is smaller then the distance is important. To calculate the probability of no-crossing the lines for all possible situations we ought to consider two cases, first when l is smaller or equal to d, and the second when $l > d$. Calculation of P for the second case are more tedious and the final equation does not look so nice. The probability for the second case is equal to:

$$P = 1 - \frac{2}{\pi} \left(\arccos\left(\frac{d}{l}\right) + \left(1 - \sin\left(\arccos\left(\frac{d}{l}\right)\right) \frac{l}{d}\right)\right)$$

Probability of no-crossing a line for the needle length twice the distance d is equal to 0.16275, in a simulation experiment the estimate value of that probability for 100 000 trials was very close to that value. It consumed me a few minutes of work to obtain estimate values of P for 20 different values of the length of the needle. But simulation approach can be more flexible then simple changing of the initial conditions. Having the simulation program for situation stated by Buffon it is relatively easy to modify it to describe another situation (we can say to be closer to reality), e.g. we can assume that the table is finite and of special shape (e.g. a round table), we can assume also that there are no parallel lines but circles.[2]

[2]We can go further to become closer to reality and assume that for some positions of the needle very close to the edge of the table the needle drops on the floor, or assume different shapes of the needle. It is relatively easy to modify the simulation program to meet that realistic assumption.

Relaxing some assumptions and/or changing the conditions to be closer to real situations leads to essential troubles for analytical treatment of the problem. I do not dare to calculate the probability of no crossing the circles on the round table. It seems to me to be rather complicated if ever possible to provide the equation describing that probability. But it is relatively easy to write a simulation program for that new situation. It occurs that the program is still relatively simple. It consists of 70 lines. I have assumed that the length of the needle is equal to 0.1 and that the table diameter equals 2. I have varied the distance d of the circles on the round table and for 30 different values of the distance d after 4 hours of computers work (for each distance I have assumed 500 000 of needle tossing to get estimation of the probability). There is no problem to assume very small distances, e.g. 0.001 (probability of no-crossing is equal to zero for that distance but for $d = 0.002$ estimated probability is greater then zero, $P = 0.000248$). The results are presented in Figure 6. For d greater then 0.5 we have only a single circle approaching the edge of the table. We see that probability of no-crossing of the single circle is not constant but slowly approaches one (for the circle on the edge the probability $P = 0.96771$). There is no problem with changing another condition of the simulation, e.g. changing the shape table to a rectangle requires small changes in one line of the program.

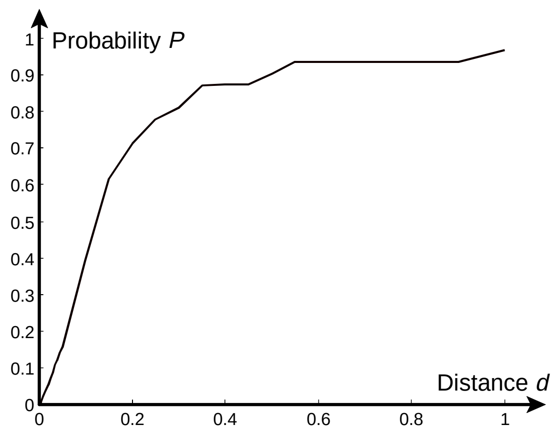


Figure 6. The Buffon experiment with the round table.

This very simple example gives us hints on advantages and disadvantages of those three approaches to modelling real processes. Naturally real situations, especially those of socio-economic ones are much more complicated then our simple needle tossing. For socio-economic systems it is very difficult (if ever possible) to make repeated experiments as it was in the case of 'technical' systems (e.g., our Buffon needle problem). It is also very difficult to build analytical models (e.g. in a form of differential equations), but even if it is possible, in most cases it is impossible to solve that equations and to get analytical solutions describing behaviour of the model. Very frequently, to obtain results and to get knowledge about dynamics of system behaviour it is necessary to build computer simulation model which reflect as far as possible a structure of real system and its mechanisms of development.

There is no space to discuss details of advantages and disadvantages of experimental, analytical and simulation techniques. The sketch of pros and cons of those approaches is presented in Figure 5. Below we list advantages and disadvantages of simulation approach and contrast it with the two other approaches.
Advantages

- Realism – most simulation models realistically reflect real processes; normally all models' elements have their counterparts in real system. This gives a possibility of graphical representations of modelled process on a computer screen. Although experimentation with real systems provides much more realism and gives a possibility to consider specific details, unnoticeable by simulation approach and analytical models. Experimentation with real systems makes possible a final verification of the hypotheses (e.g. efficiency of given policy, controllability, applicability of given medicine in clinical research). Unfortunately the final verification is mostly possible only in engineering systems and is very limited (if ever possible) in socio-economic systems. In rudimentary form realism is observed in analytical models where very frequently it is necessity to make far reaching simplifying assumptions together with limitation of a spectrum of possible models (e.g., necessity to confine the considerations to linear models) what is caused by difficulties to find analytical solution. Therefore very frequently results of analytical models are very elegant and aesthetical but do not fit to real systems and have little practical use.
- Possibilities to enquire systems which do not exist, in some extreme cases of systems which exist only in a brain of a researcher (mental systems). This can be contrasted with experimentation with real systems where the system must exist before planned series of experiments (in most situations the aim is to design optimal system).
- Time passing control – it is possible to adjust simulation time scale to required conditions (perception), to speed up simulation time (e.g., in macroeconomic considerations or palaeobiological phenomena) or to slow down (e.g. in quantum mechanics). Either very slow processes (lasting hundreds of years) and very rapid processes (of the order of 10^{-12} second) can be simulated within few seconds or minutes. Setting time scale is not possible in experiments with real systems. Very frequently dynamics of an enquired

system is too slow (decades, or hundred of years in economic system) or too quick (sub atomic physics) to be useful for collecting data.

– High elasticity of modification of optimization criterions (also goals of systems performance); analytical enquire requires specific form of the criterion, e.g. it ought to be continuous to enable calculation of differentials. Frequently type of mathematical model is determined by used criterion. In simulation models there is no such constrains (or at least are not so severe and troublesome), it is possible to apply a non-differentiable criterion (even non analytical criterions as, e.g., postulated by Herbert Simon criterion of satisfying instead of a classical criterion of profit maximizing) or to apply multi-criterion approach (e.g. relatively high profit and social stability).
– Controllability of simulation experiment. Constrains on variability of parameters values are not severe in simulation approach. It is possible to assume (or to force) constant values of some parameters or values, the possibility to investigate influences of variables being out of control in real systems. In the experiments with real systems a spectrum of possible experimental results is confined by constrained set of applicable values of control parameters, in some cases it is not possible to create a situation for critical values leading, e.g., to destruction of the real system.
– Repeatability of experiments. There is possible to repeat stochastic processes just to provide enquiry of influences of essential parameters for the same series of random numbers (being representation of specific stochastic process). Naturally it is possible to investigate behaviour of the system for exactly the same initial conditions for different series of random numbers (i.e., generate different realization of enquired process). Contrary to simulation approach a number of experiments with real systems is highly limited, e.g., due to limited experimental period or limited funds for experimentation.
– A spectrum of required knowledge of mathematical apparatus and of specific experimental methods is relatively small. In most cases only elementary knowledge of mathematics is required. An important feature of simulation approach is a possibility to gain experience during the process of building and developing the model. (What does not imply that simulation is 'nice and easy'). This can be contrasted with the analytical approach where in most cases it is necessary to apply sophisticated mathematical apparatus and methods, in some cases to such high degree that 'normal' user is not able to follow considerations.
– Relatively low costs of systems enquire. It is estimated that the costs of simulation enquire is of the order of few percent of building of real system.
– Easy way to incorporate into the model personal knowledge of people engaged in everyday activity of real systems.

Disadvantages
The list of advantages of simulation approach is relatively long but also the list of disadvantages is rather long.

- Lack of generality of obtained results. Simulation results are normally valid just for the specific conditions created to make simulation. Therefore, it is necessary to be very cautious about making any universal findings and generalization. Generality of results is provided by the analytical approach where obtained results do not depend on specific experimental conditions. Analytical models allow also an easy way of changing values of interesting parameters (in most cases it is simple calculation of the value of output for new values of the model's parameters).
- To get any conclusion it is necessary to repeat experiments many times and next to calculate average values of behaviour of enquired system. Following a history of a particular element of the system is possible but rather tedious and do not provide any general findings.
- Problems with optimizations. Simulation is very good to find answers on questions like *"What happens if ...?"* but it is much more difficult to answer question like *"What is the best for ...?"* In principle it is possible to find optimal (or near optimal) solutions but it requires a lot of work, is time and funds consuming. But on the other side in most practical cases, possibilities of an effortless finding optimal solution for analytical models is an illusion. If our requirements are not so strict and we are satisfied by having relatively good solution, simulation is very helpful. Analytical models allow for relative easy way of finding optimal solution for different values of the model's parameters but we ought to remember about simplifications made during analytical models construction.
- Relatively long time is required to build, test and validate models as well as to make final simulations to draw findings.
- Misusing simulation – we put this as the last disadvantage but it seems to be one of the most important ones. If simulation is made for an outside user it is very easy to prepare very nice looking program, with a very sophisticated interface, but inside we can find frequently unacceptable methods. In such a case naturally we obtain nice looking results of little usage.

3. The place of the simulation approach in evolutionary theorizing

The expression 'evolutionary economics' is used in many and in some cases very different approaches to analysing economic phenomena. In the most general understanding, it is used to emphasize the role of change in economic processes in opposition to the economic analysis focussed on static and equilibrium properties. In a narrow sense it relates to economic analysis based on analogies and metaphors borrowed from the theories of Charles Darwin, Alfred Russell Wallace and Jean Baptiste Lamarck. The term 'evolutionary' is used in the last decades by several economic schools, namely by:

- Economists calling themselves 'neo-Schumpeterians'. A starting point for this school is the work of Joseph Alois Schumpeter. By using the term 'evolution' or 'evolutionary' they indicate the importance of long-term economic development and innovation for economic development, and the role of entrepreneur in economic process. According to this school, the evolutionary process is a dynamical, historical process in which macroeconomic characteristics are the effects of activity of economic agents observed at the micro-level. The fundamental features of economic evolutionary process are heterogeneity of behaviour. Selection and search for innovation are two basic mechanisms of development.
- The Austrian School is also called evolutionary. The work of the founders of this school, especially Carl Menger and his theory of money and other social institution formation, contains evolutionary features as, e.g., spontaneous emergence and natural selection. Friedrich von Hayek frequently use 'evolutionary' to characterize his approach (particularly in his later books on spontaneity of development (e.g. *Fatal Conceit*).
- Institutionalist theory, initiated by the work of Thorstein Veblen, is also called 'evolutionary' (or 'post-Darwinian' economics, as Veblen sometime called it). Followers of Veblen and John Commons also use the adjective 'evolutionary' but frequently this term means for them the same as 'institutional', and they use both terms interchangeably.

Tradition of three main contemporary economic schools, namely the Austrian School, neo-Schumpeterians, and institutionalists is presented in very schematic way in Figure 7. Arrows indicate the main influences of different authors and researchers. A more detailed description of those influences and different views of evolutionary economics is presented in Kwaśnicki (1996) (see also Hodgson, 1993). Modern evolutionary economics has its roots in biology (Darwin, Wallace and Lamarck) as well as in the classical school of Smith, Hume and Ferguson. It is necessary to emphasis the influence of social sciences on the emergence of Darwin and Wallace's theory of biological evolution, based on the hypotheses of natural selection (what is indicated by arrows from Smith, Hume, Ferguson, and Malthus, Babbage and Jones).

After the first attempt to define an evolutionary approach in economic analysis at the end of the nineteenth century and the beginning of the twentieth, further progress was essentially slowed down. There are a few reasons for the chuck to further development of the idea of 'biological economics' in the first decades of the 20th century. Biological evolution was still a young science. Although Darwin's ideas significantly influenced the work of social researchers, these influences were visible at the level of concepts, not at the level of formal, mathemati-

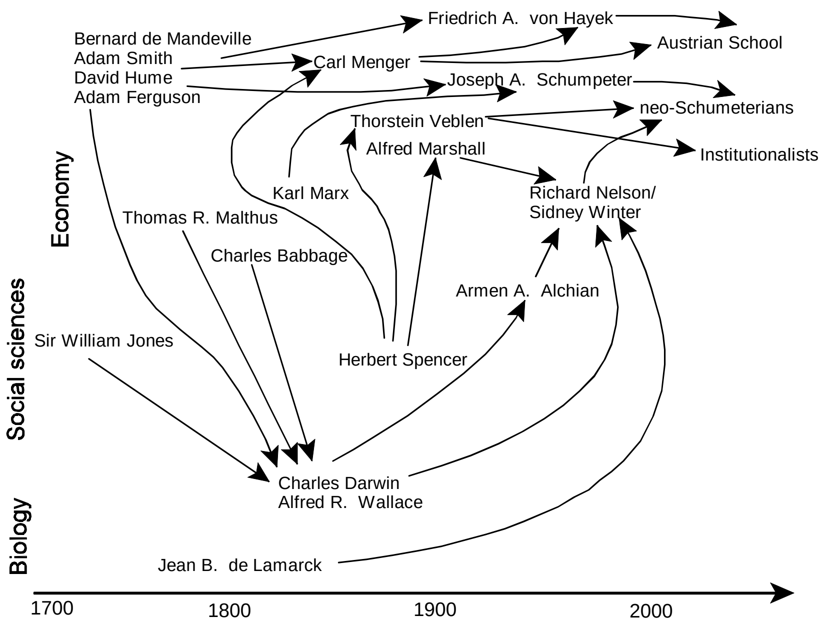


Figure 7. Roots of evolutionary economics.

cal models of socio-economic phenomena. Research was focussed on qualitative description and classification problems. Almost no progress was done in quantitative approaches which would allow the construction of mathematical models. In such circumstances application of well-known and reliable mathematical tools borrowed from Newtonian mechanics, tools developed and applied for decades by physicists, was much easier and more fertile. One of the popular themes of that period was competition as the basic force controlling economic processes. Competition was treated as a force analogous to Newtonian gravitation, allowing to reach equilibrium, but not as a selective force, in the Darwinian sense. All these economic considerations missed almost completely the problems of technological change. Diversity of products and processes, diversity observed in everyday economic life, is caused by technological change. Up to the 1950s all considerations of economic process in terms of an evolutionary perspective were confined to a verbal description. Neoclassical models have an elegant, mathematically aesthetical form and this feature has led to their popularity and wide acceptance within the economic profession. Most of these models were linear ones, mainly because of their relatively easy analytical tractability. Evolutionary models, to capture the essence of the evolutionary approach, ought to be nonlinear ones – this very requirement has not allowed for their analytical treatment. Thanks to the development of computer technology during the 1950s and 1960s it was possible to build and to analyse behaviour of evolutionary models.

Evolutionary economics is still at the initial phase of its development. The evolutionary paradigm in economic analysis is far from a mature formulation, but development of evolutionary economics in the last decades allows us to conclude that the description of economic process and behaviour of economic agents at the micro- level, as provided by researchers working within evolutionary paradigms, is far more complete and closer to reality then the description proposed by orthodox economists. But there is still no satisfactory evolutionary description of macroeconomic processes. There is general lack of evolutionary models describing the development of national or global economies. The first attempts based on the bottom-up approach lead to large-scale models of national or multinational economies. Therefore these models are very difficult to follow and there are problems with a full understanding what is going on in them. The advantage of neoclassical models is that the macroeconomic models exist, although highly aggregated and with very unrealistic assumptions but they are relatively easy to use and to understand their structures.

Further development of evolutionary economics requires efficient and very specific tools of formal analysis. As Kenneth Boulding (1991) writes: “one of the great opportunities ... for the next few decades is the development of a mathematics which is suitable to social systems, which the sort of 18th-century mathematics which we mostly use is not. The world is topological rather than numerical. We need non-Cartesian algebra as we need non-Euclidean geometry, where minus minus is not always plus, and where the bottom line is often an illusion. So there is a great deal to be done”. The simulation approach, mostly used in the analysis of nonlinear, evolutionary models in economic analysis, seems to be very useful but it still does not completely fulfill the requirements for it to be considered as a fully appropriate tool of formal analysis. (See the discussion in the following section).

Using the evolutionary approach to analyse socio-economic processes has many advantages over the orthodox, mechanistic approach, e.g., contrary to the orthodox view, the problem of irreversibility (’time arrow’) lies in the centre of interest of evolutionary economists. In contrast to the neoclassical approach, evolutionary economics focuses on a dynamic view of economic processes. Transitional stages and processes in far-from-equilibrium states are considered to be much more interesting and closer to reality. But the evolutionary approach also allows us to investigate economic processes at the equilibrium state and to compare results with those of the neoclassical approach. In most cases, evolutionary economics confirms well-known findings of neoclassical analysis. Qualitative as well as quantitative changes are also placed within the frame of interest of evolutionary economics.

An important criterion used by researchers in preferring one or another approach is the potential for further development. It seems that the neoclassical paradigm has reached the limits of its development, whereas the evolutionary paradigm, although as old as the neoclassical one, and developing much slower in the last 100 years, still has wide possibilities for further development.

The computer simulation approach may be considered as one such alternative way to develop an apparatus of economic analysis.[3] Discontinuities of development are natural phenomena observed in socio-economic processes, and in a sense, these discontinuities form the essence of socio-economic systems. In principle difference equations are applicable in economic analysis when we assume continuity of changes. But the differential calculus breaks down if one tries to apply it to describe discontinuities of development. The search for alternative approaches of economic analysis goes in different directions, for example, applications of chaos theory, fuzzy sets theory, catastrophe theory and game theory, to name only a few. Proper application of the simulation approach in economic analysis seems to be one of the most promising for further development and better understanding of socio-economic processes. Jay W. Forrester (1971) in his classical paper says about "counterintuitive behavior of social systems". Evolutionary vision of economic process in general and simulation enquiry of socio-economic system in particular, certainly are helpful in proper understanding of that 'counterintuitive behaviour'.

Three distinct evolutionary schools, namely Austrian, institutionalists and neo-Schumpeterians have been mentioned earlier. Out of these three schools only neo-Schumpeterians widely apply formal modelling and the simulation approach to economic analysis. Institutionalists and the Austrians prefer verbal and graphical representations of economic phenomena. Therefore it is not surprise that some institutionalist call neo-Schumpeterians 'simulationists'.

4. Variety of approaches to the simulation of economic development

The spectrum of simulation models within evolutionary framework in economics is wide and it is not possible to describe all of them in a short paper. In this section we will present only the most representative ones. We will not separate micro and macro models but will focus on simulation specificity of evolutionary models. Looking at the spectrum of all evolutionary models in economics we can distinguish two main streams of development. The first one relates to the work of Schumpeter and the second is based on the concept of cellular automata, within

[3]The application of computer simulations may be misused; it is very easy to make a simulation model so complicated that nobody except the builder of the model is able to comprehend and use it in research. A new formal apparatus should be very carefully designed and should be a rational combination of old mathematics developed in physics and a pure simulation approach, frequently based on a far-reaching analogy of real mechanisms of development and the model.

a general framework of artificial life and Agent-based Computational Economics (ACE).

4.1. SCHUMPETERIAN TRADITION

We will start description of Schumpeterian models from the work of Nelson and Winter.[4] Nelson and Winter (NW) models were worked out in 1970s and 1980s and presented in their 1982 book (Nelson, Winter, 1982). Nelson and Winter models suit frequently as a base or a kind of pattern for invention another evolutionary models. In NW model and in almost all models of Schumpeterian tradition firm is a basic unit of evolution. Contrary to orthodox economics, concept of a representative agent is no present in evolutionary models. Usually the economy is disaggregated into diverse individual firms influencing each other by nonlinear dynamic interactions describing search for innovation, competition (selection) and investment. In most simulation models agents use boundedly rational behavioural procedures. Learning and searching for innovation is modelled by allowing for mutation and imitation rules operating on the firms' operational parameters. Mutations are usually local within the routine space. Nelson and Winter apply a population perspective and they postulate that it is possible to specify the space in which innovative search takes place.

The assumption of macroeconomic properties flowing from microeconomic behaviour of economic agents (i.e. firms) is basic reason for necessity of using simulation to investigate these models. The first model that will be discussed is the one presented in Nelson and Winter (1982, ch. 9). This model can be seen as the first evolutionary growth model.

The state of the evolutionary process of an industry at any moment t is described by the capital stock and the behavioural rules of each firm. The state in the next moment $t+1$ is determined by the state in a previous moment. In this growth model firms use production techniques which are characterized by fixed labour and capital coefficients. Firms manufacture homogeneous products, so the model describes only process innovation. It is assumed that firms produce using a Leontief production function, therefore substitution between labour and capital is not present in the model. Invention occurs as a result of firms' search activities. Firms search for new combinations of a labour and capital coefficient. Changes of these both coefficient are not correlated therefore a phenomenon that resembles substitution between labour and capital may be observed in the simulated process. Search activities are determined by satisfycing behaviour, in a sense that a new

[4] The Nelson-Winter model has been programmed by many authors. Let me mention only two implementations available through the Internet. One was done within the DRUIDIC (Dynamic Reconstruction of Unfolding Industrial Diversity by Interactive Computing) project. The NW models programmed in Maple V can be found on Esben Sloth Andersen homepage (http://www.business.auc.dk/evolution/esa/). Murat Yildizoglu programmed the NW models in Java (http://cournot.u-strasbg.fr/yildi/NelWin.html).

technique is adopted only if the expected rate of return is higher than the firm's present rate of return. The search process may take two different forms: local search (mutation) or imitation. In the first case, firms search for new techniques, yet not present in the industrial practice. The term local search indicates that each undiscovered technique has a probability of being discovered which linearly declines with a suitably defined technological distance from the current technology. Imitation allows the firm to find techniques currently employed by other firms but not yet used in its own production process. The probability of given technique imitation is proportional to the share in output of that technique. It is assumed that if a firm engages in search it can use only one type of the search. Selection of actually used type of search is a random event with a fixed probability for each type. An additional source of novelty in the economy is entry by new firms which also search for innovation. A potential entrant enters the industry if it discovers a production technique which promises a rate of return more than 16% but it has still 0.25 probability that it actually enters the market. A value for initial capital stock of entering firm is drawn randomly.

The rate of return on techniques is the main selection force in the NW model. A firm's investment in capital is equal to its profit diminished by a fixed fraction which depends on payed dividends and capital depreciation. A firm's capital stock shrinks if profit of that firm is negative. Therefore we have second selection force which imposes withdrawing firms from the market if they do not pace of technological progress of its competitors.

To calibrate the above sketched model for the case of the Solow data on total factor productivity for the United States in the first half of the twentieth century it was assumed that firms produce a homogenous product named GNP. Using that model, Nelson and Winter address the question whether these time series of the calibrated model correspond in a broad qualitative sense to the ones actually observed by Solow.

The most developed and documented NW model which deals with the evolution of the production techniques and other behavioural rules of an industry producing a homogeneous product is frequently named as "Schumpeterian competition" (Nelson, Winter,1982, ch. 12; Winter, 1984). As in the formerly sketched model, a number of firms produce a single homogenous product. Techniques used by different firms differ in output per unit of capital, i.e. in capital productivity A. All other technique factors, as, e.g. return to scale and input coefficient are assumed to be equal for all firms. Technical change (increase of the productivity of capital) takes the form of process innovations and process imitations. Each firm chooses a technique with the highest productivity out of the three possible techniques (i.e. currently used and found through innovative and imitative processes). Probability that firms innovate or imitate depends on R&D funds determined in proportion to the level of physical capital (respectively r_{in} , r_{im}). Profit per unit of capital is calculated by including R&D costs as ordinary cost elements.

The maximum investment of a firm depends on current profit plus loans from the banks (calculated in proportion to the profit). The firm's desired investment is determined by the unit costs, a mark- up factor influenced by the market share of the firm, and the rate of depreciation. The investment process has no time-lags. By multiplying the capital stock with the new level of productivity, we have the production capacity of the firms of the industry in next period. Products price is not firm specific but is equal to all firms and flows from the downward-sloping demand function to balance supply and demand.

Winter (1984) presents an interesting elaboration of search activity and entry. Firms are partitioned into two types: primarily innovative or imitative. It allows Winter to apply a notion of technological regime depending on whether the source of technical progress is external to the firm (e.g., from public scientific knowledge bases) or from firms' own accumulated technological capabilities. These two regimes are named as the entrepreneurial and the routinized. Specific parameters exogenously impose the type of investigated regime.

Because of stochastic factors related to the process of innovation-imitation search for innovation and nonlinearities of the production-investment equations it is not possible to find analytical solutions of NW models. It is also not possible to find stochastic characteristics of these process, as, e.g., average and standard deviation of firms production. The only way to investigate these models is to use computer simulation techniques of random numbers generation and get estimated values of general stochastic characteristics, or observe peculiarities of any single realization of the industrial process.

Silverberg-Verspagen models One distinguished feature of SV models is that technological progress is embedded in vintage capital. In the model presented in Silverberg (1985) firms are self-financing using their cash and liquid interest bearing reserves. An investments plan of each firm is based on its financial strength. A firm's investment ability governs the realization of the plan, i.e., if it is realized partly or in a whole primary in the best available technology. Concurrently to the investment process the oldest vintage is continuously scrapped. Textbooks' notions of ”demand' and ”supply” are not present in the model. Instead of it firms' behaviour is placed in more realistic spaces of orders, order backlog, delivery delay, rate of capacity utilization, shipment, etc. The current level of production is constrained by a firm's maximum capacity and the production of each firm depends on prime unit labour cost (i.e., an average over all capital vintages).

Market share equation, which form fundamental mathematical description of competitive process, is formally identical to the equation first introduced into mathematical biology by R.A. Fisher in 1930 and in last decades is used in a variety of context by Eigen, Schuster, Ebeling, Feistel, and others. The equation differs from most biological applications “in that the competitiveness parameters rather being constant or simple functions of other variables, themselves change over time in complex ways in response to the strategies pursued by firms and feedbacks from the rest of the system”. The competitiveness is a linear combination of logarithms of price and delivery delay. Silverberg proposes specific pricing policy which describes a compromise between strict cost-plus pricing (markup rule) and competitive advantage of a firm (the price increases if the competitiveness is higher then average competitiveness and is reduced otherwise). This represents a compromise between short and long term profitability targets.

Experience acquired by individual firm during its development can “leak” out and became available to the rest of the industry. Logistic equation describes learning dynamics and through that way internal skill level of each firm evolves.

From some point of view the model describes the process of diffusion of new technology in the case in which a best practice technology is apparent to all agents. Standard methods of investment policy guarantee diffusion of technical progress within the industry.

Silverberg model is a set of differential equations with discredited representation of vintage capital in the computer implementation. It is highly nonlinear model. Nonlinearity is present in almost all differential equations. The replication equation of Fisher mode is itself nonlinear but also its parameters (i.e. competitiveness) are function of price and delivery delay, which changes in turn are governed by a set of difference equations. The only way to investigate properties of this model is making numerical simulation on the computer.

Similar idea that firms rely on rather simple rules of thumb or routines rather than explicit optimization procedures is applied in models developed by Silverberg, Lehnert and Verspagen (Silverberg and Lehnert, 1993), Silverberg, Verspagen, 1994, 1995). These models can be seen as continuation of the work initiated by Silverberg in 1980s. In this series of models firms undertake behavioural *imitation* with increasing probability the more unsatisfactory their performance is. Contrary to the former model worked by Silverberg, in the later models stochastic elements are present, namely those related to innovation emergence. The main difference between the Silverberg and Verspagen (1995) model and the ones presented in Silverberg (1985) and Silverberg and Lehnert (1993) is the way in which innovation is endogenized. It is assumed that in each time period, firms devote resources (R&D) to the systematic search for new production possibilities (i.e., new types of capital).

Firms must determine how much to spend on R&D in relation to either their profits or their sales. Technical change comes about as a result of the profit-seeking activities of each firm. Therefore, as in almost all evolutionary models growth is endogenized. Such important feature of modern industrial development as increasing returns, spillovers and other phenomena known from the economics of innovation are also included in some of these models. A decision problem is considered in the context of *bounded rationality* – firms (decision makers) have only vague ideas about final consequences of their actions.

The models are constructed around three basic blocks. The first block consists of equations for the rate of capital accumulation, the diffusion of new technologies in the total capital stock of the firms, and the real wage rate. The equations describe how economy evolves with a given set of technologies. Selection takes place either at levels of firms and technologies. The second block describes how new technologies and firms are introduced into the economy. The last block describes the way of influence of the evolving economy and firm learning on the firms' innovative behaviour. Collective learning phenomena are present in this block.

Each firm has a variable number of different types of capital goods utilized in production. Profit is the only source of capital accumulation. An innovation rate depends on R&D funds which consist of firm-specific portions of profit and sales. Profits gained from different vintages of capital may be redistributed in such a way that more profitable types of capital accumulate even faster and less profitable even slower, than would otherwise be the case.

Basic equations of firms' dynamics describe the share of the labour force employed on each capital stock. Production is assumed to be always equal to production capacity. It is assumed that the ratio between R&D expenditures and R&D labour input is equal to a fraction of the economy- wide labour productivity.

The wage rate is determined by the differential equation following the idea of Phillips curve. Assumed Phillips curve ensures that real wages tend to track labour productivity in the long run. The employment share equation describes how more profitable technologies (in terms of their labour productivity) tend to increase their employment share, concurrently, backward technologies tend to vanish. The wage rate equation and the employment share equation form a selection mechanism in the described economy. New technologies are continuously introduced, that implies that all technologies, after an initial phase of market penetration, will be eventually superseded from the production system. New type of capital (vintage) is created each time an innovation occurs. Because of fixed labour productivity and increasing of real wages over time it happens that at some stage of development every technology generates negative profits. It is assumed that these losses are financed by an equivalent decrease of the capital stock. It means that losses imply capital scrapping to cover the losses.

Entry of a new firm occurs only as a result of competition and compelling a firm to exit. An exit occurs whenever a firm's employment share falls below assumed threshold value. Therefore exit of incumbent firms is completely endogenous and entry only occurs in case of the exit, so that the total number of firms is constant.

It can be said that the model describers closed economy with innovating firms, generating technical change through specific learning mechanisms based on two genetic operators, namely mutation and imitation. It is also assumed that the more profitable a firm is, the less likely it will change its strategy by imitating another firm. If a firm has decided to imitate, the probability of selection another firm to imitate is proportional to its market share in output. If neither imitation nor mutation occurs, the firm simply retains its strategy from the previous period.

Dosi et al. models An interrelationship of large number of competing firms, large number of vintage capital of each firm, nonlinearities and stochastic factors presented in the SV models cause analytical tractability impossibly. Therefore, the only way to deal with the models is computer simulation. The same can be said about a number of models developed by Giovanni Dosi and his collaborators, e.g., Chiaromonte and Dosi (1993), Dosi *et al.* (1994), Dosi *et al.* (1993).

An example of the family of these models is the model aimed to explain classical phenomena of skewness of firms' size distribution from an evolutionary point of view (Dosi *et al.*, 1993). They assume that an 'industry' is composed of several 'sectors', each corresponding to particular technological and market regimes. Each 'sector' is composed of 'micro sectors' (i.e., groups of relatively homogenous products or technologies). Each firm is characterized by its age, size, and competitiveness. A firm's size and its competitiveness depend on learning. The dynamic of the markets to which the firm belongs influences also the firm's size. Competitiveness is positive real number which reflects the technological and organizational capabilities of each firm. Through learning firms are able to increase its competitiveness. Selection equations are of the Fisher type replication equations.

In the Chiaromonte and Dosi (1993) model, a firm is characterized by a single labour coefficient. The pricing strategy is based upon firm-specific demand expectations. Two important features characterize each firm, namely its technological capability (what is made in the form of input coefficients), and economic strategies, which determines how much resources the firm invests in the search for new technologies and what is products' price.

The search process takes place in a two-dimensional space of 'technological paradigms' and labour coefficients. Firms either produce 'machines' (each of which is characterized by a set of coordinates in the two-dimensional plane), or they produce consumption goods (to which they need machines as inputs). Therefore, we can speak about two-sector economy. The innovation process differs between the two sectors in the economy. In the first sector (producing capital goods) the success of innovation is determined by the number of R&D workers. For given innovation, the new capital good's productivity is drawn randomly. In the consumption goods sector, firms possess a skill level for each available capital good type. Learning process contributes to increasing skill level. This learning process has both public and private features. Correctness of firms prediction of their skill level is limited. Actual labour productivity is a function of the capital good's characteristics and the firm's skill level. Selection of capital good potentially employed by a firm from a consumption sector is based on maximization 'utility' function involving labour productivity, prices, and the order backlog. Competitiveness of a firm depends on products prices and unfulfilled demand in the previous period (the backlog of orders).

Similarly in (Dosi *et al.*, 1994) model a firm is characterized by a single labour coefficient but the search space is more similar to the one in the Nelson and Winter model. The probability of an innovation depends on R&D employment. Competitiveness is a function of price and exchange rates. Through that way technological competence (labour productivity), wages, pricing rules contribute to competitiveness formation. The market shares (the replication equation) are translated into actual production levels by considering the size of the aggregate market, which is endogenous to the model. The total size of the market is the minimum of aggregate demand and supply.

Dosi *et al.* approach is highly bottom-up simulation. The aim of the authors seems to be to start from basic mechanisms of industrial development without making any assumption about possible modelled properties of the system and to obtain the well-known properties (stylized facts) from the co-working of these basic mechanisms of development. Similar assumption was made by Kwaśnicki in his model of industrial dynamics (Kwaśnicka, Kwaśnicki, 1992, Kwaśnicki, 1994/1996).

Kwaśnicki's model This model describes the behaviour of a number of competing firms producing functionally equivalent, but not homogeneous, products. One of the distinguished features of the model is the coupling of technological development and economic processes. A firm is characterized by a set of routines applied by the firm. In order to improve its position in the industry and in the market, each firm searches for new routines and new combinations of routines (innovation) to reduce the unit costs of production, increase the productivity of capital, and improve the competitiveness of its products in the market. Each firm may simultaneously produce products with different prices and different values of the characteristics, i.e., the firm may be a multi-unit operation. Different units of the same firm manufacture products by employing different sets of routines.

Simulation of industry development is done in discrete time in four steps:

(1) Search for innovation (i.e., search for new sets of routines which potentially may replace the old set currently employed by a firm).

(2) Firms' decision making process (calculation and comparison of investment, production, net income, profit, and some other characteristics of development which may be attained by employing the old and the new sets of routines. Decisions of each firm on: (a) continuation of production by employing old routines or modernizing production, and (b) opening (or not) of new units).

(3) Entry of new firms.

(4) Selling process (market evaluation (selection) of the offered pool of products; calculation of firms' characteristics: production sold, shares in global production and global sales, total profits, profit rates, research funds, etc.).

Technological change is endogenized and the probability of finding an innovation (a new set of routines) depends on the R&D funds allocated to in-house research ('mutation') and imitation. There are two types of routines: *active,* that is, routines employed by the firm in its everyday practice, and *latent*, that is, routines which are stored by the firm but not actually applied. Latent routines may be included in the active set of routines at a future time. The set of routines employed by a firm may evolve. There are four basic mechanisms for generating new sets of routines, namely: *mutation, recombination, transition and transposition.*

On the basis of its expectations of future market development and expected decisions of its competitors, each firm decides on the price of its products, investment and the quantity of production which it expects to sell on the market. Inclusion of the element of expectations in the decision making process makes it boundedly rational. Current investment capability and the possibility of borrowing are also considered by each firm. In establishing the product price and future level of production firms take into account short term elements (profit increasing) and long term elements (to be present on the market as long as possible).

The productivity of capital, variable costs of production and product characteristics are the functions of routines employed by a firm. Each routine has multiple, pleiotropic effects, that is, it may affect many characteristics of products, as well as productivity, and the variable costs of production. Similarly, the productivity of capital, unit costs of production and each characteristic of the product can be function of a number of routines (polygeneity).

Attractiveness (competitiveness) of the product on the market depends on the values of the product characteristics and its price (products with better products characteristics and lower price are preferred by consumers). The selection equation of the competition process describes changes of the firms' shares in global output. The share of firm i increases if the competitiveness of its products is higher than the average of all products present on the market, and decreases if the competitiveness is lower than the average.

The model is rooted in the tradition established by Nelson and Winter. The main similarities to the NW model lay in the concept of routines and endogenized innovations. Important departure of this model from the NW model consists of a more realistic concept of innovation covering product and process innovations, diversity of price (there is no uniform price for all firms but firms individually decide about the price), inclusion in the decision making module the concept of agent expectation (of future market behaviour and decisions of other competitors).

Other models Winter, Kaniovski, and Dosi (1997) write that their model is a "baseline not merely in the sense of a standard for comparison, but also as a starting point for future work". Experiences of different researchers engaged in building evolutionary models in the last decades are taken into account in the WKD model. As the authors state, to bring the model into reasonable correspondence with reality some of the model's assumptions will require elaboration and modification. But surely many of the results developed in the WKD model will have heuristic value and direct application in the work of other researchers. The findings of several streams of empirical research are clearly visible in the models construction. To name only few of them: the diversity of firms and the sense of continuing, highly dynamic, disequilibrium; skewed firm size distribution; entry and exit rates at a point in time are highly correlated across industries so that industries with higher than average entry rates tend also to have higher than average exit rates; the market share of each entering cohort successively declines. Therefore it is highly justified to say that the model explores some generic properties of the processes of industrial evolution, highlighted in economic literature.

In the most general term the model encompasses a stochastic system driven by the persistent random arrival of new firms and a systematic selection process linking investments to realized profitabilities. Analytical investigation of the model's properties is presented in the paper but because of limitations of an analytical possibility this investigation is followed by a computer simulation study, showing among other things the dynamics in the number, size and age of firms.

Andersen (1997) presents a model based on Pasinetti's scheme of the structural economic dynamics of a labour economy with inclusion of an evolutionary, micro-economic foundation. The model describes the evolution of an economic system with a varying number of sectors, each of which is producing a different consumption good. The essence of this model is the assumption that consumers have a hierarchy of goods, and they consume a higher-order good when they are fully provided with the lower-order goods. Labour and knowledge are basic production factors. Innovative process allows firms to increase their productivity with respect to individual goods. Therefore, in the long-term perspective labour becomes available for the production of new consumption goods. The hierarchy of goods and the assumption about sequential fulfilment causes the emergence of "technological unemployment, which emerges if goods are not provided to a sufficient degree". Slow productivity development in the production of new goods leads to a slowdown in the overall rate of growth, and it can occur irrespectively of productivity growth in old sectors. To raise long-term growth the concept of "anticipatory R&D" is introduced.

A micro-based simulation model of national economy which integrates micro activities was developed by Gunnar Eliasson (Eliasson, 1985, 1989). The project of micro-to-macro model was initiated in 1975 and was calibrated to describe the development of the Swedish economy. Firms and household are the basic units of the model. It is not a fully evolutionary model, but contains some evolutionary features and Schumpeterian innovative behaviour. Technical change is introduced at the firm level through new investment. The decisions of firms' managers are mathematically modelled by a search process for proper decisions based on a trail and error procedure. To be closer to reality the principle of 'maintain or improve profit' (MIP) is included in the submodel describing the behaviour of a firm. Long-term investment decisions and short term production search are also included in the submodel of a firms behaviour. Long-term economic development primarily depends on the capital market. Investment and growth of potential capacity at the micro level are driven by the difference between the perceived rate of return of the firm and the interest rate.

Another approach to describe innovation processes is proposed by Bruckner, Ebeling, Jimenez Monta o and Scharnhorst (1993). They start from observation of physicists that "relationship between micro- and macro-level descriptions become important and led to questions of fundamental relevance" and that "relatively independent of the nature of the subsystems mainly the manner of their coordination is important for the demonstration of the well-known macroscopic phenomena of spontaneous structure formation." The authors apply general n- dimensional birth-death transition model to describe technological development. It is assumed that firms contain different plants using different technologies. In a general term, the system is described by a number of fields (which in a case of technological process are production units used by different firms applying specific technology i. Elementary process of self-reproduction, spontaneous generation, self amplification (i.e. non-linear self-reproduction), sponsoring, error reproduction, cooperative and non-cooperative exchange, spontaneous decline and self-inhibition are a base theoretical concept of the model. Development of the system is described by a Master Equation system defining probability distribution of technologies.

4.2. AGENT-BASED COMPUTATIONAL ECONOMICS

Artificial life (a-life) is the name of flourishing, multidisciplinary field of research that attempts to develop mathematical models and use computer simulations to demonstrate ways in which living organisms grow and evolve. It is hoped that through this way deeper insights into the nature of organic life will be gained together with better understanding of origin metabolic processes and in a wider sense of the origin of life. A-life will stimulate new approaches in computer science (especially artificial intelligence) and robotics. The term artificial life was coined in the 1980s by Christopher Langton who organized the first a-life workshop at Santa Fe in 1987. But it does not mean that similar studies, under different names, had not been done before the1980s. William Shakespeare wrote: "What's in a name? that which we call a rose; By any other name would smell as sweet". In fact two men have made very similar theoretical research under the name of self-replicating (or cellular) automata. John von Neumann, the Hungarian-born mathematician and a pioneer of computer science, and the Polish mathematician Stanislaw Ulam in the early 1950s had begun to explore the nature of very basic theoretical forms called self-replicating, cellular automata. Their intention was to apply this basic concept to the growth, development, and reproduction of living creatures. These theoretical, mathematical ’cells’ can be used to simulate biological and physical processes by repetitively subjecting each cell to a simple set of rules, e.g., every cell has a colour that changes according to its update rules and the colours of its neighbouring cells. Von Neumann and Ulam proved that, using a rather complex set of rules, it is possible to draw an initial configuration of cells in such a way that the configuration would ’reproduce’ itself. These cellular automata consist of a lattice of cells. Each cell is characterized by specific values which can change according to fixed rules. A cell’s new value is calculated on the basis of its current value and the values of its immediate neighbours. It is shown that such cellular automata naturally form patterns, reproduce and ’die’.

Langton used the work of von Neumann as a starting point to design a simple a-life system that could be simulated on a computer. In 1979 he developed an ’organism’ that displayed many lifelike properties. The loop-shaped ’creature’ reproduced itself in such a way that as new generations spread outward from the initial organism they left ”dead” generations inside the expanding area. In the opinion of Langton the behaviour of these forms mimicked the real-life processes of mutation and evolution.

Economist Thomas Schelling was one of the researchers who in the 1970s tried to apply a-life techniques to social science. In fact he did not use a computer but pennies and dimes that he moved around a checker board according to simple rules. In this way he created an artificial world in which he showed, among other findings, how even slight preferences for living and working with one’s own kind can result in extreme segregation.

There are numerous examples of agent based-modelling, some of them are presented in this book. Biologist Tom Ray created ’agent’ programs in his laptop. The aim of each agent was to make a copy of itself in memory. Ray assumed a finite lifetime of each program. He left the programs running all night and in the morning he noticed that his agents were engaging in the digital equivalents of competition, fraud and sex. When the program-agents copied themselves random changes of their code occurred. So it can be said that they mutated and evolved. Naturally most mutations were destructive and ’died’, but some changes let an agent do its job better in a sense that they consisted of fewer instructions and were able to copy themselves quicker, more reliably and run faster. The shorter versions replicated quicker and very soon outnumbered their larger ’competitors’.

The a-life approach is sometime called ’agent-based modelling’ to pinpoint its mathematical difference from the to differential equations approach. We can write down the differential equations for interacting population of individuals (e.g. Lotka Volterra equation of prey-predator system) but we can also follow individual histories of each animal (element, agent) and summarize their histories into more aggregative characteristics. These two approaches are essentially different but it is difficult to decide which is more important. Contemporary a-life researchers try to identify the distinctive behaviours of living creatures and then use them to devise software simulations that 'move, eat, mate, fight and cooperate' without incorporating those features explicitly into the modes of behaviour of these elements. Most a-life creatures consist of nothing more than a few lines of program code and live on landscapes made of pixels and data sets. The receipe to prepare a-life software (or 'silicon' species, as it is sometime called) is rather simple: prepare an environment in which the synthetic organisms can act, create a few hundred individuals to populate it and define a set of rules for them to follow. Try to simplify the problem as much as possible while keeping what is essential. Write a program which simulates the simple rules with interactions and randomizing elements. Run the program many times with different random number seeds to attempt to understand how the simple rules give rise to the observed behaviour. Locate the sources of behaviour and the effects of different parameters. Simplify the simulation even further if possible, or add additional elements that were found to be necessary. We can summarize this approach in following 'equation': *Agents (microlevel entities) + Environment+ Dynamics = A-Life.*[5]

In this approach, life is treated as a kind of game in which each agent struggles for existence with the mixture of chance and necessity by applying a set of basic behavioural rules. A small number of rules can generate amazingly complex patterns of behaviour, such as groups of independent agents organizing themselves into a semi-isolated groups of agents. This feature makes the a-life approach a potentially powerful research tool.

Current efforts of a-life researchers are focussed on searching for so-called emergent hierarchical organization (EHO). The aim of this kind of modelling is to discover whether, and under what conditions, recorded computer-simulated histories exhibit interesting *emergent properties*. The term 'emergent properties' means that they arise spontaneously from the dynamics of the system, rather than being imposed by some external authority. Observed order, like specific evolution of an industry with its initial, mature and declining phases, emerges from the aggregate of large number of individuals acting alone and independently.[6]

A similar approach has been applied in economic analysis, called either *artificial economics* or *agent-based economics*. The intention is very similar to that of a-life: allow for economic interactions between artificial agents initially having no knowledge of their environment but with abilities to learn, and next observe what sorts of markets, institutions and technologies develop, and how the agents coordinate their actions and organize themselves into an economy. One example of such an approach is the work of Marimon, McGrattan, and Sargent (1990), who

[5]We ought to apply the above receipt very consciously, responsible and scrupulously. Albert Einstein has advised that: “The best explanation is as simple as possible, but no simpler.” Similarly another great thinker, Alfred North Whitehead instructed: “Seek simplicity ... and then distrust it!”.

[6]The same theoretical vision of development can be found in the liberal political tradition. In modern times the best representative of this tradition is Friedrich Hayek, who for decades insisted on the importance of spontaneous order and the role it played in the emergence of some essential features of social systems.

show how trade and money emerge. Santa Fe Institute team (Brian Arthur, John Holland, Richard Palmer and Paul Taylor) is working on modelling artificial stock markets (Taylor, 1995).

Sugerscape One interesting application of ACE is Epstein and Axtell's Sugerscape simulation. Their model represents a natural, bottom-up approach to behavioural patterns which emerge out of the interactions of individuals. They summarized their models and presented simulation results in Epstein, Axtell (1996). Their work on 'Growing Artificial Societies' is a part of the 2050 Project, a collaborative effort of Brookings, Santa Fe Institute, and World Resources Institute. The main aim of this project is to identify conditions for sustainable development on a worldwide scale.

The basic assumptions of the Sugerscape model are rather simple. The authors create a grid of 50 by 50 squares. Each square contains from zero to four units of "sugar". The grid is inhabited by a few hundred creatures represented by dots. The creatures (agents) live on sugar (and nothing else), consuming from one to three units per iteration. Every agent is born into this world with a metabolism demanding sugar, and each has a number of other attributes, such as a visual range for food detection, that vary across the population. These creatures can see from two to four squares in all directions, and they can move as far as they can see. On a computer screen agents are coloured dots occupying some fraction of the squares. The sugar is shown as mounds of yellow that disappear as the dots eat them but that grow back when left alone.

Each 'year' the creatures are considered in random order, and when its turn comes they move from square to square according to a simple rule: look around as far as your vision permits, find the unoccupied site richest in sugar, go there, and eat the sugar. As it is consumed, the sugar grows back at predetermined rate. Every time an agent moves, it burns an amount of sugar determined by its given metabolic rate. Agents die when they fail to gather enough sugar to fuel their activities. We can image that agents' movement brings them into contact with other agents, with whom they interact. There are rules governing sex, combat, trade, disease transmission, cultural exchange, inheritance, etc. At any time, the interacting agents differ in their age, culture, wealth, vision, economic tastes, immunocompetence, and so forth. Unlike standard aggregate, or 'representative agent', models, artificial societies are heterogeneous and full of diversity.

Sugar ought to be replaced and the replacement can be either full (four unit squares are instantly restored to four units, etc.) or partial, such as one unit per year up to the square's starting level. Those simple rules cause the emergence of rather complex behaviours. As we can expect, the creatures with long vision and low metabolism do the best. The number of creatures is kept constant: if one dies, it is replaced by another with random metabolism and vision.

By adding to the agent's characteristics an additional string of a few bits specifying gender, sex and reproduction can be introduced. To evolve an agent must select a neighbouring agent at random. If the neighbour is of the opposite sex and of reproductive age, and if one of the two agents has an empty neighbouring site (to hold offspring), a child is born. The child inherits a mixture of its parents' genetic attributes. It is possible to add sexes with mating and inheritance (i.e., the computer equivalent of chromosomes and genes) as well as such characteristics as age (and life span), cultures and education.

The Sugerscape can be a multi-peak landscape. If there are two mountains (as in most simulations) initially randomly distributed agents quickly gravitate toward the two sugar mountains. A few individuals can accumulate large stocks of sugar, building up a great deal of personal wealth. They are agents with superior vision and a low metabolic rate and have lived a long time. Agents combining short vision with a low metabolic rate, manage to subsist at the fringes, gathering just enough to survive in the sugar badlands but not looking far enough to see the much larger sugar stocks available just beyond the horizon.

Interestingly, even this rudimentary model reproduces the kind of strongly skewed distribution of wealth generally observed in human societies – where a few individuals hold most of the wealth and the bulk of the population lives in relative poverty.

In one of series of a experiments, the question concerning of the distribution of accumulated sugar after an agent's death is pursued. One possibility is to pass this sugar to the agent's offspring. How does this cultural convention influence evolution? The Sugerscape model suggests that agents who might otherwise have been eliminated are given an extra advantage through inheritance. The average vision of the population doesn't increase to the same high level eventually reached in a population where no wealth is passed on.

It is also possible to add combat. One rule might be that the creature with the most sugar wins and takes the loser's supplies. Each playing piece has a particular pattern of allowed movements, and the game's rules shape the battle. The combatants can try out different strategies directing bold attacks, mounting stubborn defences, or waging wars of attrition across the grid. Various combat rules lead to patterns of movement that differ from those produced by the standard 'eat all you can find' rule. Some combat rules lead quickly to strictly segregated colonies, each clinging to its own sugar peak and, and in other cases, one side eliminates the other.

The Sugerscape model also offers insights into other phenomena, such as the introduction of trade. In this case, the landscape contains heaps of two resources: sugar and spice. The agents are programmed with different metabolic rates, or preferences, for each of the two commodities. They die if either their sugar or their spice store falls to zero. A mathematical formula called a welfare function allows each agent to compute how close it is to sugar or spice starvation. The agent then strives to gather more of the commodity it needs. An additional system of rules specifies how agents bargain for and exchange sugar and spice according to their needs. These rules enable the researchers to document how much trade takes place and at what price exchanges occur. When agents are allowed to live forever, so long as they never run out of food, the sugar-spice model shows that the average trade price converges to a stable level. Economic equilibrium emerges just as text book market economics predicts.

It seems that the Sugerscape model is able to explain such stylized facts as the formation of culturally distinct groups, the emergence of skewed wealth distributions, or the appearance of population centres. At its simplest level, the Sugerscape model represents a kind of hunter-gatherer society. In the opinion of the authors, Sugerscape "can examine population growth and migration, famine, epidemics, economic development, trade, conflict, and other social issues." But Thomas Schelling notes that such agent-based modelling shows that social norms can arise out of very primitive behaviour, though it doesn't necessarily demonstrate how the norms actually came about.

The authors say their model usually mimics early agricultural societies, not modern economic life. Sugerscape is more a metaphor than a realistic depiction of society. The landscape and agent characteristics are simple proxies for the more complicated things that occur in the real world.

5. Common platform

A variety of different approaches to evolutionary modelling of socio-economic system exist and the number of different models is proliferating. Communication between researchers and the possibility of applying different models to the same kind of phenomena are very limited. The situation is worsened by different operating systems and computer languages to implement evolutionary models. It seems that to facilitate further progress in evolutionary modelling of socio-economic phenomena and to aid researchers with a rather limited knowledge of computer programming, it is necessary to develop widely accepted tools to build, test and analyse evolutionary models. It frequently happens that full comprehension of evolutionary model by other people than their creators is very difficult. A few years ago Giovanni Dosi proposed that a common platform be developed for variety of users to facilitate model development and communication of different researchers with different professional backgrounds. The first attempt to build such a common platform was done within the Systems Analysis of Technological and Economic Dynamics (TED) project at IIASA. Marco Valente (1997) presents such a computer package for simulation in economics. He calls the package LSD (Laboratory for Simulation Development). LSD aims to build models within the Schumpeterian tradition although ACE-like models can also be implemented. A number of such common platforms exists within the ACE stream of research. This two approaches are described below. The third possibility of a common platform can be seen in the well-established of Jay W. Forrester and his collaborators known as System Dynamics. The possibility of using System Dynamics, especially its newest implementation represented by *the* STELLA package is presented, in the end of this section.

LSD Valente (1997) explains the concept of *simulation models* used in LSD and gives instructions for its use. He also provides a short tutorial in the use of the package, implements three models and describes LSD interfaces for running simulations of existing models. The examples show that it is possible to implement complex models but it seems that LSD is far from being user-friendly.

A library of ready-to-use functions dealing with the technical details of a simulation model allows modelers to concentrate exclusively on the theoretical contents of the model. The graphical interfaces allow an easy exploration of the model and the setting of the parameters for a simulation run. These two features are controlled by a model manager and a model interpreter. Both the model manager and interpreter are model independent: they adapt a set of standard graphical interfaces and a computational engine to any model. After a model is loaded, LSD behaves as a stand alone program, specifically written for the simulation of that model.

Users define a number of abstract entities (Objects) without any specification of the actual computational contents. A gradual specification of the behaviour of such entities adapts the abstract definitions to more and more specific instances. LSD provides an abstract definition of Object containing all the machinery to run the implementation of the Object itself. Hence, users can concentrate entirely on the ”creative” part of building a simulation model by defining Objects derived from the abstract one. To derive a new instance, the modeller just needs to give a name to the Object and to its elements (that is, variables or parameters). The abstract definition of LSD Objects also provides connections which can be used to link Objects to each other, to create the structure of a model. The computational content of a model (i.e. the equations) is expressed as a list of functions, one for each variable label. LSD provides functions which facilitate the writing of equations, allowing modelers to express computations as if they were using an equation editor. For example, LSD retrieves variables by using only their labels and deals with the scheduling of computations. A model run with LSD ensures high efficiency of computation because the model interpreter has very little computational overhead, producing the equivalent of the output from C++ code. The models written with LSD can be decomposed into their fundamental components, which can then be re-used in other models.

LSD distinguishes three types of components of a model: structure, equations and initial data. It is possible to define and/or modify at different times the components, in order to test parts of the model or run reduced forms. The structure of a model in LSD is defined in terms of its Objects and the relations among them. The model is defined in order to be highly modular; that is, to be easily modified and expanded. The equations of a model must be written as C++ code, extended with the library of LSD functions. Any information related to the model is included in the LSD functions, allowing modelers to use a syntax similar to writing difference equations on paper. The final result is an easy to use ”equation language” producing very fast code, and hence suited for heavy computational models. The initial data are used to set up a simulation model before running an actual simulation. They are stored in a text file, together with other technical information (number of steps, variables to save, etc.). Users of LSD models can use a simple and effective graphical interface to modify the initialization of a model.

ACE platforms ACE software is very diversified and also very problem specific. We will mention only a very selected number of platforms but there is a good Web site (http://www.econ.iastate.edu/tesfatsi/ace.htm) where it is possible to find references to ACE software.

Two platforms, namely ’The Swarm Simulation Platform’ and ’A Strictly Declarative Modelling Language (SDML)’ seems to be the most versatile software for further development of a’common platform’ for wider society of researchers.

The Swarm Simulation Platform was developed by Santa Fe Institute researchers. The software aims to combine object-oriented simulation capabilities used in an artificial world and those needed in an industrial world. Special attention is made to handle information flow versus material flow. Part of the software is based on genetic algorithms to deal with problems of assembly line sequencing. The practical applications of developing software within a framework like Swarm include improved manufacturing operations on the shop floor, better understanding of distribution chains, and a method for of forecasting demand. Swarm is essentially a collection of software libraries, written in Objective C, developed for constructing discrete event simulations of complex systems with heterogeneous elements or agents. Some lower-level libraries, which interface with Objective C, are also written in Tk, a scripting language that implements basic graphical tools such as graphs, windows, and input widgets. Swarm depends on the Unix operating system and the X Windows graphical interface.

A Strictly Declarative Modelling Language (SDML) is a modelling language implemented in SmallTalk. The software stresses computational multi-agent modelling of decision-making in complex environments, with a focus on strategic behaviour by corporate managers and government.

Another system is SimBioSys, developed for general agent-based evolutionary simulations in both biology and the social sciences. SimBioSys is designed to handle simulations comprising the following four features: (a) a world defining the virtual environment where the simulation occurs, (b) populations of autonomous agents inhabiting the world, (c) programs driving the behaviour of the agents, and (d) genetic mechanisms emulating natural selection which act on the agents' programs.

The Trade Network Game (TNG) combines evolutionary game play with preferential partner selection. Successive generations of resource- constrained traders choose and refuse trade partners on the basis of continually updated expected payoffs, engage in risky trades modelled as two-person games, and evolve their trade strategies over time. The modular design of the TNG framework facilitates experimentation with alternative specifications of market structure, trade partner matching, expectation formation, and trade strategy evolution. The TNG framework can be used to study the evolutionary implications of these specifications at three different levels: individual trader attributes; trade network formation; and social welfare. The TNG has been implemented in C++.

Herbert Gintis has developed Borland Pascal 7.0 code that implements a general iterated game of the following form. Agents in a population are randomly paired for game play and obtain fitness payoffs. A genetic algorithm involving haploid reproduction and mutation is then used to evolve the agent population.

STELLA – System Dynamics The modelling and simulation field known as System Dynamics has been developing for the last 35 years. The foundation of this methodology was laid in the early 1960s by Jay W. Forrester at MIT. What makes using System Dynamics different from other approaches to studying complex systems is the use of feedback loops. Stocks and flows help describe how a system is connected by nonlinear feedback loops. Running "what if" simulations to test certain policies on such a model can greatly aid in understanding how the system changes over time. System Dynamics combines the theory, methods, and philosophy needed to analyse the behaviour of systems in not only management, but also in environmental change, politics, economic behaviour, medicine, engineering, and other fields.

System Dynamics adheres to viewpoints and practices that set it apart from other fields dealing with the behaviour of systems. In contrast to the endogenous viewpoint, economists often imply that the economic system is almost in equilibrium almost all the time with important behaviour arising only from unexpected exogenous forces. The System Dynamics emphasis on endogenous behaviour. All information is admissible to the process of model building. Information from the mental data base is recognized as a rich source of knowledge about structure and the policies governing decisions.

Recent software advances, especially the user-friendly STELLA program, facilitate the interaction between mental models and computer implementations. System Dynamics can be considered as candidate for a common platform to build evolutionary models. It can be used by people not familiar with computers and programming. Naturally not all evolutionary models are implementable using STELLA, but most of them are. This opinion is especially supported by new features of the recent version 5.0 of STELLA. STELLA has one very important feature, namely arrays. In former versions to model a number of firms competing on a market it was necessary to define separately a structure (characteristics and relationship) for each firm. Now it is possible to define a structure for one firm and let that same structure (but with different firm specific values) be applied to all other firms. Thanks to this ability the visualization of a model is much clearer. To implement the Nelson and Winter model in STELLA I needed about 3 hours of work (see Figures 8 and 9). Building models with STELLA is easy, the software was designed to be user-friendly.[7] One of STELLA's advantages is the 'Control Panel' features which facilitates testing and simulation of the model. To build control panels we have large number of possible blocks, like sliders, knobs, loop pads, programmable buttons, graph pads and graphical devices, and many other. Figure 9 presents also simple control panel to run Nelson and Winter model.

6. Conclusions

Simulation is one of the most promising techniques to investigate modern socio-economic processes. The imitation of reality (i.e., using substitute objects instead real processes) is a fundamental feature of the simulation approach. From this point of view simulation ought to be distinguished from simply using computers to make calculations. The imitation feature is present in both streams of simulation evolutionary economics, i.e., the Schumpeterian tradition and agent-based economics (ACE). One feature distinguishes Schumpeterians from advocates of ACE approach, namely the more realistic concept of time. In most Schumpeterian simulations there is a connection between of simulation time and real time. The ACE models tend to use arbitrary units of time and it is difficult to relate the dynamics of change in these models to the real flow of time. Therefore it is difficult to estimate such important characteristic as the time of emergence of particular properties. This difference between the Schumpeterian and the ACE approaches ought to spur the dialogue between the two almost isolated groups of researchers and help to define a common platform to use in the analysis of real economic processes.

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[7]The specific way of STELLA design (especially using limited number building blocks to define complex models structure) is strongly influenced by people who in their childhood have built wonderful constructions using very limited number of types of blocks offered by LEGO, now when adult they try to pass their childhood experiences into professional life to facilitate (and make it fun) their everyday duties.

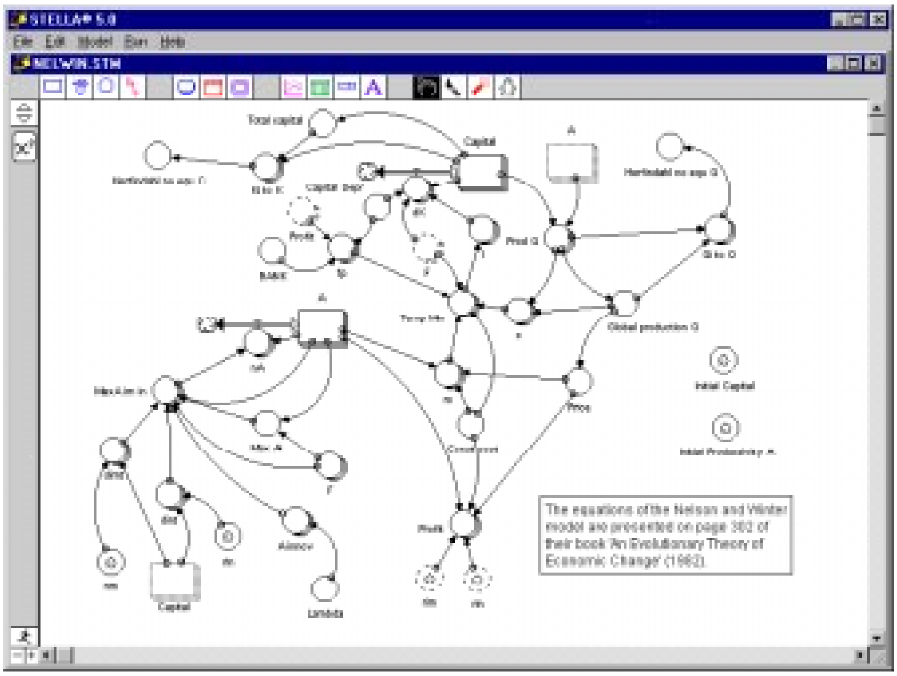

Figure 8. The Nelson and Winter model written with STELLA.

9-17.

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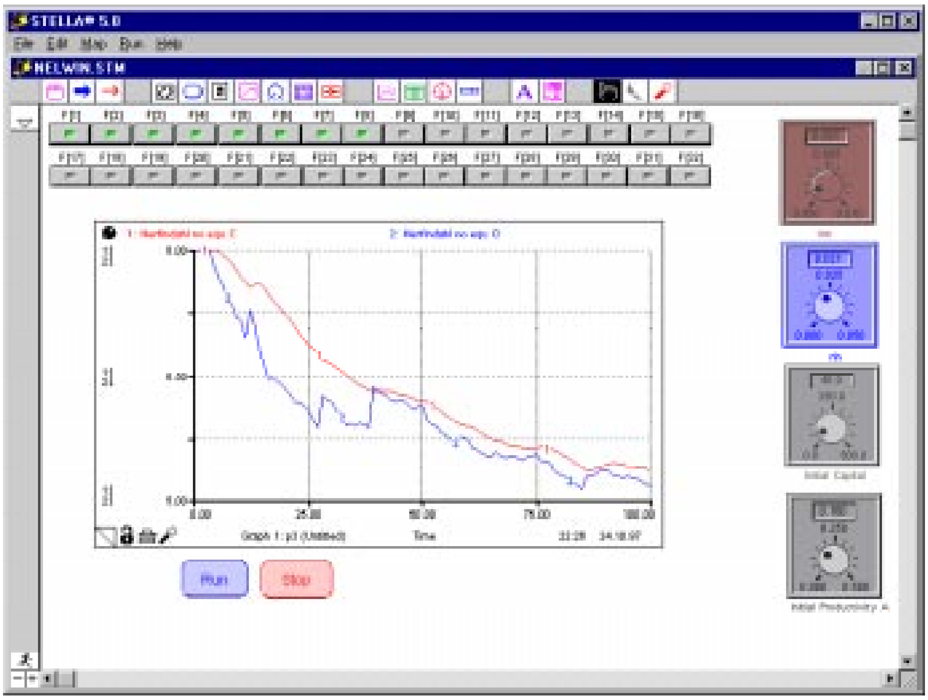

Figure 9. Simple control panel to run Nelson and Winter model.

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