

INTERDISCIPLINARY DESCRIPTION OF COMPLEX SYSTEMS

Scientific Journal

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Editors

Josip Stepanić, Editor-in-Chief

editor@indec.s.eu; Faculty of Mechanical Engineering & Naval Architecture, I. Lučića 5, HR – 10000, Zagreb, Croatia

Josip Kasač, Assistant Editor

josip.kasac@indec.s.eu; Faculty of Mechanical Engineering & Naval Architecture, I. Lučića 5, HR – 10000, Zagreb, Croatia

Mirjana Pejić Bach, Assistant Editor

mirjana.pejic.bach@indec.s.eu; Faculty of Economics and Business, Trg J.F. Kennedyya 6, HR – 10000, Zagreb, Croatia

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EDITORIAL

Welcome to the new issue of the *Interdisciplinary Description of Complex Systems*.

This issue contains five articles spanning diverse aspects of complex systems and methodologies for their research.

Author G. Gündüz starts from the notion well established and regularly utilised in chemical dynamics, the autocatalysis. The author develops the mechanism that autocatalysis embraces all processes which are causes of a whole class of complexity and evolution. Before proceeding, let us point the interested readers to another article of the same author “Ancient and Current Chaos Theories” which is published in the *INDECS* 4(1).

In his article, B. Ness develops and applies systems thinking & analysis related simulation model in order to integrates past data and near-future predictions about the sugar production.

M. Schatten and M. Žugaj start from the notions which originated within the context of researching Nature and structures in it formed without purposeful human influence. They apply these notions, as well as document the past cases of their previous applications, in the field of practical organisation science.

Author J.A. de Aquino develops agent based model, a simplified and rather generic version of whole branch of possible, more complex and complicated models, to analyse dynamics of cooperation.

Finally, D. Gurka in his article reveals contemporary, already traditional, scientific and cultural manifestation which gradually developed from markings of the life of Hungarian scientist and educator Gyula Farkas.

Zagreb, 30 June 2011

Josip Stepanić

AUTOCATALYSIS AS THE NATURAL PHILOSOPHY UNDERLYING COMPLEXITY AND BIOLOGICAL EVOLUTION

Güngör Gündüz*

Department of Chemical Engineering, Middle East Technical University
Ankara, Turkey

Regular article

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ABSTRACT

The importance and different aspects of autocatalysis in evolution was analyzed. The behaviour of autocatalytic reactions mainly the Lotka-Volterra and the Schlögl equations were discussed in terms of phase change, entropy, and their oscillation frequency. The increase of complexity as the general direction of evolution was examined on some patterns in terms of both their entropy and information content. In addition, the relation between stability and functionality, stability and cohesion were discussed. It was concluded that evolution drifts in the direction of increasing complexity as a kind of natural philosophy to counteract the increase of entropy in the universe.

KEY WORDS

autocatalysis, entropy, evolution, complexity, information, oscillation frequency, cohesion

CLASSIFICATION

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*Corresponding author, *η*: ggunduz@metu.edu; (90) 312 210 26 16;
Kimya Mühendisliği Bölümü, Orta Doğu Teknik Üniversitesi, Ankara 06531, Turkey

INTRODUCTION

The theory of biological evolution did not only have a spectacular impact on human knowledge of biological systems, but also founded a close relationship between many disciplines of science such as, chemistry, physics, geology, and philosophy; yet sociology, psychology, economy, and similar other fields use evolutionary concepts to evaluate long term changes. In early 19th century physical and chemical principles had not yet been strongly introduced into biology, and Darwin could make his reasoning on some philosophical and observational facts. He used the ‘causality principle’ of ancient natural philosophy and Newtonian mechanics to establish a physical ground for the evolution of living organisms. He considered the Malthus principle of ‘limited food supplies but geometric multiplication of populations’ as the driving force in Newtonian sense for the fight for survival. And then Adam Smith’s principle of economic progress ‘speciation brings in gain for competition’ helped Darwin to come up with the idea of ‘competition for food is the driving force, and speciation may bring in advantage for survival’. The molecular basis of ‘speciation’ could be understood decades later with mutations on DNA through different mechanisms which could be described by statistical mechanics, chemical kinetics, and biochemical interactions. The intricate relations of parameters in evolution are too complicated [1].

The apparent paradox between the entropy principle and the evolution has been the concern of physicists, because the former drifts everything in the universe into disorder while evolution drifts into order and complexity. Schrödinger’s suggestion ‘living things feed on negative entropy’ somehow surmounts the problem, but stays as a natural fact rather than a proof. The problem has been much better tackled by the concepts of nonequilibrium thermodynamics, nonlinear phenomena, chaos, and complexity. In the last few decades the nonlinear theory revolutionized our understanding of natural phenomena, because, most natural phenomena come out through a process, and in the words of Prigogine anything which comes out through a process is ‘happening’, not an ‘event’. Time appears in almost all physical equations as second order derivative, and the physical equations cannot differentiate between the past and future; that is, $t \rightarrow -t$ substitution leaves the physical equation invariant, therefore most of the equations of physics describe ‘event’ not ‘happening’. However, Boltzmann’s H-theorem is first order in time, and entropy has a time direction. In nonlinear theory the evolution of any process is described by multiple equations which provide correlation of some of the parameters, and the irreversibility is naturally embedded within the process. It is now generally accepted that irreversibility is not identical to entropy but more than that. Irreversibility can increase both entropy and information, and the increase of information content of a system runs parallel with the increase of its complexity. Complexity is not sufficient for survival but it is necessary [2].

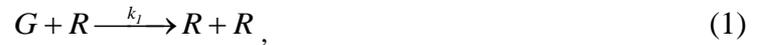
‘Competition for survival’ can well explain the mechanism of natural selection but lacks to explain the ‘molecular evolution’ in nonliving world. Darwin’s second important contribution to the ‘selection’ mechanism of evolution is ‘sexual selection’ which does not also have direct correspondence in nonliving world, but ‘chemical affinity’ may somehow explain the preference of occurrence of certain products in the soup of many reactant chemicals. The ‘adaptability’ of living organisms can be explained in terms of ‘thermodynamic stability’. In Ancient times the philosopher Thales claimed that magnet has the properties of animate because it moves. Hippias and later Aristotle objected to this idea and they said magnets do not have the fundamental attributes of animates such as, autonomous locomotion, perception, primitive desires, judgment, and act of will. In biological world discussion goes on viruses whether they are living species or not. The fundamental property of all living organisms is that they self-multiply, and viruses cannot do it by themselves but must use host cells. The

theories proposed to explain evolution must in fact come out from very general natural principles, and physical laws. Evolution is one of the most general natural phenomenon, therefore, evolution theories must also base on very general universal facts. The first biological evolution theory in the history was proposed by the great philosopher Anaximander (~610-550 BC), and irreversibility of forms once generated plays a predominant role in his explanation of the existence of different species in nature. He was the first person before Darwin claiming that all living beings sprang out of sea long ago.

All living organisms desire to multiply, and so do viruses. In nonliving world the increase of entropy also fragments the objects and increases the number of pieces, but this is not self-multiplication. There are different examples on similarity growth in nonliving world such as crystal growth, or chain growth of a polymer where monomers combine to make bigger and complex structure. The question is then, does entropy decrease in crystal growth or polymer chain growth as in the case of living organisms? In fact they are both ordered structures. Whether it is biological world or nonliving world self-multiplication stands as the most general phenomenon to understand evolution in the most general sense. It is better to use the term ‘autocatalysis’ instead of self-multiplication, because it involves the concept of converting others into itself usually in an irreversible manner.

AUTOCATALISYS

An autocatalytic reaction is simply given by $A + B \xrightarrow{k} A + A$, where the reactant A converts B into A , and the product is all A . The chemical reaction rate constant ‘ k ’ denotes the probability of reactions taking place. Fisher proposed in early 1920s that prey-predator interactions are random phenomena like the collisions of atoms. Around the same time Lotka proposed a chemical kinetic basis of prey-predator interactions, and the model was improved by Volterra in 1930s. Considering only three species grass (G), rabbit (R), and fox (F) we can write their interactions in the form of the following chemical reactions.



The differential equations governing the rate of growth of rabbit and fox can be given by,

$$\frac{dR}{dt} = k_1'GR - k_2RF = k_1R - k_2\beta_R^{-1}RF \quad (4)$$

$$\frac{dF}{dt} = k_2\beta_F^{-1}RF - k_3F \quad (5)$$

where the rates are based on the number of species on the right side of equations since each rate is irreversible, and R and F denote the number of rabbits and foxes, respectively. Volterra called the constant β^1 equivalence number. Specifically, β_R^{-1} denotes the ratio of number of rabbits lost per unit time to the number of foxes gained. The solution of these equations yield sinusoidal change for both species and one can simply show this by Fig. 1.

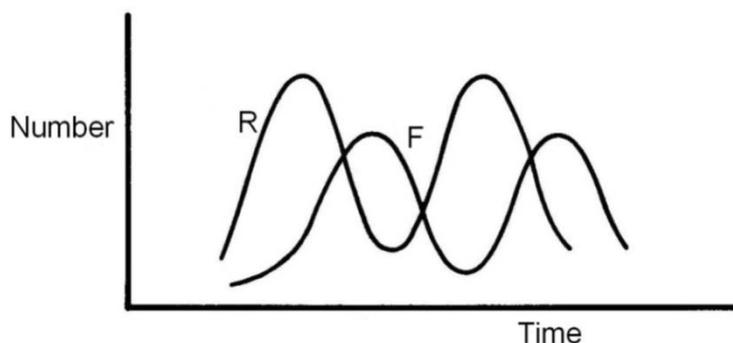


Figure 1. Change of rabbit-fox populations in Lotka-Volterra problem.

The increase of rabbit population makes increased amount of food available for fox, which, in turn increases in number in time. Then rabbit population decreases, and after a while some of foxes die due to starvation and fox population also starts to decrease with a time lag. Then rabbit population starts to increase, and so on. The kinetics of reactions entirely depend on the chemical reaction constant ' k ' in (4) and (5). We can interpret ' k ' in terms of characteristic properties of prey and predator. The meaning of ' k ' is very clear for two interacting gas molecules ' A ' and ' B '. For A and B to react the sum of their kinetic energies must be above a threshold energy so-called activation energy.

In Lotka-Volterra problem ' k ' is a resulting constant of all properties and characteristics of animals. For instance in (4) and (5) ' k_2 ' denotes the ability of foxes to catch rabbits. For simplicity we may not mind about most of the biological characteristics such as vision, hearing, being at alert, brain functions, etc. of the both animals but consider only their ability to run. So we can show their speed distribution by the first distribution in Fig. 2.

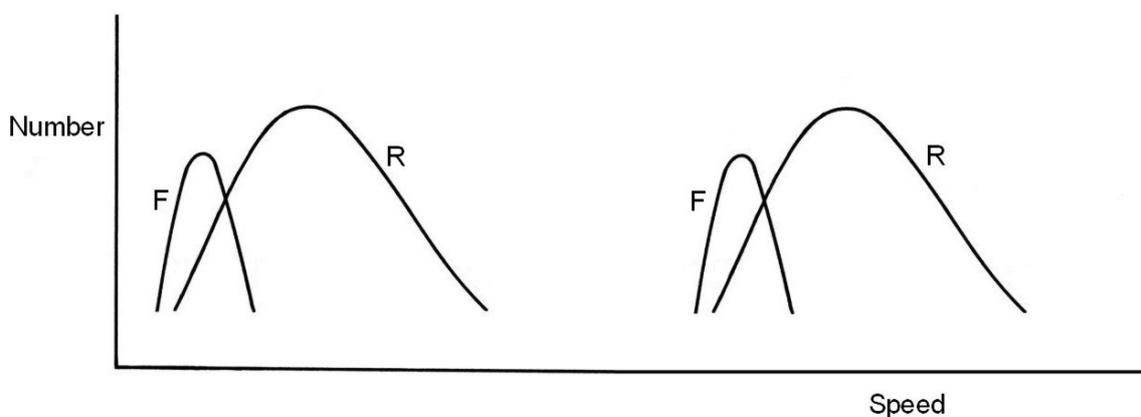


Figure 2. Speed distribution of prey (R) and predator (F).

It is clear that only fast running preys can survive as they can easily run away from the predators, and also only fast running predators can survive as they have advantage over low speed predators for catching low speed preys. In this respect the mechanism of survival has resemblance to the dynamics of chemical interaction, i.e. equations (1)-(5) are based on this principle. Evolution tells us that in the long run the characteristics of species change; and in our simple case both prey and predator evolve to become fast runners as in the second distribution of Fig. 2. The distribution of F & R at higher speeds (e.g. the second case) is an oversimplification, and it can occur only if the proportions among k_1 , k_2 , and k_3 do not change. However k_1 , k_2 , and k_3 at higher speeds are naturally different than the ones at lower speeds. This is, because, even for simple gas molecules chemical reactivity expressed in terms of rate constant ' k ' depends on energy (i.e. on temperature) through Arrhenius or

similar relations. The change of ‘ k ’ with temperature is actually due to increase of kinetic energies of molecules, which, changes the impact parameter between colliding molecules. In turn, the number of electronic excitations increase and more number of molecules get involved in reaction. The occurrence of any chemical reaction changes either thermal or configurational entropy, or both; otherwise, the product molecule wouldn’t be stable. A change of entropy does not warrant the persistence of the new state occurred; it is likely that the process may reverse. However, evolution is an irreversible process in the long run.

ENTROPY OF OSCILLATING SYSTEMS

The entropy of prey-predator can be determined by following the usual procedure. The change of chemical potential ‘ μ ’ due to change in number from a steady ‘ n_s ’ by a fluctuating number of ‘ n' ’ can be given by the following equation where R_G is gas constant.

$$\mu - \mu_s = R_G T \ln \frac{n}{n_s} = R_G T \ln \left(\frac{n_s + n'}{n_s} \right) = R_G T \ln \left(1 + \frac{n'}{n_s} \right) \approx R_G T \left(\frac{n'}{n_s} \right) \quad (6)$$

The entropy production rate ‘ σ ’ due to fluctuations in populations can be expressed by,

$$\sigma = \frac{dS}{dt} = \sum_j X_j J_j = \frac{1}{T} \sum_i^k \left[-\mu_i \frac{dn_i'}{dt} \right] = \frac{1}{T} \left[-\mu_R \frac{dn_R'}{dt} - \mu_F \frac{dn_F'}{dt} \right] \quad (7)$$

where J is reaction rate (i.e. flux), and X is the gradient of the driving force. The substitution of (6) into (7), along with replacing $n_R = R$, and $n_F = F$ gives,

$$\sigma \approx R_G \left[-\frac{R'}{R_s} \frac{dR'}{dt} - \frac{F'}{F_s} \frac{dF'}{dt} \right] \quad (8)$$

One can also show after some algebra that,

$$\frac{dR'}{dt} = -k_2 \beta_R^{-1} R_s F' \quad (9)$$

$$\frac{dF'}{dt} = k_2 \beta_F^{-1} F_s R' \quad (10)$$

Now these two equations can be substituted in (8) to find entropy. However, (8) does not include equivalence numbers which need to be introduced. Then one gets,

$$\sigma \approx R_G k_2 (R' F' - F' R') = 0 \quad (11)$$

This shows that the system is stable against small fluctuations around the steady state values. The system rotates around the steady state without getting into it. The point corresponding to the steady state is a center. In other words the oscillating populations as shown in Fig. 1 do not produce any entropy. So we can say that autocatalytic processes do not produce entropy but provide oscillations in the system. Zero entropy change means the system resists to persistent changes, and the system accomplishes this by moving from a thermodynamic equilibrium point to a limit cycle, because, the plot of the change of populations of prey and predator with respect to each other gives a limit cycle. So the Lotka-Volterra model or other kinetic models cannot explain the irreversible and persistent changes in the course of evolution.

The persistent changes in evolution yield new changes in the shapes of living organisms, and these structural changes can be discussed in terms of ‘configurational entropy’. The structural changes come out from the accumulation of mutations on DNA, and therefore configurational entropy has one-to-one correspondence with the change of mutations and thus the information content of DNA, as if the change of the meaning of a word by changing the order of characters. The mutations thus change the constants ‘ k_i ’ for all types of interactions of

species, their physical abilities to sense preys or predators around, their communications with the things in their environments, and thus their abilities for their fitness or adaptability, their sexual attraction, etc. Therefore the shape of the second distribution in Fig. 2 depends on how ‘ k_1 ’, ‘ k_2 ’ and ‘ k_3 ’ change in time with respect to each other. Actually, the constants are time dependent for an evolutionary process, and the differential equations like (4) and (5) must involve time dependent rate constants; but there is no way to express the exact timely changes of ‘ k ’ values as nobody knows the future pathways of evolution; nevertheless, short term predictions can be done for the evolutionary dynamics of interaction rates between species since ‘ k ’ does not change fast in time. All dynamical equations of physics like classical mechanics, electromagnetism, relativity, and quantum are insensitive (i.e. exhibit symmetry) to the change of sign of time; one cannot go to past or future, and they tell exactly what happens at present. The only equation which has a time direction is Boltzmann’s H-theorem as mentioned earlier, though Lorentz and coriolis forces have some kind of time symmetry problems. Therefore evolution has a very close relation to entropy, because both have time direction.

DIRECTION OF EVOLUTION

Evolution has two fundamental characteristics, (i) time asymmetric, and (ii) drifts to higher complexity. The former is like entropy, while the second is exactly opposite to entropy. In the philosophical sense evolution stands as the dialectic counter part of entropy, they share a common root (i.e. time asymmetry or irreversibility), and they also contradict each other; entropy drifts the system towards fragmentation in time while evolution pushes the existing system towards complexity. Irreversibility is not identical to entropy and disorder, it can also generate order.

In the earlier discussions it was shown that the creation of order in the form of periodic oscillations in time domain from disorder (e.g. from Maxwellian like distributions) is possible through autocatalytic reactions (e.g. Lotka-Volterra problem). It was also shown that such systems do not exhibit irreversibility as they have zero entropy for overall change. The irreversibility in autocatalytic reactions comes out through nonlinear or chaotic growth.

The simplest autocatalytic reaction is the growth of microorganisms on an agar plate, and first studied and modeled by Verhulst in 1870s. The rate of growth of population ‘ x ’ on agar obeys the following equation,

$$\frac{dx}{dt} = \mu x(1 - x). \quad (12)$$

where the constant ‘ μ ’ denotes the growth rate constant. Then on, there have been several models for population growth but logistic equation popularized by May has drawn much attention used for discrete time demographic model [3]. It is nonlinear difference equation, and given by

$$x_{n+1} = \mu x_n(1 - x_n). \quad (13)$$

The population x_n becomes x_{n+1} after a discrete time interval. There are two parameters here; x_n corresponds to the growth parameter whereas $(1 - x_n)$ corresponds to the controlling parameter. The large magnitudes of μ can push the system into chaotic growth. In fact the growth described by the Verhulst and the Lotka-Volterra equations can be chaotic depending on the magnitude of μ [4, 5].

Whether the change of population is oscillatory or chaotic does not help to understand the persistent change due to evolution. However nonlinear dynamics and chaos has a number of interesting properties exhibited exactly by evolution, and they can be summarized as:

- it is irreversible; you cannot revert the anatomy of man to its homo erectus or earlier shape,

- irreversibility introduces pattern formation; the anatomy of organisms change in a persistent way,
- entropy increases with irreversibility; the higher the extent of irreversibility the higher the entropy produced. The larger the extent the species changed in evolution, the less they are alike to their ancestors,
- pattern formation occurs through the change of parameters (or dimensions) at certain proportions. The scaling of dimensions gives ‘fractal dimension’. The course of evolution results in dimensional changes and the proportions in anatomic changes may follow scaling relations that can be traced from the measurements on fossils. These changes can even turn into geometric proportions as first noted by D’Arcy Thomson [6],
- system has memory; all organisms carry the memory of their parents, the closer the chronological parent the more it is memorized. Darwin noticed that the toe of human fetus separates out from forefinger as in monkeys, but then comes back near forefinger before birth. Human coccyx is a remnant of tail,
- the thermodynamics of chaos is non-equilibrium thermodynamics, and resonance interactions may dominate over random interactions. A chaotic system has many periodicities and thus frequencies, so resonance interactions play an important role. Organisms exhibit cyclic or periodic behaviors. Seasonal migration of birds, butterflies, etc., hatching or menstruation in some animals in integer multiples of seven days in accordance with periods of tides, and insect clocks all imply the periodicities involved in the lives of organisms [7],
- the complexity increases as the system grows; the complexity of evolved organisms increased in the course of evolution from prokaryotes to humans.

All these similarities between chaos and evolution introduced a new aspect to understand the dynamics of evolution [8-12]. What is naturally selected, sexually selected, adapted to environment, or has better fitness, etc., can be all expressed in terms of interaction rate constant k in mathematical modeling. It is the collection of k 's of all kinds, and the coordination of the appropriate biochemical reactions that provide survival. At the molecular level it is the information content of DNA that determines the values of different k 's of an organism. The change of k is possible only if mutations occur on DNA by changing the order of existing bases. In other words information originates from the sequence of several bases; that is, a segment of polymeric chain generates information. Naturally, some mutations are passive, and the information content is not actively changed.

ENTROPY, INFORMATION, AND COMPLEXITY

According to Ancient philosopher Anaxagoras ‘there is everything in anything, and everything in nature is *sperma* (i.e. seed)’, and some sperma multiplies itself and becomes dominant. Finally the attributes of objects result in from the dominant spermas. According to this way of thinking atoms are sperma of molecules, molecules are of higher order structures, unit cells are of crystals, monomers are of polymers, nucleotides are of DNA, words are of sentences, musical notes are of melodies, and individuals are of society. Whether it is biological, or social, cultural, molecular, cosmological, etc. evolution, it is the information (which is the sperma) that evolves. It is the information of ‘gene’ (selfish or not) that tries to multiply itself. Since evolution drifts towards complexity the information content in an evolving system should increase in a firm manner to hold up the uniformity of the system. In other words there must be a kind of synchronized correlation between components of the system. However, it is known that the entropy increases also as the complexity increases. So

for an evolving system towards higher complexity the increase of information should exceed the increase of entropy. As an example consider Fig. 3.

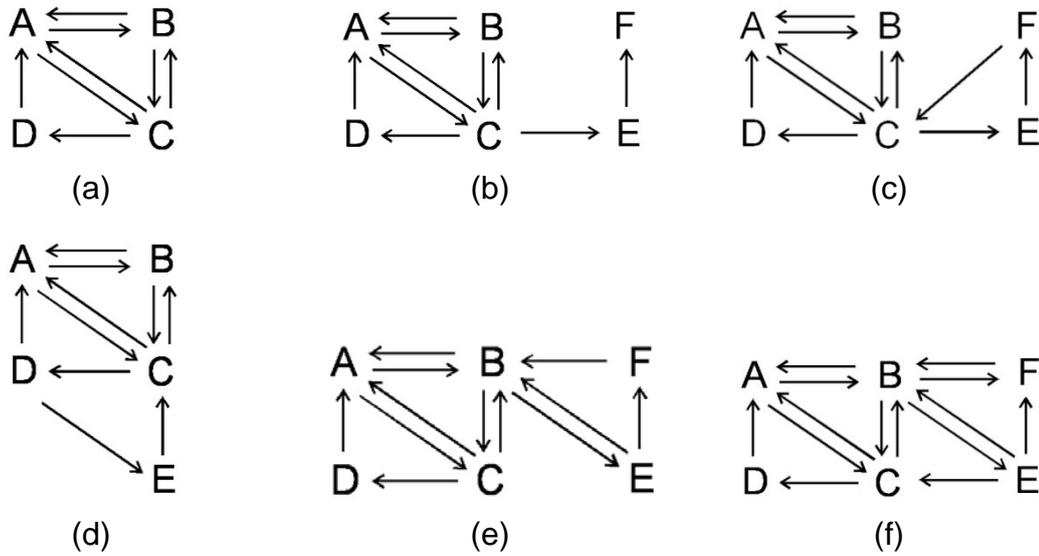


Figure 3. Evolving complexity.

Figure 3a represents a configuration made from two subsystems ACD and ABC, the former is a directed cycle, whereas the latter is reversible either direction. ACD can well represent prey-predator system of three species, as well as three subsequent information obtained from the transcription of DNA such that information A induces C which induces D, and it induces back A. The ABC cycle is an extreme case, it may not be realistic but it is mathematically important as the limiting case of extreme complexity. The entropy and information of each pattern seen in Fig. 3 can be found from the following equations utilising logarithm function with base 2:

$$S = \sum_i p_i \log_2 p_i \tag{14}$$

$$I = S_{\max} - S. \tag{15}$$

The probability is based on the controlling parameter, for instance D controls only A in Fig. 3a. Values calculated are tabulated in Table 1.

Table 1. Entropy and information of patterns depicted in Fig. 3.

Figure	<i>S</i>	<i>I</i>
3a	1,05	1,95
3b	1,26	2,06
3c	1,52	1,94
3d	1,20	2,12
3e	1,16	2,65
3f	1,19	2,62

In Fig. 3b branching occurs at C, and compared to Fig. 3a entropy increases from 1,05 to 1,26, and information from 1,95 to 2,06. The increase in entropy is more than the increase in information, that is, $\Delta S_{ba} = S_b - S_a = 0,21 > \Delta I_{ba} = I_b - I_a = 0,11$, therefore the system is not going in the direction of complexity as we go from Fig. 3a to Fig. 3b. In Fig. 3c the new triangle FCE is the mirror image of ACD. Although entropy keeps increasing ($\Delta S_{ca} = 0,47$)

information keeps almost constant ($\Delta I_{ca} = -0,01$), and therefore FCE is not recognized as something similar to ACD by the system.

However, if a new triangle is generated on the already existing ACD as DEC as seen from Fig. 3d, then entropy decreases but information increases when compared to Fig. 3c, such that $\Delta S_{dc} = -0,32$ and $\Delta I_{dc} = 0,18$. So the order in Fig. 3d is higher than the order in Fig. 3c; thus, the pattern of Fig. 3d is much more favored than the pattern of Fig. 3c. The system recognizes DEC something similar to ACD in Fig. 3d. In other words, ACD behaves as a template creating its own copy DEC, that is, ACD autocatalyzes itself, and it also acts as a kind of nucleation site. A well known and well studied example of the geometry repeating itself is Benard convection, where repetition of hexagonal pattern takes place. Here autocatalysis decreased entropy and increased order and information. If we consider Fig. 3a and 3d we see that both entropy and information increases as we go from Fig. 3a to 3d, but the increase of information is slightly more than the increase of entropy, that is, $\Delta S_{da} = 0,15 < \Delta I_{da} = 0,17$. Therefore the system is ready to go into further complexity on the repetition of the same procedure. Thus it can be said that ACD has been the generator of DEC in the mathematical sense, i.e. ACD reproduced itself in the form of DEC. In autocatalytic reactions the increase in information can come out to be more than the increase in entropy. In Fig. 3e ABC reproduced itself as BFE. Compared to Fig. 3a entropy increased little bit ($\Delta S_{ea} = 0,11$), but the increase in information is quite large ($\Delta I_{ea} = 0,70$). Fig. 3a is duplicated in Fig. 3f, that is, ABCD repeats itself as BFEC. Although Fig. 3f seems to be more symmetric than Fig. 3e the entropy slightly increases ($\Delta S_{fe} = 0,03$) but information decreases ($\Delta I_{fe} = -0,03$). It seems that there is a kind of two competing structures (or configurations) in Fig. 3f; one is ABC and BFE and the other is ACD and BEC. However in Fig. 3e E is not connected to C, and the contribution of ACD is somehow depressed by ABC and BFE. The generation of BEC in Fig. 3f enhances the contribution of the similar structure ACD, and thus each of the competitive structures make significant contributions to entropy, which, in turn, decrease information. This situation is similar to the case of entropy of mixing, where, maximum entropy is achieved when two species were mixed at equal molar concentration. The repetition of ABCD on two-dimensional surface results in tessellation, which has two different structures; one is ABC with reversible (i.e. two-way) paths and the other ACD with irreversible (i.e. one way) path. If ACD also had two-way pattern then the tessellation would be perfectly symmetrical with minimum entropy. Such structures naturally cannot easily branch and cannot easily evolve to other structures. Therefore, similarity which is provided by autocatalysis acts like the controlling parameter in evolution. In other words branching pushes the system to gain new entropies while autocatalysis counteracts and tries to decrease entropy. In wild life the increase of the population of one type of species at the expense of others naturally decreases the overall entropy of that territory. If one species overdominates through overmultiplication all others may go extinct drifting the system towards minimum entropy. Co-evolution sustains entropy at a fluctuating but certain level.

The increase of complexity of pathways for metabolic reactions or to synthesize proteins for structural materials is in accordance with the increase of the complexity of the whole organism; naturally reptiles and birds have more complexity than bugs, and mammals than all others. The increase of complexity more or less correlates with the size of DNA; larger size implies larger information content. However this is not always true, lungfishes have much more DNA than other fishes, and amphibians than reptiles and birds. This is called 'C-paradox' and solved by the discovery of noncoding DNA.

COMPLEXITY AND PHASE CHANGE

There must be some explanation for the extraordinary increase of DNA in some species. While mammals have a mean C-value of 3,5 pg and most species less than 3,3 pg, there are some striking jumps in some groups of organisms. For instance cartilaginous fishes have a mean C-value of 5,7 pg, amphibians 16,2 pg and lungfishes 90,4 pg [13]. These species are transient species; bone has evolved after cartilaginous fishes, atmospheric oxygen could have been utilized by lungfishes, and animal life on earth (e.g. land) has become possible with amphibians. These major changes resemble to phase changes in materials, and the group dynamics of molecules in each phase displays entirely different collective behavior; for instance molecular dynamics of carbon black is much different than that of graphite, and of liquid water than that of vapor. Mutations occurring on a certain portion of DNA are naturally expected to yield new informations, perhaps at the expense of loss of some part of previous information. Evolutionary diversification depends on gains and loss, and one can trace the diversification by studying the changes in metabolic pathways [14, 15]. Small changes if they are critical can yield sharp morphological changes [16].

For the type of information needed for major changes mutations should accumulate not on the existing part but preferably in some other parts of DNA. So the increase in the size (e.g. length) of DNA provides new regions for the accumulation of new mutations and thus new information, which, in time overwhelms the former information in an effective way, and a new group of species evolve in time. So whenever major changes are needed such as change from cartilage to bone, from fin to lung, or from sea life to land life, long DNA is needed. The network of all information resulting from the transcription of DNA, the network of protein synthesis, the network of metabolic reactions, or reactions to synthesize structural materials wouldn't depict major change in the long run if mutations took place on the already existing units of DNA. Such mutations could probably introduce smooth changes from one type of form to another such as the change of eye or skin color, or the change of length of tail, ear etc. The information needed for the major change from fin to lung should not occur on the same portion of DNA; it will cause nothing but confusion, because an organ will otherwise be two-functional, and a conflict occurs between them. However, this is not what happens in living species. For instance each enzyme has only one function and catalyzes only one reaction. Only in very primitive cases confusions are allowed, for instance overlapping transcription is allowed in viruses but not in bacteria. The absorption of dissolved oxygen in water by fins and the respiration of atmospheric oxygen by lung can be both achieved simultaneously during evolutionary period only if they are separated from each other and controlled by different network of reactions.

In evolutionary period fins and lung have the same functionality except that the mechanisms of oxygen intake are different, and the mechanism of oxygen absorption from water is substituted by the mechanism of oxygen absorption from atmosphere. This substitution reaction can be simply evaluated by autocatalytic reactions. In market economy the substitution of one commercial product in the market by a new product in time can be well evaluated by (12) or (13), i.e. by Fisher-Pryer type of equations [17, 18]. Two competing mechanisms one overwhelming the other in evolution can also be studied by the same logic. Fins and lung are two different systems though they serve the same purpose. The change from one system to another can be viewed as a change from one state to another, or from one phase to another. The question then is, 'can we understand phase change by autocatalytic reaction systems?' The answer of this question was given several decades ago by Schlögl [19]. In fact pattern formation was first studied by Turing in a seminal paper to investigate chemical morphogenesis [20]. Different autocatalytic reactions are presented in Table 2.

As mentioned earlier the Lotka-Volterra type of autocatalytic reactions yields oscillations. The intermediate agents B and C seen in the first column of Table 2 disappear in the final step, and the overall reaction is simply, $A \rightarrow E$. In the Brusselator the overall reaction is $A + B \rightarrow D + E$, and it also gives oscillations [21]. The Schlögl equations are in between and two initial reactants transform to a single product, as $A + B \rightarrow C$.

Table 2. Autocatalytic reactions.

Lotka-Volterra	Brusselator	Schlögl-1	Schlögl-2
$A+B \rightarrow B+B$	$A \rightarrow X$	$A+2X \rightleftharpoons 3X$	$A+X \rightleftharpoons 2X$
$B+C \rightarrow C+C$	$2X+Y \rightarrow 3X$	$B+X \rightleftharpoons C$	$B+X \rightleftharpoons C$
$C \rightarrow E$	$B+X \rightarrow D+Y$		
	$X \rightarrow E$		
Overall:			
$A \rightarrow E$	$A+B \rightarrow D+E$	$A+B \rightleftharpoons C$	$A+B \rightleftharpoons C$

The solution of Schlögl-1 gives [19],

$$k_c C = X^3 - 3X^2 + fX \tag{16}$$

where the rate constant k_c is for the reverse direction from C to B and X , and $f=k_B B$ where k_B is the rate constant for the reaction of B and X to yield C . For $f < 3$ equation (16) has three possible roots. Then (16) has the same mathematical form for the first order phase transition equation, that is the Van der Waals equation or the virial equation of state given by,

$$p = \frac{RT}{V} - \frac{a_1}{V^2} + \frac{a_2}{V^3}. \tag{17}$$

Actually the potential leading to this equation is fourth order in X , and it, in turn, gives a double-well solution each representing a different phase [19].

Schlögl also showed that there exists a relation between g and f as follows,

$$g = f - 2. \tag{18}$$

where $g = k_c C$. This equation is of the same form with Gibbs phase rule with zero variance, with f corresponding to the number of phases and g to the number of components. If we have a many component system (i.e. many predators besides B) the number of phases will change accordingly. Every persistent change is irreversible and $g = 0$, because $k_c \rightarrow 0$ for irreversibility, so $f = 2$. That is, C is one of the phases, and the other is $A + B$.

The solution of Schlögl-2 gives [19],

$$c = X^2 - (1 - b)X, \tag{19}$$

where $c = k_c C$, and $b = k_B B$. Note that c was used instead of g in (19). First order transitions are reversible such as liquid-vapor transitions. However, second order transitions such as demagnetization are irreversible. The irreversibility can be imparted in the final step in Schlögl-2 by setting $k_c = 0$, which in turn yields $c = 0$. Then (19) gives,

$$X = \begin{cases} 1 - b, & b \leq 1, \\ 0, & b > 1. \end{cases} \tag{20}$$

This is the condition of second order phase transition. If X , b , and c stand for the magnetization M , temperature T , and magnetic field H , respectively, then $b = 1$ corresponds to the critical temperature (*Curie temperature*) above which magnetization disappears.

There is in fact a close resemblance between magnetization and autocatalytic change [22]. A magnet magnetizes iron particles and converts them into new magnets, and in an autocatalytic

reaction like $A + B \rightarrow A + A$ the molecular configuration of B is converted into the molecular configuration of A . So an existing magnetic field (i.e. the predator) induces a change in the randomly configured spins and re-orientates and align them (i.e. predator uses the proteins of the prey for its own growing structure or to sustain its own molecular configuration), and as temperature increases the order is lost (i.e. if preys gain new properties beyond a threshold value, then, predators may not catch them and they die of starvation and go extinct). The same logic can be applied also to the change in DNA. If a mutation or set of mutations improve the adaptability of a species then they multiply more in number, and if mutations exceed a certain threshold the configuration on DNA so changes that the species gains a relatively strong new property or functionality not owned or weakly owned by its predecessors.

IRREVERSIBILITY AND FUNCTIONALIT

The Schlögl-1 and the Schlögl-2 equations are essentially similar, and $2X$ is needed in Schlögl-1 whereas only X is needed in Schlögl-2 for autocatalysis. So Schlögl-1 is more difficult to achieve than Schlögl-2, as also the case in first and second order phase transitions; the former needs large energy at the transition temperature. To have permanent change we need to have irreversibility that can be achieved when $k_C = 0$ as mentioned above. So whether it is small changes due to mutations or sharp changes in the long run can be explained in terms of second and first order phase transitions, and the kinetics of these transitions can be explained in terms of Schlögl autocatalytic reactions. Prigogine and his colleagues studied the irreversibility by so-called Λ -transformation and the complex spectral theories. These two approaches are not equivalent [23]. However, it is very easy and somehow trivial to understand the irreversibility in chemical world in terms of chemical reactions; because, chemical reactions are noncommutative and thus persistent irreversibility is apt to survive. The irreversibility is related to the gradient of driving force, and the higher the gradient the higher the irreversibility. In nonequilibrium thermodynamics a current associated with a flow such as heat, mass, electric, or chemical change can be put into a general form of

$$J_i = \sum_j L_{ij} X_j \quad (21)$$

where L is known as phenomenological coefficient, and X is the gradient of the driving force. The dissipation function σ which is the rate change of entropy S per unit time is given by,

$$\sigma = \frac{dS}{dt} = \sum_j X_j J_j = \sum_i \sum_j L_{ij} X_j J_j. \quad (22)$$

Thus the increase of the magnitude of driving force increases the entropy production rate and thus the extent of irreversibility. River running slowly in a valley may have eddy currents pushing the flow backward whereas water flow through steep landscape is irreversible. In chemical systems the gradient disappears at equilibrium conversion, and if the chemical potential between the reactant and product is too high the equilibrium is achieved at complete conversion, which is named as irreversible reaction. Since the chemical potential of any chemical substance is never zero, there is no absolute irreversibility in the chemical sense. As a consequence, Aristotle's philosophical view of continuous 'combination-dissociation' forms the foreground of evolution. This view needs to be coupled with entropy to provide stability of the new forms, patterns or structures formed. Usually a functionality is associated with the change occurred. Otherwise too many mutations helping nothing may devastate the working system of organism, and its fight for survival may become inefficient and difficult.

Autocatalysis is a kind of intermediate step to convert A into C through employing X , which disappears in the final state, otherwise there would be no change of A into C . Although it is possible also to convert A into C by means of ordinary catalysis, this process is usually an entropy increasing process. It is very difficult to evolve complexity without autocatalysis,

which essentially minimizes entropy production and induces order which is needed for the increase of complexity. According to the Curie principal ‘the symmetry of an effect is no higher than a cause’. In chemical transformations the configurations change from one form to another. The change like $A + X \rightarrow X + X$ is a symmetry increasing (i.e. entropy decreasing) process. The overall entropy increases if we consider not only the configurational but also thermal component. In fact the motions will be reversible if the driving forces depend only on geometric configurations; the irreversibility sets in when the forces or velocities of interacting components vary in time if the dependence is asymmetric [24]. The reversibility occurs if the reversibility of momentum is not different than the reversibility of time [25].

It is known from the analysis done on spin glass systems that in the low-temperature limit the ground state entropy is negative. The proof is given in literature [26] and utilizes an equation having the same mathematical form as (20). So it can be said that at ground state where fluctuations are minimized autocatalytic reactions of type Schlögl-2 also has negative entropy. It is logical to extend it to other autocatalytic reactions also.

Autocatalysis naturally inherits nonlinearity and distorts the symmetry of the Onsager’s phenomenological coefficients. Consider the chemical system given in Fig. 4, where cross-effects occur.

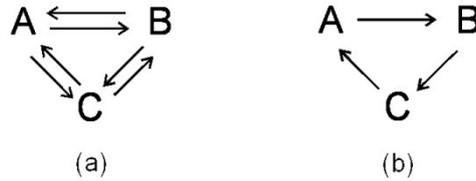


Figure 4. Reversible and irreversible cyclic reactions.

The one-way cyclic balancing seen in Fig. 4b is prohibited by the principle of detailed balancing. It says when equilibrium is established between reactants in a reaction system, any branch of reaction and its reverse must take place at the same rate or equal frequency. This is called the principle of microscopic reversibility [27]. In fact one-way cyclic reactions especially seen in ecology like ‘fox feeds on bird which feeds on frog which feeds on flies, which feed on dead fox’ never reach true equilibrium although asymptotically stable equilibrium is achieved; that means the change in the number of any of the species with time has oscillations. The equilibrium for the reaction seen in Fig. 4a can be achieved only when the Onsager phenomenological coefficients defined by ‘ L ’ in (23) have symmetric properties,

$$L_{11} = \frac{(k_{AB}+k_{AC})n_{Ae}}{R}, L_{12} = -\frac{k_{BA}n_{Be}}{R}, L_{13} = -\frac{k_{CA}n_{Ce}}{R} \quad (23)$$

where n_e refers to equilibrium numbers. The symmetry properties imparts $L_{12} = L_{21}$, $L_{23} = L_{32}$, and $L_{31} = L_{13}$. Under these conditions the irreversibility cannot be achieved and no change occurs since entropy change is zero. However the nonlinearity inherited in autocatalytic reactions as seen from (4), (5), (12), (16) and (19) distorts the equilibrium conditions and favors the temporary rise of one species against others. It naturally invalidates the Onsager principle which is good only at small driving forces which can be Taylor expanded.

According to (11) autocatalytic reactions yield zero entropy at small fluctuations. This result was achieved as the chemical potential was approximately taken to be equal to $R_G T n'/n_S$ which was obtained after linearization of (6). The nonlinearity can be taken into account by taking the chemical potential to be equal to $R_G T \log(1+n'/n_S)$ from (6). Its substitution in (7) yields, for $\sigma > 0$,

$$-(k_2 \beta_R^{-1} R_S F') \log\left(1 + \frac{R'}{R_S}\right) (-k_2 \beta_F^{-1} F_S R') \log\left(1 + \frac{F'}{F_S}\right) > 0. \quad (24)$$

It can be put into the form,

$$\left(1 + \frac{R'}{R_S}\right) < \left(1 + \frac{F'}{F_S}\right)^\alpha \quad (25)$$

where

$$\alpha = \frac{R' F_S \beta_F'}{F' R_S \beta_R'}. \quad (26)$$

The fox population is always smaller than rabbit population, so it is logical to assume that $F_S \ll R_S$. So it is logical to assume $R'/R_S < F'/F_S$. By using the series expansion,

$$(1 + x)^\alpha = 1 + \alpha x + \dots \quad (27)$$

we can write (25) in the form,

$$1 + \frac{R'}{R_S} < 1 + \alpha \frac{F'}{F_S}. \quad (28)$$

Its simplification gives,

$$\frac{\beta_F'}{\beta_R'} > 1. \quad (29)$$

This condition seems trivial but it is essential to get irreversibility (e.g. $\sigma > 0$) in evolution. The number of predators lost must be sufficiently high to satisfy (29) in a three-body system. However, it does not have to be so in a many-species system of wild life, because, different possibilities may result in different varying ratios for (29) in the network formed from many feeding pathways. However, (29) essentially points out that the Malthus principle of ‘limited food supplies but geometric multiplication of populations’ can constitute the very basic irreversibility principle in evolution. In fact, Boltzmann believed that nonlinearity in the universe may underlie the origin of irreversibility.

Autocatalytic reactions tend to lower entropy as they push the system towards the domination of one type of species, but they also introduce irreversibility if the dominance of one species is controlled by rate of birth of preys and hunting capabilities of predators. In other words the coexistence and coevolution of many species provides sustainability and persistence of prevailing situation; the more the number of species the less the dominance of one species, and the more the irreversibility.

Another important implication of (29) is that the number of preys must be more than the number of predators, because, not all molecules of preys hunted by predators are transformed into molecules of new borne predators. So (29) is a kind of efficiency relation in terms of material content of species. In fact, in classical thermodynamics there is a very close relation between entropy and efficiency; the high entropy production leads to lower efficiency. Efficiency is inherent to all real processes taking place in a finite time interval in nature, and thus entropy production or irreversibility is inherent to all processes. Autocatalysis tries to minimize entropy production, but its inherent nonlinearity leads to entropy production, and thus provides irreversibility.

As a summary we can notice that autocatalysis introduces several fundamental issues; (i) it provides oscillatory changes between species as in Schlögl-1 and Schlögl-2 given in Table 2, (ii) lowers entropy due to speciation, (iii) leads to complexity, and (iv) provides nonlinearity and the reversibility of momentum becomes different than the reversibility of time; in other words, the reaction like Schlögl-2 prevails in evolutionary systems with $k_C = 0$. In fact this last property is the most important property of autocatalysis. It lowers configurational entropy but its nonlinear dynamics imparts irreversibility. The oscillations of autocatalytic reactions damp in time due to decrease of one of the components, and finally terminate with a pattern formation which is an irreversible end. A good example to this is Belousov-Zhabotinsky reactions [28, 29]. In biological evolution the rate constants k 's change in time as mentioned

earlier, which in turn change the oscillatory dynamic balance (or quasi-equilibrium) between species. As a result new equilibria are established even though some of the species may go extinct or new species come into occurrence in the long run.

Let us assume certain functionality was achieved after a series of phenomenon as a useful property for the organism. If another one achieves slightly different mutations but gains the same property in a less cumbersome series of steps of reactions, then the second organism spends less energy in the overall and may utilize its remaining energy in somewhere else to achieve additional property. So the second organism gains higher chance for its survival. In other words the configurations of networks of biochemical reactions form the basis of the efficiency of the system. It, in turn, affects both the present adaptability of the species to their environment, and also the potentiality of their offsprings to the conditions in future. In fact the final system evolves from the contribution of many interactions. It is not only the network of reactions but also the chemical rate constants affect the efficiency of reactions. Two systems with same set of chemical reactions having different rate constants yield different entropies, because, entropy generated in the steps of reactions will be different. So in the overall the Kolmogorov-Sinai entropy will be different, and in the final step different configurations or patterns either in the form of network of reaction pathways or in the form of anatomical structure will come out. So reaction rate constant has decisive effect both on the form of final state, and also on the extent of irreversibility.

In nonlinear or chaotic growth entropy and complexity both tend to increase together. The pattern formation in chaotic growth or any change of form is mainly determined by the existence of singular or fixed points. In chemical reaction network systems the number densities, the reaction rate constants, and the equilibrium constants of reversible reactions all play important roles for the value of fixed points besides the way the pathways of the network are connected to each other. These parameters, therefore, also determine the way functionality evolves and also the memory developed since memory is related to fixed points [30].

The gain of information through mutations may not always be useful for a single species, but it is good for the entire herd; the more the mutations in the herd the more the chance to achieve future equilibrium for some of them. Mutations leading to functionality are the useful ones for success in survival. There, autocatalysis plays an important role; the set of reactions leading to functionality should be amplified. That is, a pattern representing certain functionality should form with high efficiency. In the chaotic behavior of logistic curve entropy keeps constant between two bifurcation points, but it increases right after the bifurcation [31]. Autocatalysis can reduce the increase of entropy while information content or complexity keeps increasing at larger extents, meanwhile the number of functionalities increase. So what actually evolve are information content, complexity, and functionality. It is the complex property or quality not quantitative measures that evolve. Entropy increases fragmentation and quantity, evolution counteracts against fragmentation and enhances the complexity of properties.

The functionality must be unique and must not be interfered by other interactions. If we eliminate the B-pathways and the reversing paths in Fig. 3d and Fig. 3c we get Fig. 5a and Fig. 5b, respectively.

Figure 5a is a four component system, and Fig. 5b is a five component system. It is clear that Fig. 5a has lower entropy than Fig. 5b. This is, because, CD is common for both ACD and CDE in Fig. 5a, and ACD truly autocatalyzes itself in the form of CDE. In Fig. 5a C controls only D, and D controls both A and E, whereas in Fig. 5b C controls both D and E. The asymmetry in Fig. 5b leads to an increase in entropy, and thus Fig. 5b has relatively higher irreversibility

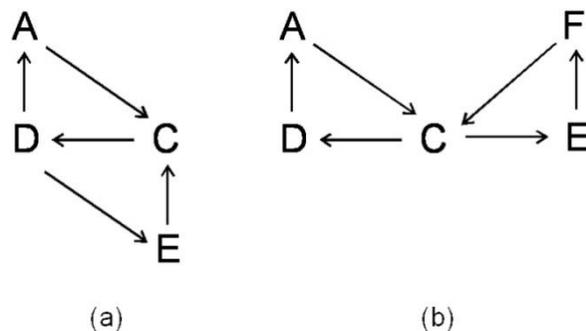


Figure 5. Branching.

than Fig. 5a. In Fig. 5a the new patterns can be achieved through the growth on DE and CE. However, in Fig. 5b the new patterns can be achieved through the growth on CE, EF, and CF. In other words, CEF in Fig. 5b has three degrees of freedom while CDE in Fig. 5a has two degrees of freedom. Therefore Fig. 5b is more likely to result in more new patterns and thus associated functionalities. The increase of entropy naturally leads to new possibilities and thus branching in network configurations. In chaotic dynamics the changes are so sensitive to initial conditions that a tiny change can lead to an abrupt great change since differentiability is lost in chaos. Actually in chaos the frequent bifurcation points represent branching, and so the higher the chaos the more the chance for new patterns or new functionalities. Chaos brings in higher chance for differentiation.

The increase of the number of functionalities in a system is usually achieved through the increase of complexity. However, a specific functionality has its own set of operations and interactions not much interfered by others. Otherwise specific jobs couldn't be achieved. For instance, each enzyme does have and actually should have only one job. In this respect its functionality is unique and persistent. To achieve the stability the molecular size of enzymes are usually huge, and thus the configuration of the active site is not disturbed. So the evolution of a specific functionality takes place at the expense of the decrease of interfering reactions. For instance if we write down the entire chemical rate equations and put the rate expressions into a matrix form, then the matrix belonging to Fig. 3c will have less number of matrix elements than that of Fig. 3f; the former has 20 zeros while the latter has 15 zeros in the matrix. If we let F to denote certain functionality then it is controlled only by E in Fig. 3c, but by both E and B in Fig. 3f. The interference by B decreases the persistence of F and its due function in Fig. 3f. The symmetry breaking is necessary for the generation of new functionalities. There are more reversible reactions and thus more number of interfering elements in Fig. 3f than in Fig. 3c. So Fig. 3c is more likely to generate new functionalities. A similar situation also occurs in the transcription of DNA. The segment transcribed serves only one job, and some part of the same segment is never transcribed for another job, that is no overlapping occurs. However, overlapping transcription is allowed in viruses as mentioned earlier, which are the most primitive and the least complex organisms.

OSCILLATION FREQUENCY

As mentioned before a simple Lotka-Volterra system is an oscillatory system with zero entropy production. These oscillations originate from stochastic behavior, and are not limit cycle found in rate equations [32, 33]. The frequency of oscillations can be evaluated by linearizing the set of equations given by (4) and (5). That is, we look for the solution in the form,

$$R = R_s + R' e^{cot} \text{ and } F = F_s + F' e^{cot}, \quad (30)$$

where R_s and F_s are steady state values of R and F , respectively; and they can be found in terms of rate constants by setting the rate equations (i.e. eq.4 and 5) to zero. R' and F' are the fluctuations around their steady state values. Equation (30) can be substituted in (4) and (5) and the solution for ω can be obtained after linearization. One then gets,

$$\omega = \pm i\sqrt{k_1 k_3} \quad (31)$$

It is seen that ω is pure imaginary quantity and periodic fluctuations are undamped, that is, the oscillatory behavior seen in Fig. 1 lasts forever. The oscillation frequency is given as

$$\nu = \frac{\omega}{2\pi} = \frac{\sqrt{k_1 k_3}}{2\pi}. \quad (32)$$

The Lotka-Volterra problem can be expanded to include more species as seen from the first column of Table 3.

Table 3. Other Lotka-Volterra problems.

Expanded Lotka-Volterra	Branched Lotka-Volterra
$A+B \xrightarrow{k_1'} B+B$	$A+B \xrightarrow{k_1'} B+B$
$B+C \xrightarrow{k_2} C+C$	$B+C \xrightarrow{k_2} C+C$
$C+D \xrightarrow{k_3} D+D$	$C+D \xrightarrow{k_3} D+D$
$D+E \xrightarrow{k_4} E+E$	$C+F \xrightarrow{k_6} F+F$
$E \xrightarrow{k_5} \text{extinct}$	$D+E \xrightarrow{k_4} E+E$
Overall :	$F+G \xrightarrow{k_7} G+G$
$A \rightarrow \text{extinct}$	Overall :
Pathway :	$E \rightarrow \text{extinct}$
$A \rightarrow B \rightarrow C \rightarrow D \rightarrow E \rightarrow \text{extinct}$	$G \xrightarrow{k_8} \text{extinct}$
	Pathway :
	$D \rightarrow E \rightarrow \text{extinct}$
	□
	$A \rightarrow B \rightarrow C$
	□
	$F \rightarrow G \rightarrow \text{extinct}$

As before, the solution can be found by substituting $k_1 = k_1'A$ since A does not essentially change. The β values also can also be dropped off or absorbed in the rate constants. One gets

$$\omega^4 + \left(\frac{k_1 k_2 k_5}{k_3} + \frac{k_1 k_3 k_5}{k_4} + k_3^2 \frac{k_1 k_3}{k_2 k_4} \right) \omega^2 + \frac{k_1^2 k_2 k_5^2}{k_4} = 0. \quad (33)$$

For mathematical simplicity we set $k_1 = k_2 = k_3 = k_4 = k_5 = 1$. Equation (33) then becomes

$$\omega^4 + 3\omega^2 + 1 = 0. \quad (34)$$

Its roots are

$$\omega_{1,2} = \pm 1,618i \text{ and } \omega_{1,2} = \pm 0,618i. \quad (35)$$

The roots are pure imaginary as in the case of three-species Lotka-Volterra problem and the oscillations are not damped.

Now we can introduce branching to the Lotka-Volterra equation as seen from the second column of Table 3. The solution for this branched case yielded six roots, and they were all pure imaginary. Every new step introduced in prey-predator models introduces a new frequency. From oscillations point of view the system is a collection of different oscillations

in a way that they are somehow synchronized; the change in one frequency influences the overall behavior. The change in one of the frequency in the long run period can be due to mutations occurring. The other frequencies must cope up with the change; in other words the entire system must coevolve. Prey-predator interactions and competition with similar kinds both affect coevolution [34].

The Lotka-Volterra type interactions no matter how many species are involved or how they are branched always have purely imaginary ω values. In other words, in wild life the populations are oscillatory, and the entire system is somehow at steady state. So what pushes evolution is the change of rate constants ' k 's in time, and it is due to mutations occurring at the genes of species.

When Schlögl-1 was examined with the same procedure it yielded two roots for ω . One is real positive and the other is real negative with no imaginary component. These roots denote that we have a saddle point. So it can go either direction towards stability or to instability. This is expected, because, Schlögl-1 represents a state with first order phase transition. The change from one phase to another phase can be well understood as a change from unstable to stable state, or vice versa.

The ω values for Schlögl-2 were also similar to those of Schlögl-1 with one positive and one negative value. However if we set, $k_C = 0$, that is if $C \rightarrow B + X$ is prohibited in the last column of Table 2, then the roots come out to be,

$$\omega_1 = 0, \omega_2 = -(k_{AB} + k_{BC}), \quad (36)$$

where k_{AB} involves also ' A ' in molar quantities. Therefore we get a straight line instead of a singular point or saddle point. Since the sign of ω_2 is negative it represents stability, i.e. the fluctuations die out in time. So the system is stabilized through irreversibility. This is an important conclusion, because, natural phenomena reach equilibrium by producing entropy in open systems. The condition $k_C = 0$ stabilizes the system, and the final stability is achieved through the accumulating formation of C .

COHESION OF INTERACTIONS

A network entropy is generally defined in terms of the number of vertices ' V ', such that [35, 36],

$$\Delta S \sim \log V. \quad (37)$$

In prey-predator systems a predator feeds on many different preys, so this equation can be written in the form,

$$\Delta S \sim \sum_{i=1}^V p_i \log p_i \quad (38)$$

where V denotes the number of predators, and p_i denotes the probability (or the fraction) of preys that the predator feeds on. The number of prey-predator interactions can be visualized as a network, and the higher the number of edges emanating from a vertex the higher the cohesion of interactions. In other words the edges emanating from the vertex denotes the variety of preys that the predator feeds on. As V increases the entropy change also increases. A crowded wild life with increased number of predator species (i.e. high entropy state) makes evolution difficult, because, there will always be a predator around to hunt a mutated prey. The probability of survival of preys increases if predators diminish for some reason (i.e. if entropy decreases). In fact geological disasters accelerate the evolution of new species at the expense of disappearance of others. Mammals of mouse size first appeared by the end of third geological period, and they dominated the world by the mass extinction of about 90-95 % of species including dinosaurs about seventy five millions years ago. Mammals would probably never so much evolved into their present forms if there had happened no geological disaster due to fall of giant meteorite on Yucatan region.

The sexual preferences of males or females can also be represented by a network. The strong preferences decrease the number of edges emanating from a vertex which represents a male or female, and the cohesion naturally gets weaker. It, in turn, facilitates the occurrence of new species.

In a network, entropy increases as the number of vertices increases, but cohesion increases if the number of edges connecting different vertices increases, that is, cohesion depends on the density of connections of vertices. Complexity depends on both; the increase of the number of vertices and the increase in the number of edges connecting vertices contribute to the increase of complexity.

The decrease of the number of interactions or the decrease of cohesion in any network system leads to (i) increased chance of functionalization, (ii) increased rate of evolution by allowing species with different mutations to survive, and (iii) increased rate of speciation due to strong sexual selection.

COHESION AND OSCILLATION FREQUENCIES

The number of frequencies generated depends on the number of species in the system, and the reversing paths of interactions do not contribute to the number of frequency. The number of oscillation frequencies gives an idea about the complexity of a system, the higher the number of frequencies (i.e. the higher the number of vertices in a network) the higher the complexity. However, this is not sufficient, because Fig. 3b and Fig. 3d have equal number of steps, yet Fig. 3d has lower entropy and higher information than Fig. 3b as seen from Table 2. The interaction between the components of Fig. 3d is tighter than that of Fig. 3b; in other words, Fig. 3d has higher cohesion than Fig. 3b yielding higher complexity. As mentioned above complexity depends on both the number of vertices (i.e. species) and the interactions between them. It was also mentioned above that autocatalytic effect in Fig. 3d is stronger than that in Fig. 3b. In other words the structures which have higher uniformity or symmetry is naturally expected to depict higher cohesion as crystals have higher cohesion than amorphous materials of same atomic/molecular structure. By the same token the similarity of oscillation frequencies to each other in a complex system represents the level of cohesion in that system. Such systems are relatively more stable, and subject to a low profile evolution. In these systems the similarity of frequencies represents a state where resonant coupling is more likely, and coherence prevails. Systems with low level cohesion or with dissimilar oscillation frequencies involve higher asymmetries, and are apt to subject to higher level of branching and thus to evolution.

A system always reacts in a way to stabilize itself in a coherent form. Mutations destabilize it, and evolution forces it to stabilize at future conditions. Since the overall entropy in the universe always increases the matter falls apart from each other. In other words cohesion decreases in cosmological time in accord with the increase of entropy. The decrease of cohesion naturally decreases the interactions within the system, and it becomes more susceptible to interact with other objects outside the system. The decrease of cohesion and thus the decrease of mutual interactions in the system can be recovered by introducing new controlling parameters. It can be provided only by the addition of new components to the system. The new components naturally add new oscillation frequencies, and thus new behavioral modes, and increased complexity. So evolution drifts in the direction of stabilizing a loosened system by increasing its complexity. In other words, it is a reaction to the increase of entropy in the universe. Since the least action or minimum energy principle is a fundamental law of nature evolutionary processes obey it by frequently employing autocatalytic dynamics.

CONCLUSIONS

Autocatalysis forms the foreground of evolution, and natural selection as a mechanism of evolution takes place among different species which try to autocatalyze themselves either through competition for food or for sexual partner. Autocatalysis is an entropy reducing process since it attempts to decrease the number of other competitors. The mutations change the chemical reaction rate constants of interactions between species; therefore, the irreversibility in evolution is associated with the irreversible change in rate constants. Autocatalysis can also explain sharp changes like first order phase change, and irreversible changes like second order phase change. The increase of entropy due to irreversibility is counteracted by the increase of information which could be achieved through the increase of complexity, which depends both on the number of components and the number of interactions in a network system. Evolution is slow if the interactions between the components of the entire system are intense, or if cohesion in the system is high; otherwise, evolution is accelerated. Evolution propagates in the direction of increase of complexity. The number of oscillations associated with autocatalysis increases with the number of components in a system. The similarity of oscillation frequencies gives an idea about the cohesion strength in a system.

In this manuscript autocatalysis as the underlying principle of evolution and complexity was discussed from different aspects. Computer simulations need to be done to carry out specific case studies and to have better understanding of the evolving specific systems.

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AUTOKATALIZA KAO FILOZOFIJA PRIRODE KOJA JE PODLOGA KOMPLEKSNOŠTI I BIOLOŠKE EVOLUCIJE

G. Gündüz

Odsjek kemijskog inženjerstva, Bliskoistočno tehničko sveučilište
Ankara, Turska

SAŽETAK

Analiziran je značaj različitih vidova autokatalize u evoluciji. Ponašanje autokatalitičkih reakcija, prvenstveno opisanih jednadžbama Lotke-Volterra i Schlögl, razmatrano je u okviru promjene faze, entropije i pripadnih frekvencija osciliranja. Porast kompleksnosti kao opći smjer evolucije analiziran je jednim djelom pomoću njihove entropije i informacijskog sadržaja. Zaključeno je kako su evolucijski pomaci u smjeru porasta kompleksnosti jedna vrsta filozofije prirode koja se suprotstavlja porastu entropije svemira.

KLJUČNE RIJEČI

autokataliza, entropija, evolucija, kompleksnost, informacija, frekvencija osciliranja, kohezija

AN INTEGRATED SUSTAINABILITY ASSESSMENT OF THE SWEDISH SUGAR PRODUCTION SYSTEM FROM A LIFE-CYCLE PERSPECTIVE: 2003-2015

Barry Ness*

Centre for Sustainability Studies (LUCSUS), Lund University
Lund, Sweden

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ABSTRACT

The article presents a sustainability assessment of the beet-to-sugar production system in Sweden from 2003 until 2015. It focuses on the life-cycle phases of beet growing, beet transport and sugar processing. Based on the Swedish sustainable development strategy, eight indicators in environmental and socio-economic domains based significantly on EU price and production quota changes are assessed. The study also appraises the autumn wheat-to-flour production system as an alternative scenario to provide a better understanding of the overall impacts on the region of the effects of the EU price and quota changes. The method used is a system analysis (simulation) model developed with the software STELLA 9.1. The study is a part of a broader regional sustainability assessment that focuses on the sugar sector in Sweden. Model results of the combined sugar and flour systems show general declines in agricultural landscape diversity and revenues earned in the region with only slight decreases in the number of full-time jobs in the region. Results also reveal decreases in the amount of nutrient runoff, fossil fuel energy use, greenhouse gas releases and field chemical use, with more substantial decreases in biodiversity via the suspension of organic beet growing in the region.

KEY WORDS

sustainability assessment; sugar; Sweden; life-cycle perspective; STELLA software

CLASSIFICATION

JEL: C31, C32, O18, Q13, Q15, Q18, Q41, Q47

*Corresponding author, η: barry.ness@lucsus.lu.se; +46 46 222 4809;
PO Box 170, 22100 Lund, Sweden

INTRODUCTION

Concerns have been raised in recent decades regarding the sustainability of the European beet sugar production systems e.g. [1-4]. The discussion has not only focused on the regional environmental impacts from the sugar production chains, but it has also centred on the impacts – significantly economic – caused by European sugar policies on sugar production systems in- and outside of Europe. At the same time as these concerns have been lodged, sugar beet growing in European Union (EU) member countries in past decades has also grown to represent an economically integral part of European agriculture – propelling the EU in the recent past to the position of the second largest exporter of sugar in the world. The situation changed, however, in 2002 when the cane sugar-producing countries of Brazil, Australia, and later Thailand, sought consultations with the World Trade Organisation (WTO), alleging the EU's violation of its obligations for sugar under the WTO Uruguay Round Agricultural Agreement [5]. The three countries claimed that EU exports, and re-exports of imported sugar, should be considered as subsidized exports – creating a situation where the agreed upon quantity limit of 1,3 million tons of subsidized exports was being overshot by about 3 million tons annually e.g. [6]. To fend off retaliatory actions, subsequent reforms of the trade distorting system in the EU have been underway since the reform agreement by the EU Council of Ministers in November 2005 and formal reform adoption in February 2006 [7]. The EU sugar sector restructuring has meant step-wise cuts up until the year 2010 in both sugar and beet prices as well as individual member-country production quotas with the overall goal of removing six million tons of sugar from production. The proposed policy modifications have meant large cuts in EU intervention prices, or more specifically, a 36 % decrease in the price of sugar and a 39,5 % reduction in the beet price paid to farmers [8].

There have been a multitude of studies focusing on EU sugar policy changes e.g. [8-11]. The vast majority of these studies, however, have concentrated only on the economic implications of EU sugar policy changes brought about to create a more equitable global sugar trading market. But what have been impacts of the sugar production system on regional *sustainability* – that is, its impacts on a wider set of both socio-economic and ecological system (SES) parameters? Furthermore, what are the expected future regional effects on the wider set of sustainability based on the on-going EU sugar policy reform efforts along with forecasted sugar consumption trends?

With an emphasis on the EU reform measures the aim of this paper is to assess the significant impacts of the regional sugar production system in Sweden from 2003 to 2015. Based on Swedish sustainable development strategy (SDS) priorities, eight SES indicators from the sugar production system – focusing on the life-cycle production phases of beet growing and harvest, sugar beet transport and sugar processing are estimated. Furthermore because the decrease in sugar production, and hence beet growing, does not automatically correspond to a decrease in agricultural production in the region, the equivalent parameters for the alternative production scenario of autumn wheat growing for flour is assessed as one alternative for the land area previously devoted to beet growing. The goal is not to exhaustively assess each individual parameter, but it is to rather analyse the main contributors from each respective system for each production phase in order to gauge overall impacts from policy reforms. The objective is to estimate the wider indicator set, showing potential trade-offs between each indicator as well as provide a more realistic production scenario for the region given larger sugar policy changes.

The paper begins with the background to the Swedish sugar sector and the indicators selected. Through the use of a computer simulation model, it assesses the indicators for the Swedish beet-to-sugar production system based on EU sugar quota levels for Sweden. The paper then estimates the same indicators for the wheat-to-flour system, and combines the two to determine the aggregated impacts from the combination of both systems. The study is a part of a broader regional sustainability assessment focusing on the Swedish sugar sector. The model has been developed for analysing alternative production scenarios, which will be the focus of subsequent analyses, which will be focused on in subsequent papers.

METHODS AND MATERIALS

The method used was an integrated assessment model (IAM) using STELLA 9.1 software (see: <http://www.iseesystems.com>). STELLA is a stock and flow-based software where the practitioner can create and run simulations over time. Impacts for each of the eight indicators were calculated for each of the three sugar life-cycle production phases, weighted in a common unit (e.g. CO₂-equivalents) and then, where applicable, aggregated with other production phases. The autumn wheat-to-flour scenario included the same indicators, but included five production phases. Materials for the background comprised of academic literature on other sugar and flour systems and governmental reports focusing on Swedish sustainable development and environmental quality priorities. Materials for the model included statistical data for both the sugar and flour systems from a variety of sources – including government statistics, other sugar and flour system assessments as well as industry-specific data. The model relied on region- or industry-specific data when available.

BACKGROUND

SWEDISH SUGAR PRODUCTION

The beet-to-sugar production system in Sweden is similar to production systems in many other EU countries. It has been subject to continual economic rationalization pressures – particularly since WWII [12]. In 2003, the two remaining processing facilities in Sweden produced roughly 417 000 tons of sugar originating from 50 000 ha of beet growing area; roughly 85 % of the beets are grown in the region of Scania at the southern tip of the country [13]. In Sweden, beet growing has represented one key part of a larger multi-year crop rotation system. Due to pest and plant disease problems, beets can at most be only grown on the same plot of land every fourth year.

The Swedish sugar production system is controlled by a complex set of both preferential and restrictive trading rules of the EU Common Agricultural Policy (CAP), which has effectively protected the European agricultural market system from outside competition. But due to ongoing internal and external reform pressures, more substantial reforms of the CAP have taken place in recent decades. Situated within the CAP system is the Common Market Organization (CMO) for sugar. The sugar CMO is the specific rules and regulations governing the sugar system in the EU. Also called the *sugar regime*, the CMO for sugar has, until recently, managed to exempt itself from any of the broader CAP policy changes. The sugar CMO is made up of three main elements: guaranteed prices, import protection and export subsidies [14]. These building blocks ensure the domestic preservation of the system through holding out outside sugar penetration into the EU except in cases where special import arrangements have been made with formal colonies in Africa, the Caribbean and Pacific Island (ACP) countries plus India, or special agreements with a group of least developed countries through accords such as the Everything but Arms (EBA) agreement. The result of the different measures has been an EU price for sugar that has been as much as three-times the world market price for sugar.

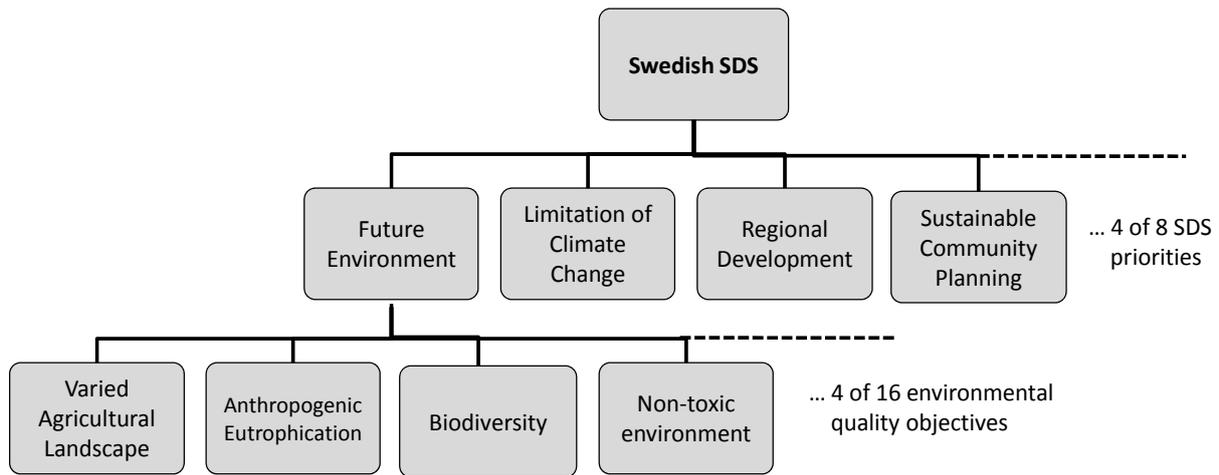


Figure 1. Swedish priority areas used in the study. The centre row describes the SDS priority area whereas the bottom row is the Environmental Quality Objectives.

INDICATOR BASIS

Assessment indicators are based on the Swedish SDS [15, 16] and the 16 Swedish environmental quality objectives (EQOs) [17], which are a part of the sustainable development strategy. Both the SDS and EQO were selected because they are used commonly as the priorities at the national level as well as at regional and local levels. The Swedish SDS consists of eight SDS core areas. Four of the eight broad priority areas were chosen because of their direct relevance to the sugar sector: *the future environment*, *limitation of climate change*, *regional development* and *community planning* (Figure 1, centre row). The 16 EQOs were established in the late-1990s and have been incorporated as sub-priorities of the SDS priority area of future environment (Figure 1, bottom row). They include a broad collection of environment-focused goals, many of which have direct relevance to agriculture and agro-industrial production systems. The four EQO areas chosen for this study are *a varied agricultural landscape*, *anthropogenic eutrophication*, *a rich diversity of plant and animal life* and *non-toxic environment* [17]. Table 1 displays the SDS parameters, the relevant environmental quality objective or the SDS sub-priority and the specific indicator calculated in the model. Hectares of sugar beet growing in the region were chosen to represent the goal of the varied agricultural landscape. Because of the fertile soils and Sweden's most favourable climatic conditions where beet growing is carried out, there is not a threat that a significant

Table 1. Table showing Swedish sustainable development strategy parameters, specific environmental quality objective or SDS sub-priority and the representative indicator measured in this study.

SDS parameter	Environ. quality objective/ SDS sub-priority	Specific indicator
The future environment	Varied agric. landscape	Beet area planted (ha/yr)
The future environment	Zero eutrophication	N & P leaching (t PO ₄ eq/yr)
The future environment	Rich plant/animal diversity	Eco-beet growing (ha/yr)
The future environment	Non-toxic environment	Herb. & pest. use (t/yr)
Limitation climate change	Reduced climate impact	GHG release (t CO ₂ eq./yr)
Regional dev. & conditions	Regional development	Full-time jobs (jobs/yr)
Regional dev. & conditions	Regional development	Revenues (thousands €/yr)
Sustain. comm. planning	Sustain. energy & transport	Fossil fuel use (GJ/yr)

share of the growing areas will disappear, except to peri-urban expansion processes. The agricultural landscape can however become less diverse with a decrease in the amount of beet growing in the region – a region dominated by cereals production. The second parameter that has presented challenges in recent decades is anthropogenic eutrophication of water bodies in and around southern Sweden. The challenge has led the goal of zero human-induced eutrophication, where agriculture is responsible for 49 % of nitrogen leaching and 45 % of phosphorus leaching to water in Sweden [18]. The most recent EQO is a rich diversity in plant and animal life. The indicator of organic beet growing (ha) was selected to represent a cropping system that allows a richer diversity in plant and animal life in and around beet growing areas through the absence of field chemical use (i.e. insecticides, herbicides, pesticides), synthetic fertilizers, etc. The final EQO-based parameter is the indicator of total pesticide, herbicide and insecticide usage. It was selected to represent the objective of a non-toxic environment, with the goal of eliminating man-made or natural compounds that represent a threat to human health or biological diversity. The main greenhouse gas (GHG) releases from the three life-cycle phases were calculated to represent Sweden's second SDS goal of a limitation of climate change and the overarching goal of a decrease in GHG emissions of four percent below 1999 levels by 2008-2012 [16]. The gases included in the analysis were CO₂, CH₄ and N₂O.

Parameters that were included directly in the SDS were the area of regional development that place priorities on the socio-economic development. For this category two indicators were used: the number of full-time jobs (in year-round-equivalents) in the respective production phases, and the gross revenues generated for sugar beets and sugar production as indicator for the sugar system and the gross revenue from the sale of wheat and the production of flour for the alternative production chain. Finally, fossil fuel usage was used as the indicator for the core area of sustainable community planning in the sub-priorities of energy and transport systems and infrastructure to represent national ambitions to reduce fossil fuel use.

Table 2. Prices and production quotas used in the simulation model [13, 18, 25].

Year	2003	2004	2005	2006	2007	2008	2009	2010-15
Beet price (€/t)	46,7	46,7	46,7	32,9	29,0	27,0	25,5	25,5
Sugar price (€/t) ²	632	632	632	631	631	541	404	404-450 ²
Quota (000 t)	417	405	406	372	354	327	403	328 ³
Wheat price (€/t)	90	93	100	113	150	274	153	121-140 ²
Flour price (€/t)	318	318	318	318	344	466	397	395-390 ²

¹Prices denote white sugar.

²Represents a step-wise increase (or decrease) in prices.

³Quantity signifies the national production quota plus an over production of 15 %.

MODEL AND ASSUMPTIONS

QUOTA SYSTEM AND GENERAL ASSUMPTIONS

The unit of analysis (functional unit) for the study is 50 000 ha of arable land in southern Sweden corresponding to the initial area used to produce the annual production of sugar (raw and white) for 2003, a representative production year prior to the sugar sector policy reforms. The model used actual Swedish production amounts for 2003 to 2009 and the proposed EU-CMO Swedish reform quota amounts for 2010-2015. The Swedish portion of the EU sugar quota from 2011 to 2015 was assumed to be the same as 2010 amounts based on present production quantity agreements. By-product production (e.g. molasses, beet pulp, animal feeds) and their corresponding revenues were also included in the calculations. Actual by-product commodity prices were taken from multiple Swedish Statistical Yearbooks e.g. [13, 18]. Future price

developments for these commodities were assumed to stabilize somewhat above 1997-2006 averages as specified in the OECD-FAO World Agricultural Outlook 2009 [25]. The sugar consumption life-cycle phase was not included in the model because of the multiple distributional paths sugar takes after being processed, e.g., food industry, beverage industry, confectionary industry, retail sales, further refining. A summary of beet, sugar, wheat and flour prices and quotas can be found in Table 2. The model was divided into a number of subparts (e.g. beet and sugar production, processing energy use, transport emissions, etc.), which used the parameter-specific input data from Tables 2-6. Special aggregation subsections were then created to weigh and compute aggregated quantities for each indicator area over time.

BEET GROWING AND HARVESTING

Basic assumptions for sugar beet growing are presented in Table 3. Average beet yields were based on real data from 2003 until 2009. The average yields fluctuate significantly annually due to such factors as precipitation and temperature. For the model created, average beet yields from 2010 were assumed to increase by roughly 1 t/(ha × yr) until 2015. Nitrogen and phosphorous leaching is a complex processes with many factors involved such as soil properties, water transport fertilization, and soil management. The model used average leaching amounts from studies in South Sweden on the types of soils most common to beet growing [23, 26]. N₂O releases from field were calculated as percentage of nitrogen applied. Economic calculations included only the costs paid to growers for the agricultural commodities or the revenues generated by sugar and flour producers. The purchase of extra quota amounts or the sale of a percentage of annual sugar production, likewise any additional profit-sharing agreement amounts between the beet grower and sugar processor, were not included in the model. Furthermore, neither one-time CMO sugar restructuring pay-outs nor general EU agricultural support pay-outs were included. All prices are in given in Euros (€) and were denoted as real prices. An exchange rate of 9,3 SEK per € 1 was used when data was acquired in Swedish Crowns. Because beet growing is part of a crop rotation system, the number of growers cannot be attributed to only beet growing. The number of growers was determined by dividing the average amount of beet hectares per grower divided by average farm size in Southern Sweden and then multiplied by the total number of growers.

Table 3. Basic beet growing model assumptions.

Area	Assumption	Source
Initial beet area (ha)	50000	[13]
Beet yield (tons/ha)	49,5	[13]
Ave. farm holding size (ha)	49,6	[13]
Ave. beet growing area (ha)	13,2	[12]
Growing energy use (MJ/ha)	21800	[19]
Beet N use (kg/ha)	115	[20]
Field treated N (%)	100	[13]
N in PO ₄ -equivilents	0,42	[21]
P use (Sw. Class III) (kg/ha)	25	[22]
Field treated P (%)	79	[13]
P205 in PO ₄ equivalents	3,06	[21]
N field runoff (kg/ha)	19	[23]
N ₂ O releases field (% N)	3	[17]
N ₂ O in CO ₂ equiv.	310	[24]
Total field chem. Use (kg/ha)	2,64	[18]
Beet area treated with chem. (%)	95	[18]

BEET TRANSPORT

Basic sugar beet transport (to processing facility) assumptions are shown in Table 4. Additional details on the Swedish sugar beet transport system can be found in [27]. All transport was assumed to be done by lorry; in reality a certain small percentage of beets are transported via tractor. All trucks were assumed to be fully loaded (36 t). Fuel type was assumed to be conventional diesel (MK1). The fuel use rate used was an average of the loaded rate to the facility and the empty load rate back to the field; the rate was based on actual industry data [*Personal communication with beet transport representative, 2006*]. The vehicle types were assumed to be a combination of Euro 2 and Euro 3 trucks. The number of full-time jobs in beet transport was determined through transport industry data.

Table 4. Model assumptions for sugar beet transport.

Area	Assumption	Source
Distance to facility (km)	50	[13]
Lorry fuel use rate (l/km)	0,52	Personal communication
CO ₂ release rate (kg/l diesel)	2,6	[28]
Beet payload weight (t)	36	Personal communication
Diesel energy content (MJ/l)	40,9	[29]

SUGAR PROCESSING

Sugar processing assumptions are provided in Table 5. There were two processing facilities remaining in Sweden up until the closure of facility 2 in 2006. Facility 1 was responsible for roughly 62,5 % of total sugar production; facility 2 produced the final 37,5 % [30, 31]. Facility 1 is significantly fuelled by natural gas; facility 2 was operated mainly by fuel oil. The processing facility produces two types of sugar: white and raw sugar. Each has a different price determined by the sugar CMO. In 2007 60 % of facility one's production was white sugar; the other 40 % produced was raw sugar (*Personal communication with sugar industry representative 2008*). Sugar prices were assumed to decline gradually from € 631/ton for white sugar in 2006 to € 404/t for processing year 2009. Prices for raw sugar were € 497/t in 2006, declining to € 335/t for 2009 [7]. Based on the OECD-FAO predictions, prices for both commodities were assumed to rise slightly in the period 2010-2015 due to increasing global demand for sugar and biofuels [25]. Sugar processing jobs were calculated as the number of full-time year-round employees of each respective facility. Seasonal workers were determined

Table 5. Model assumptions for sugar processing.

Area	Assumption	Source
Facility 1 processing (%)	62,5	[30]
Facility 2 processing (%)	37,5	[31]
Average sugar in beet (%)	17	[13]
Facility 1 N release (kg/t sugar)	0,144	[30]
Facility 1 P release (kg/t sugar)	0,002	[30]
Facility 2 N release (kg/t sugar)	0,117	[31]
Facility 2 P release (kg/t sugar)	0,002	[31]
Nat. gas use Fac. 1 (MWh/t sugar)	0,12	[30]
Fuel oil use Facility 2 (t/t sugar)	0,12	[31]
CO ₂ nat. gas release (kg/kWh)	0,21	[24]
CO ₂ fuel oil release rate (kg/l)	3,16	[31]
White sugar pro'd (% of total)	60	Personal communication
Jobs facility 1 (jobs/t sugar)	0,0007	[32]
Jobs facility 2 (jobs/t sugar)	0,0011	[32]

by dividing the number of workers divided by the length of the sugar processing season.

WHEAT-TO-FLOUR SYSTEM

Basic wheat-to-flour system assumptions can be viewed in Table 6. The flour production chain was used because it represents a likely alternative to sugar beet growing in the region – especially with recent commodity price increases for wheat. The wheat yield in the model was assumed to be 8 t/ha, which compares to a Swedish statistical average of 7,93 t/ha for the region [13]. The wheat was assumed to have 15 % wet weight content [20]. The wheat system was assumed to have a catch crop planted after harvest, which has been estimated to reduce nitrogen leaching by an additional 30 % [23]. Energy and fuel use and emissions for the catch crop were included in the calculations.

Table 6. Assumptions for the wheat-to-flour production system.

Area	Assumption	Source
Wheat yield (t/ha)	8	[20]
Growing energy use (MJ/ha)	16800	[34]
Wheat N use (kg/ha)	165	[20]
Wheat N runoff rate (kg/ha)	16	[35]
Wheat P use (kg/ha)	24	[22]
Wheat P runoff rate (%)	0,31	[26]
Wheat field chem. use (kg/ha)	0,61	[18]
Wheat payload (t)	11	[20]
Distance to silo (km)	10	Own estimation
Tractor diesel consumption (l/hr)	8	[18]
Lorry payload weight (t)	37	[39]
Distance to mill (km)	40	Own estimation
Wheat transport (h/load)	3	Personal communication
Energy use drying (kWh/t)	43,4	[36]
Wheat to flour ratio	1,28	[37]
Processing natural gas (m ³ /t)	1,14	[38,39]
Flour energy use (MJ/kg flour)	1,05	[33]

Wheat transport between field and dryer/grain storage facility was assumed to be carried out by the grower with a 75 kW four-wheel-drive four cylinder turbo diesel tractor pulling a trailer with an 11 ton wheat net payload; the one-way distance was assumed to be 10 km with a tractor using conventional diesel fuel (MK1) with a consumption rate of 8 l/h [23]. All wheat was assumed to be transported via lorry to the flour mill [*Personal communication with flour industry representative, 2008*]. The average single way distance was assumed to be 40 km, which represents the actual distance from a silo in the centre of the region to the mill in central Malmö. Since net payloads are similar, fuel use rates were assumed to be the same as beet transport. Flour production energy use was taken as an average of two industrial sized mills operating in Sweden [33]. Wheat prices were obtained from the online Swedish agricultural news, *ATL* (<http://atl.nu/marknad>), and based on Swedish prices at the start of each year. Conversions were then made to €/t. Flour prices were obtained from industry sources in SEK/kg and converted to €/t. Price developments for both wheat and flour were assumed to stabilize at a rate below the 2008 price peak but higher than the 1997-2006 average based on the World Agriculture Outlook [25] prognoses.

RESULTS AND DISCUSSION

Figures 2-4 illustrate the results until 2015 for each of the eight indicators. The three lines depict the beet-to-sugar system, the wheat-to-flour system and aggregate results for the combined systems. Results show that there will be general impact decreases in many of the environment-focused indicators. Whereas there will be general decreases in the two socio-economic indicators due to the decreases in annual sugar production quantities.

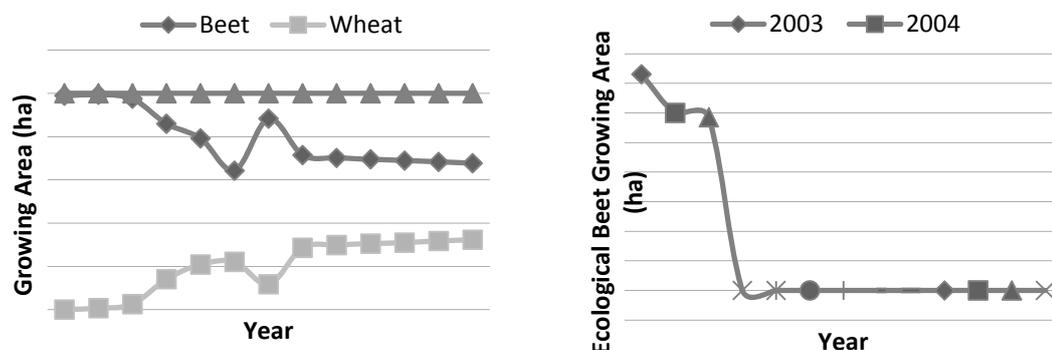


Figure 2. Land use model results for conventional beet growing and ecological beet growing. Results show the gradual decline in a varied agricultural landscape through conventional beet growing due to EU quota changes and general technology improvements. Results also depict a decrease in plant and animal diversity because of the closing of ecological beet production.

MODEL RESULTS

Land use

Figure 2 shows the two land use indicators under the Swedish SDS parameters of future environment. Simulation results (Figure 2 top) show a decrease in the goal of varied agricultural landscape with the sugar policy change in conjunction with the land being devoted to the flour production. The upper horizontal line denotes the 50,000 ha reference growing area. Due to the quota changes the figure illustrates the almost continuous decline in growing area from the 50,000 ha to under 34,000 ha by 2015 – with the vast majority of the decreases taking place during the 2006-2010 quota reduction period. The modest reductions for the final five years were largely due to technology-driven beet yield increases. The difference between the two lines is made up by the increasing amounts of growing area devoted to autumn wheat growing. The overall result is a less-varied agricultural landscape due to the increase in cereals growing area in the region. It is acknowledged that in reality a larger diversity of crop types would be planted (e.g. rapeseed, peas, other cereals) based on such aspects as commodity prices and the individual grower's rotation system. Further development of the model to include a greater diversity of alternative production and/or cropping systems will be carried out in the future. It should also be noted that larger yield efficiencies or even environmental impact decreases could be realized through the introduction of genetically modified (GM) beet growing, which would give differing results. Bennett, Phipps and Strange (2006) for example have compared GM system with conventional beet growing systems in different locations in throughout the EU.

The starkest change comes with the results for the category of rich biodiversity for the region through the indicator of ecological beet growing (and sugar production). The lower graph in Figure 2 describes the sharp decline in eco-beet growing – from a high of 1462 ha in 2003 to zero in 2006. The reason for the decline was the closure of the facility 2 between production years 2005 and 2006 resulting in no organic beet growing contracts being issued or organic sugar being produced in Sweden beyond 2005. It is not expected that ecological beet growing for sugar production in Sweden will emerge again in coming decade due to adequate supplies from past regional production and due to the ability to import organic cane sugar from South America (*Personal Communication with sugar industry official, 2008*). The assessment also assumed that the organic beet growing was not replaced by organic wheat growing as with the conventional production system due to the overall minuscule amounts of organic wheat production taking place in the region, namely 500 ha of organic wheat growing versus roughly 85 000 ha of conventional wheat growing [18].

Environmental indicators

Figure 3 shows the three indicators under the SDS parameters of future environment and limitation of climate change. It shows that there will be overall decreases in GHG releases, nitrogen and phosphorus runoff (eutrophication) and field chemical use with the sugar policy changes in conjunction with the switch to the wheat-to-flour system. The top graph displays the results for greenhouse gas releases from each system and the aggregated amounts for both production systems for the SDS priority of limitation of climate change. There is a decrease in greenhouse gas releases in the beet production chain for Sweden from 282 000 t CO₂-equivalents in 2003 to just under 208 000 t by 2015. Furthermore, because the flour

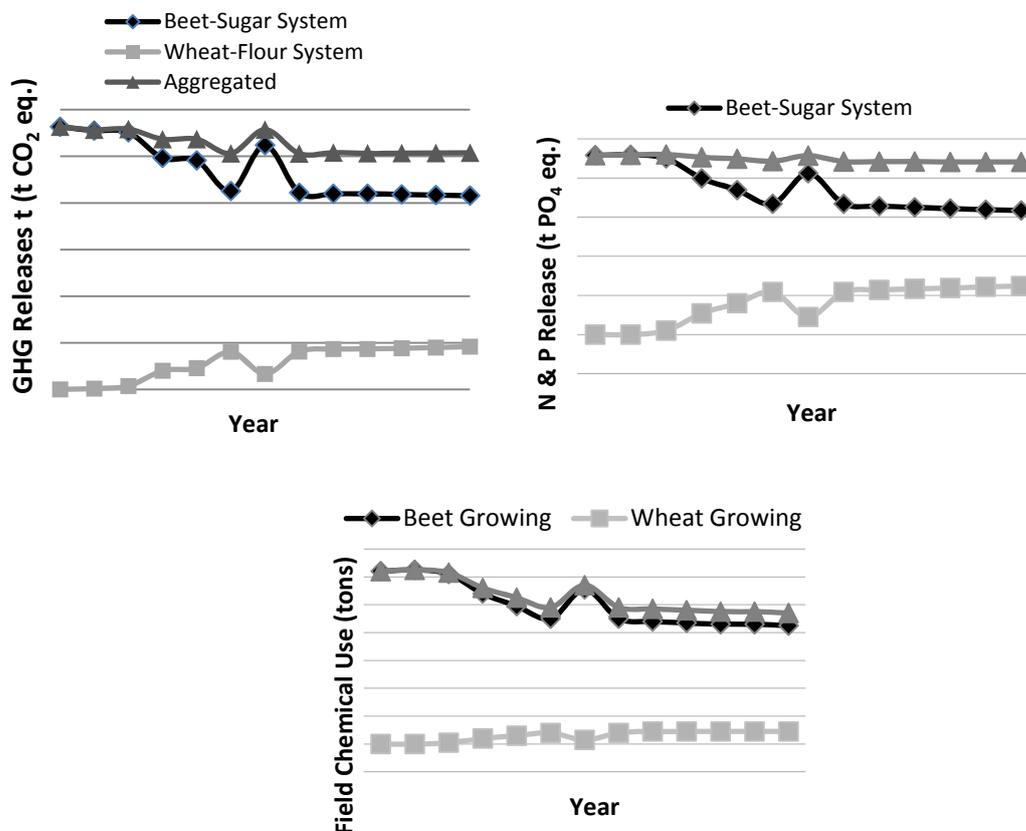


Figure 3. Model results for the three environmental indicators all showing similar patterns due to the beet quota decreases.

production system was less energy intensive in comparison with the sugar production system despite there being more life-cycle phases, there was an overall decrease with both systems from the 282 000 t at the beginning of the study to 253 000 t in the final assessment year – creating an almost 30 000 t CO₂-equivalent decrease by 2015.

Results are similar for the two main contributors to eutrophication, namely nitrogen and phosphorus runoff (centre graph). There is a substantial decrease in the amount of nitrogen and phosphorus leaching to waterways through the decreased sugar production from roughly 458 t PO₄ equivalents in 2003 to just over 317 t in 2015. With the inclusion of the flour production chain, results showed that there is also an overall slight decline in the quantity with the switch to the wheat system due to slightly lower nitrogen and phosphorus leaching rates of 17 t with the wheat growing system and a decrease in flour processing compared to sugar production, with a decrease from the 458 t PO₄ equivalents to 441 t with the combined systems. Despite the model results, it is also acknowledged that there could be an increase in runoff rates with the change-over to the autumn wheat system. The leaching rates used in the model were not based on the amount of macro nutrients applied to the field. The significant increase in the amount of N use with the wheat system, 165 kg/ha compared with 115 kg/ha for the beet growing system, could mean increased leaching from the wheat system. Additional analysis would need to be carried out calculating the nutrient balances of both systems and the effects of the catch-crop often planted after wheat harvest.

Field chemical use (bottom graph) decreases significantly for both beet growing and for the aggregated beet and wheat growing systems. With the decrease in beet growing in the region due to the policy changes, the beet growing system experiences an overall annual decrease from 124 t of insecticides, herbicides and fungicides to 85 t by 2015. Furthermore, due to the less intense use of chemicals for the autumn wheat system, aggregated chemical use for both systems also falls from the 124 t in 2003 to 94 t in 2015. It should be emphasized however that these are strict quantity decreases for field chemical use and say nothing about the overall toxicity on humans or impact on biodiversity from each of the specific field chemicals.

Socio-economic indicators

Figure 4 shows simulation results for the remaining three (socio-economic) indicators under the SDS areas of regional development and sustainable community planning. There are significant negative changes in the SDS priority area of regional development. The values from both beets and each of the two types of sugar (i.e. raw and white) decrease not only because of the Swedish production quota decrease, but decreases are also due to on-going price decreases for both beets and sugar. The revenues in 2003 were determined to be € 243 million and € 153 million by 2015. However, it should be noted that decreases in aggregated revenues are prolonged because of the general rises in both wheat and flour prices between 2006 and 2008, but then decline sharply with the assumed price reductions between 2008 and 2010. Revenues then recover slightly and stabilize due to the assumed price increases after the 2010. Total revenues from the combined systems decrease from € 243 million to € 169 million at the end of the assessment period – with much of the revenues coming from the sharp 2007-08 price increases for wheat and flour.

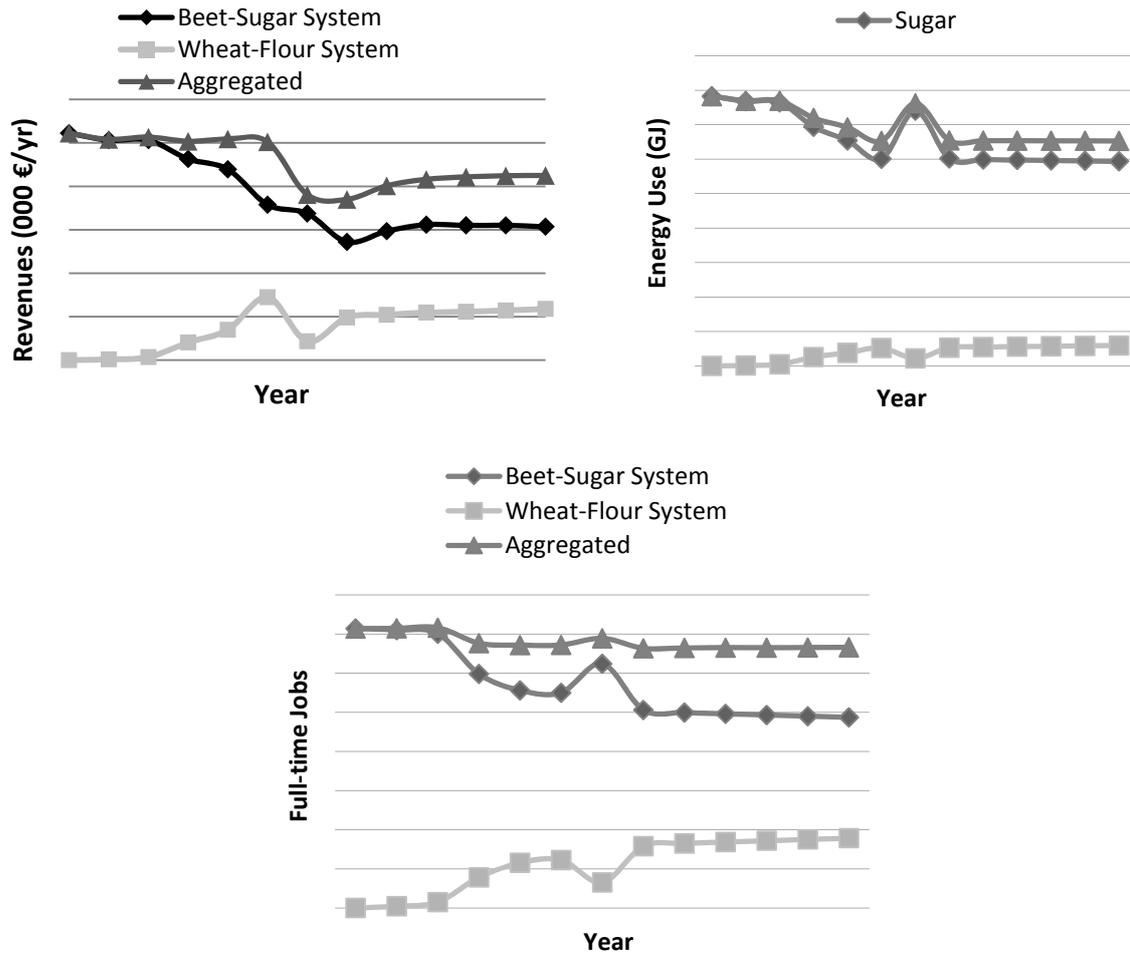


Figure 4. Model results for the three socio-economic indicators of production chain revenues, energy (fossil fuel) use and full-time jobs. The graphs show general decreases in all three aggregated indicators.

The centre graph in Figure 4 shows the results for the indicator for the goal of reduced fossil fuel use under the theme of sustainable community planning. As with numerous other indicators, there is an improvement (i.e. decreased use) with throughout the assessment period. The sugar production system shows the decrease of just below 4 million GJ of energy used in 2003 to an expected use of just under 3 million GJ by 2015. Aggregated results from both systems show an overall decrease to 3,26 million GJ. Due to modernization processes already carried out at sugar facility 1, the model assumed no efficiency gains or fuel type changes. But due to past rises in oil prices, it would be expected that additional fossil fuel use reduction measures would take place in both production systems throughout all life-cycle production phases.

Finally, the results for the other socio-economic domain indicator of full-time employment positions in the SDS area of regional development are provided in the bottom graph. The figure shows that full-time employment position losses by roughly one-third in response to the Swedish production quota reductions. The most significant changes to the sugar system occurred with the closure of production facility 2 for the 2006 production season – decreasing from just over 1400 jobs to below 1200. The numbers of full-time jobs for the combined systems in 2015 were just over 1300, which represent roughly a ten percent decrease in the number of jobs over the total assessment period.

ASSESSMENT APPROACH

Results of the study generally show that there will be both positive and negative implications due to the sugar quota and price changes for Sweden. Much of the early concerns in response to the changes by regional industry officials, grower organisations, etc. predicted dire consequences for the industry and region. Viewed in isolation there were significant impacts in the forms of job and revenue losses for the region; conversely improvements were recognised with a majority of the environment-focused indicators due largely to the energy and resource intensity of the sugar production chain. The inclusion of the wheat-to-flour system in the model represented one relevant and established production chain to utilise the land areas no longer devoted to beet growing. In a regional perspective, the inclusion of the system for understanding overall impacts on sustainability, in some cases positive, in others negative. The study reveals that such changes, such as beet production quotas and prices, cannot be viewed in isolation, but rather from the perspective of a complex mix of systems interacting and reacting with each other.

The study used the wheat-to-flour production system as the alternative for the land no longer devoted to sugar beet growing and sugar production. It is acknowledged that in reality with the decrease in sugar production in the region, the beet growing area would be distributed amongst a variety of cropping, and ultimately, food, and now more commonly, energy production systems. Relevant systems for southern Sweden include oats, rye, peas, rapeseed, etc. Another alternative that is being experimented with in the region, with the potential for large implications on land use patterns in the region, is beet (and other crops) for biofuels production, and in particular biogas. If done incorrectly, adding such production systems has the potential to create land use pressures and environmental impacts; at the same time, investments in the production chains can stimulate new rural development and job growth in non-urban regions.

It is acknowledged that the IAM created for the assessing the two systems could have also been performed using alternative assessment approaches (e.g. Life Cycle Assessment [LCA], Environmental Impact Assessment) e.g. [40] (for a more detailed description of other assessment tools see e.g. [41]). The stock and flow model represented a flexible approach. The software allows for the flexibility in including both environmental and socio-economic parameters and the interaction and feedbacks between them into a single model. LCA software has only begun in recent years to include both domains.

Because of the flexibility of the software, it is envisioned that future model use and experimentation can be expanded in a number of possible directions. One obvious starting point is to forecast the impacts from different national sugar quotas (including no national production quota), changing sugar and beet prices, efficiency rates, average transport distances, etc. All of these areas have the ability to be altered over time in the model, making it an useful tool for expanding and testing different regional land use and production scenarios over longer time perspectives. Furthermore, the addition of new assessment parameters, or even new production chains, can be added into the existing model with relative ease. Despite the approach's flexibility, a negative aspect is the time required for initially creating and verifying the IAM.

CONCLUSION

This article has assessed the sustainability of the Swedish sugar production system from 2003 until 2015 – with the intention of incorporating a wider assessment perspective. Based on the Swedish sustainable development strategy, the study focused on eight SES indicators. The article also used the autumn wheat-to-flour productions system as a scenario to gain the wider

perception of impacts on the region than just the effects of the EU sugar production and price quota cuts. Results of both systems combined included declines in landscape diversity and revenues earned in the region with slight decreases in the number of full-time jobs. Results also showed improvements (i.e. decreases) in the amount of nutrient runoff, fossil fuel energy use, greenhouse gas releases and field chemical use. The largest changes came in the area of biodiversity, with the suspension of ecological beet growing in the region.

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INTEGRIRANA PROCJENA ODRŽIVOSTI ŠVEDSKE PROIZVODNJE ŠEĆERA SA STAJALIŠTA PERSPEKTIVE ŽIVOTNOG CIKLUSA 2003.-2015.

B. Ness

Centre for Sustainability Studies (LUCSUS), Lund University
Lund, Sweden

SAŽETAK

Članak razmatra procjenu održivosti proizvodnje šećera iz šećerne repe u Švedskoj od 2003. god. do 2015. god. Fokusira se na faze životnog ciklusa rasta šećerne repe, njenog transporta i proizvodnje šećera. Na temelju strategije održivog razvoja Švedske, postavljeno je osam indikatora iz domene okoliša i socio-ekonomske domene koji su u znatnoj mjeri povezani s europskom cijenom i promjenama proizvodnih kvota. Članak uzima u obzir jesenski proizvodni ciklus brašna iz žita kao alternativu radi boljeg razumijevanja ukupnog utjecaja regije na europske cijene i proizvodne kvote. U članku se koristi simulacijski model sustavne analize razvijen pomoću programa Stella 9.1. Modeliranje je dio šire regionalne procjene održivosti koja se fokusira na proizvodnju šećera u Švedskoj. Rezultati modeliranja kombinirane proizvodnje šećera i brašna pokazuju općenito na smanjivanje raznolikosti agrikultura i smanjivanje zarada u regiji usporedo s neznatnim smanjenjem broja stalnih radnih mjesta u regiji. Rezultati također pokazuju smanjenje toka hranjivih tvari, uporabe fosilnih goriva, emisije stakleničkih plinova i uporabe kemikalija na poljima, kao i značajnije smanjenje bioraznolikosti zbog slabljenja organskog uzgoja šećerne repe u regiji.

KLJUČNE RIJEČI

procjena održivosti, šećer, Švedska, perspektiva životnog ciklusa, softver Stella

BIOMIMETICS IN MODERN ORGANIZATIONS – LAWS OR METAPHORS?

Markus Schatten* and Miroslav Žugaj

Faculty of Organization and Informatics, University of Zagreb
Varaždin, Croatia

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ABSTRACT

Biomimetics, the art and science of imitating nature and life for technological solutions is discussed from a modern organization theory perspective. The main hypothesis of this article is that there are common laws in nature that are applicable to living, social and likewise organizational systems. To take advantage of these laws, the study of nature's principles for their application to organizations is proposed – a process which is in product and technology design known as bionic creativity engineering. In a search for most interesting concepts borrowed from nature we found amoeba organizations, the theory of autopoiesis or self-creation, neural networks, heterarchies, as well as fractals and bioteaming which are described and reviewed. Additionally other concepts like swarm intelligence, stigmergy, as well as genesis and reproduction, are introduced. In the end all these ideas are summarized and guidelines for further research are given.

KEY WORDS

biomimetics, organization theory, autopoiesis, network science, bionic creativity engineering

CLASSIFICATION

JEL: B52, L22, M14

*Corresponding author, η: markus.schatten@foi.hr; +385 (0) 42 390891;
Faculty of Organization and Informatics, Pavlinska 2, HR - 42 000 Varaždin, Croatia

INTRODUCTION

Since the beginning of human history humans were inspired by nature and tried to incorporate such ideas into (better) solutions for everyday life. Biomimetics, biognosis, biomimicry, or bionic creativity engineering is the art and science of imitating nature and life for technological solutions. Many common products today like fasteners (George de Mestral, 1948), waterproof paint (Wilhelm Barthlott, 1982), windmill rotor turbines (Frank Fish, 2006) etc. were inspired by nature.

For example, after a walk in 1948, Swiss inventor George de Mestral had to clean his dog from all the burs it acquired during the walk. He discovered tiny hooks on the burdocks, and was amazed on how they got stuck on the dog's fell. After analyzing them under a microscope he invented a fastening system as a locking tape that was imitating the burs. It consisted of one cloth strip covered with tiny hooks and another covered with tiny loops. After the necessary preparations, he patented a new type of fastener, which he named *Velcro*, from "vel" – velvet, and "cro" – from the French word "crochet" – a small hook. Even if fashion designers did not accept his invention at first, such fasteners were used in lots of situations from the first heart implantation to space journeys like the Apollo mission from 1972, and as we know are in common use today [1; pp. 79-81].

Similarly in 1982 the botanist Wilhelm Barthlott discovered a waterproof surface on lotus leaves which was able to clean itself through waterdrops that fell on it. The secret was in tiny micro- and nano-structures that had a special angle that forced the water to turn into drops and wash all the dirt away. Barthlott patented his discovery and named it the "lotus effect" which was successfully applied to a biomimetic paint called *Lotusan* [1; p. 83].

Another success story of biomimetics includes the one of the functional morphology professor Frank Fish. He was wondering why humpback whale fins have little bumps all over the edges. He created a model based on the fin and discovered it sliced through the water with less resistance than a similarly sized smooth-edge fin. He applied his idea to windmill rotor turbines, and the results showed better performance than usual smooth-edge blades [1; p. 85].

In information systems there are also obvious metaphors borrowed from nature. For instance, genetic optimization algorithms use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover; neural network classifiers and recognition systems are inspired by the human brain and nervous system; while ant colony and swarm intelligence optimization and problem solving systems simulate social insect colonies.

As argued, there are lots of such examples in technology, information systems and product engineering but what about organization theory? Do nature's laws also apply to organizations, and if yes, can we use these laws to improve them?

In the following we shall introduce nature-inspired concepts defined in modern organizations, some of which are discussed in section 2. In section 3 the outlined concepts are analysed and discussed in order to show if they are laws of nature or metaphors. In the ending section 4 final conclusions and guidelines for future research are provided.

EXISTING CONCEPTS

The social sciences have a long history of applying biological metaphors to their research. *"All theories of organisation and management are based on implicit images or metaphors that persuade us to see, understand, and imagine situations in partial ways. Metaphors create insight. But they also distort. They have strengths. But they also have limitations. In creating ways of seeing, they create ways of not seeing. Hence there can be no single theory or*

metaphor that gives an all-purpose point of view. There can be no 'correct theory' for structuring everything we do." [2]. One of the metaphors Morgan's book describes is the one of observing organizations as biological organisms. Such living systems, and likewise organizations, adapt to environmental conditions, have their life cycles, needs, homeostasis, evolution, health, illness etc. [3].

On the other hand, the theory of autopoiesis or self-creation, a theory aiming on describing the essence of life, was introduced to the social sciences and formal organization theory by Niklas Luhmann [4, 5]. Autopoiesis, when following Maturana and Varela, is what distinguishes living from any other systems. This metaphor is especially interesting since it underlines that structures of nature replicate themselves in social and organizational systems.

Are organizations and living systems equivalent, similar or are the similarities just in the eye of the observer? In the following subsections we will try to discuss few representative biomimetic ideas in modern organizations that will hopefully yield better insight: (1) the amoeba organization, (2) neural networks and heterarchies, (3) the fractal company, (4) bioteaming, (5) swarms and stigmergy, and (6) genesis and reproduction. One should mention here that these are of course not the only ideas found in organization theory literature, but others exist like the fishbone diagram [6] or the spider's web [7].

THE AMOEBEA ORGANIZATION

The concept of the amoeba organization (or single cell organization) was firstly introduced in the company W.L. Gore & Associates in 1958. At that time the whole organization of this company was futuristic and science fiction in the eyes of commoners. Wilbert L. (Bill) Gore who founded it together with his wife Vieve had been additionally proclaimed anti-manager. The organization resided on principles like complete decentralization, self-organizing teams, flat hierarchy and organizational chaos [8].

The concept of the amoeba is a biocybernetic metaphor since its original ancient Greek meaning implies change or changeability. Especially a known subform of the *Amoeba Proteus* the so called *Amoeba Chaos Chaos* underlines the connection between chaos theory and this kind of organization. The amoeba organization relies on two simple but strong principles: (1) the organization is a process, not a structure, and (2) the organization is a complex (chaotic) system [8].

The metaphor implies that amoebae are simple single-cell organisms that are effective and functional, change their form even if the core organization remains constant, and they are able to learn from and react to outer impulses. If we take these ideas into an organizational context we get small (in the case of W.L. Gore & Associates a unit may have 150-200 employees) divisional or operational units consisting of self-organizing teams with a very flat (or not existing) hierarchy where team leaders are chosen depending on the particular situation.

If an amoeba senses a potential victim it dynamically creates a pseudo-hand and absorbs the victim. Likewise teams are established if a new opportunity is sensed in the environment of the organization and (like a pseudo-hand) try to take advantage of it. Similar to the amoeba, organizational units change their shape by changing their internal relations, teams and members. Still the structure of the unit remains consistent.

In the case when a unit outgrows the limit of employees, a new unit gets established. Likewise the amoeba reproduces itself through division [8].

Another example of an amoeba organization can be found in the Japanese Kyocera Corporation that reorganized its 50 divisions into 400 amoebas (Figure 1) [9]. Amoebas in this

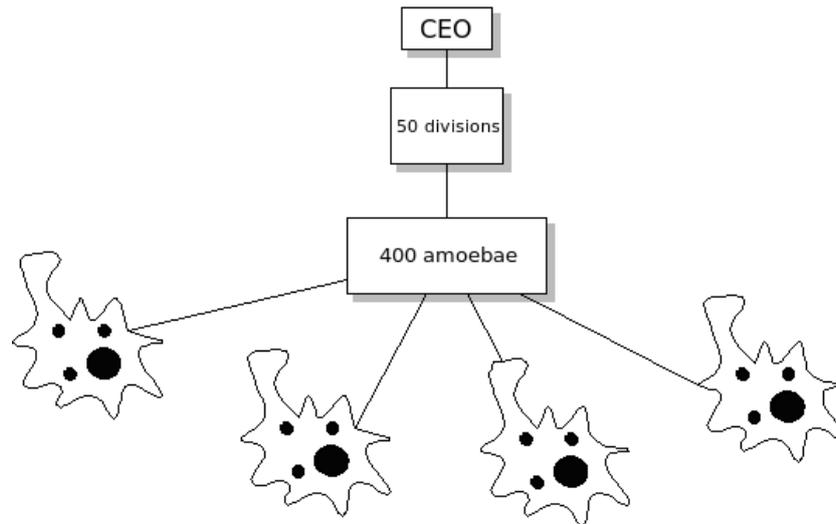


Figure 1. The amoeba organization of Kyocera Corporation [9].

company are self-organizing units that are responsible for their own business. Every amoeba has its own finance and human resource management. Amoebae do business together in an internal market environment, and are constantly in search for better customers. Depending on the situation in the environment they can be divided into smaller units or integrated with other amoebae [10; pp. 179-202].

The amoeba organization represents an organizational suprastructure [11; pp. 129-131] that is founded upon autonomy, flexibility and self-management [12, p. 263]. One can also observe that an amoeba organization does not exist by itself but is incorporated into some type of hierarchical structure [12; p. 264] which implies its superstructural nature.

AUTOPOIESIS IN ORGANIZATIONS

Autopoiesis, a pseudo-Greek word coined from $\alpha\upsilon\tau\acute{o}$ (auto) for self and $\pi\omicron\iota\eta\sigma\iota\varsigma$ (poiesis) for creation, production or forming was first coined by the Chilean biologists Humberto Maturana and Francisco Varela [7] to label the type of phenomenon which they had identified as the definitive characteristic of living systems [13].

Using the metaphor of autopoiesis, German sociologist Niklas Luhmann developed his theory of social systems based primarily on communication. He introduced the concept of autopoiesis to formal organization theory as well, basing his reasoning on a special subset of communication – decisions that, following Luhmann, build up the organization [8].

When discussing autopoiesis in the context of organization theory, one needs to make a clear distinction of two basic concepts. First there is the concept of organization used in three ways: (1) organization in an institutional sense – denoting a system of consciously coordinated people's activities with a common goal [14; p. 5], (2) organization in Maturana's and Varela's sense – denoting the instrumental participation of components in the constitution of a unity [15; p. 315] or basically a system of relations that build up a unity and (3) organization in Luhmann's sense – denoting a system of decisions [16; p. 106].

As second, there is the concept of structure that is used in two ways: (1) structure in the (traditional) sense – denoting a system of relations between organizational units, as well as (2) structure in the sense of Maturana and Varela – denoting the medium upon which the organization (in Maturana's and Varela's sense) of a unity functions. To prevent possible

confusion we shall use the terms organization and structure in their traditional senses if not stated otherwise.

As mentioned before, the concept of autopoiesis was first introduced to characterize living systems, as opposed to any other system. The original idea was to develop a new perspective of perception and cognition by stating that cognition is a phenomenon of the living. Thus it was necessary to find out what characterizes living systems which led to the notion of autopoiesis that became the core of the new perspective [13].

Varela gave the following definition of autopoietic systems:

“An autopoietic system is organized (defined as a unity) as a network of processes of production (transformation and destruction) of components that produces the components that:

- through their interactions and transformations continuously regenerate and realize the network of processes (relations) that produced them; and
- *constitute it (the machine) as a concrete unity in the space in which they [the components] exist by specifying the topological domain of its realization as such a network.*” [17; p. 13] adapted from [18].

Maturana stated that “... *autopoietic systems operate as homeostatic systems that have their own organization as the critical fundamental variable that they actively maintain constant.*” [15; p. 318]. Thus the concept of autopoiesis, at a most basic level, involves organizational preservation and componental (re-)production [13].

According to Luhmann, social systems are meaning processing systems and this is what distinguishes them from other types of systems such as biological ones [19; p. 104]. “*A social system comes into being whenever an autopoietic connection of communications occurs and distinguishes itself against an environment by restricting the appropriate communications. Accordingly, social systems are not comprised of persons and actions but of communications.*” [20; p. 145]. Social systems are networks of communication that produce further communication and only communication and are thus autopoietic systems [19; pp. 104-105].

Luhmann argues that there are three types of social systems: interactional, organizational and societal which differ mostly in terms of the ways they constitute themselves as well as the ways they select and form their boundaries. Interactional systems are comprised of communication between a set of people by making a distinction between people one talks *with* and people one talks *about*. Societal systems do not rely only on communication taking place, but also on previous (*stored*) communication. Organizational systems are special since they are formed of a special type of communication – decisions that set up the possible future states of the system.

As one can see from these various aspects there are a few crucial concepts one should have in mind before any discussion about autopoiesis. First, there is a distinction between structure and organization (in Maturana’s and Varela’s sense). While structure is something that is visible (observable) from the outside, organization is unobservable and inside of the system. Structure comprises of a set of components or elements that are exchangeable (meaning that components change during time) and the mutual interactions between these components. Organization comprises of the relations between these components and is stable over time. That means that structure does change but organization remains stable even if the components that make up the structure change over time due to interaction of the system with its environment.

This connection between an autopoietic system and its environment is denoted as structural coupling. “*The result of structural coupling is an autonomous and strictly bounded system,*

that has nevertheless been shaped extensively by its interactions with its environment over time, just as the environment has been shaped by its interactions with the system.” [21].

The mechanics of the process of autopoiesis as described by Maturana and Varela are kept strictly within the bounds of an autopoietic system. Thus autopoietic systems are closed in terms of operational and organizational closure [21]. While in living systems structure is comprised of biological processes, in social systems structure is according to Luhmann comprised of communication. Organization (in Maturana’s and Varela’s sense) is then comprised of the particular relations between certain communicative events.

Another important concept is the reproduction of components. While one can easily depict this process in living systems (e.g. living beings feed themselves with food from their environment that eventually, after certain processes, becomes an integral part of the living being facilitating thereby regeneration of the process) in social systems this reproduction is less obvious. If we follow Luhmann, then communicative events are reproduced by previous communicative events, or in the case of organizations (in Luhmann’s sense) decisions reproduce new decisions.

NEURAL NETWORKS AND HETERARCHIES

Neural networks are a new generation of computer software designed to function similar to the human brain. Such software consists of processing elements called neurons. Every processing element is able to send and receive signals to other elements. Some scientists see an interesting similarity between such structures and communication in organizations. Some communication lines grow stronger over time if used intensively whilst other channels weaken or even cease to exist.

The idea of a heterarchical organization comes from the neuropsychological research of the human brain conducted by Warren McCulloch in 1945. He concluded that the human brain must have a heterarchical organization as opposed to previously defined hierarchical models. He described this organization as a neural network which is specifically designed for parallel information processing [22; p. 3].

The concept of a heterarchical organization (or network organization) is based on the following principles: an organization consisting of organizational units that are mutually connected through information links (often based on modern information technology), are mutually independent, heterarchically organized (as opposed to hierarchy), and operate internally and externally (with their environment) in most cases sharing some common goal. Organizational units can in this context be either individuals, teams, departments, divisions and even entire organizations, or groups of organizations by the fractal organization principle [14; pp. 149-151] as argued further. If we apply such a concept to an organization, we get a structure which interrelationships are not strictly defined, but rather activated, or self-regulated depending on the particular situation.

An interesting metaphor for this kind of organization is the fishnet organization, depicted on Figure 2. If we observe a fisher’s net on the coast, it seems completely nonhierarchical. But if we take one node and lift it up, we get a hierarchical structure. By lifting further nodes and putting down the old ones, we can see the dynamical creation of new and the destruction of old hierarchical structures. Thus the fishnet organization tries to combine the modern concept of heterarchy and the usual human habit of tendency to hierarchy and order [23].

FRACTAL PRINCIPLES AND THE FRACTAL COMPANY

The concept of a fractal company (Ger. *die Fraktale Fabrik*) was first introduced by Hans-Jürgen

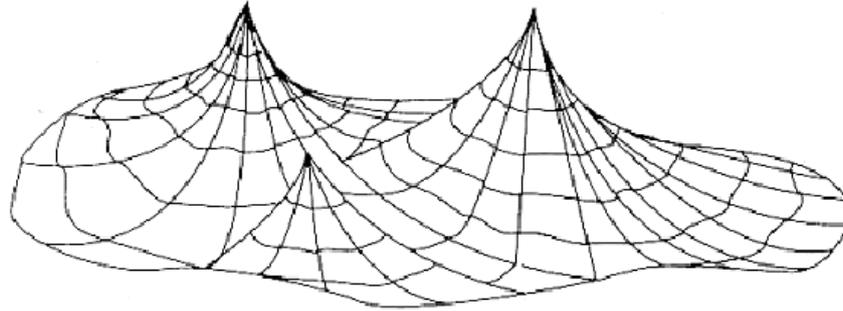


Figure 2. The fishnet organization (taken from Johansen, R. and Swigart, R.: *Upsizing The Individual In The Downsized Corporation P: Managing In The Wake Of Reengineering, Globalization, And Overwhelming Technological Change*. Perseus Publishing, 2000.).

Warnecke [24] who claimed that organizations are similar to complex systems that are characterized by fractals. This concept was in a way an answer to similar Japanese and American concepts adapted to the European market [25; p. 1].

The term fractal was introduced by Mandelbrot to denote an object that has a certain degree of statistical self-similarity on every observed resolution and is generated by an infinite number of recursive iterations. By observing a fractal one can recognize a certain pattern. By taking a closer look (possibly under a magnifier) the same or similar pattern can be observed on lower and lower levels.

A fern twig has some characteristics of a fractal (one twig is similar to the smaller twigs it consists of, which in turn consist of even smaller twigs). By applying this concept to organizational structure one could observe fractals in the form of individuals, departments, divisions, process flows, decisions and other organizational subsystems. The main objective is to find the fundamental pattern that will yield deeper insight to the organization as a whole and align to this pattern on lower and lower levels.

In Warnecke's sense a fractal is an autonomous organizational unit that has its objectives and a function that can be clearly described. Typical characteristics of a fractal are self-similarity, self-organization and self-optimization [25; p. 1].

Self-similarity means that the goals of particular fractals (from the individual in the organization, until the organization as a whole) match into a harmonic mutual objective. Self-organization means that particular fractals have their own autonomy concerning ventures and decisions according to the self-similarity rule, e.g. objectives have to be harmonized with upper and lower fractals. Self-optimization means that fractals continuously optimize their self-initialized work and decision making [26; p. 34]. Figure 3 shows the fractal principle where the spiral connecting the individual fractals represents the business process.

BIOTEAMING

Bioteaming, the most obvious biomimetic application in organizations [27, 28] deals with virtual, networked business teams that operate on the basis of natural principles which underpin, as the authors claim, nature's most successful teams. Some of these teams include single-cell and multicellular organisms, the human immune system, the nervous system (including the brain), micro-organisms such as bacteria and social insects (ants, bees and termites), jellyfish, geese, monkeys, dolphins, big cats, forests, rivers, ecosystems, the Earth (as Gaia) etc. [27; p. 18.].

In essence, bioteaming is a set of simple rules and procedures for self-organizing, virtual, heterarchic teams written by managers for managers and thus gained considerable attention in the business community. Terms like symbiosis, swarming and clustering are used to provide

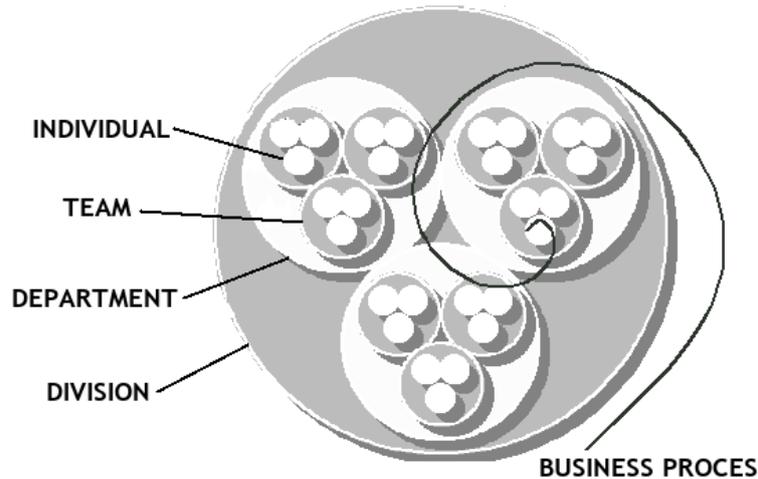


Figure 3. The fractal principle.

a suitable biomimetic terminology for decentralized teamwork, social networking, empowerment and other well known practices. Still bioteaming presents a set of elaborate practices that can easily be implemented into organizations.

SWARMS AND STIGMERGY

The term swarm intelligence was first introduced by Beni, Hackwood and Wang [29-34] in the context of cellular robotics. Swarm intelligence can be defined as “*any attempt to design algorithms or distributed problem solving devices inspired by the collective behavior of social insect colonies or other animal societies*” or simply as “*the emergent collective intelligence of groups of simple agents.*” [35; p. 7]. A swarm is a “*collection of autonomous individuals relying on local sensing and reactive behaviors interacting such that a global behavior emerges from the interactions*” [36], whilst on the other hand the term swarm prediction is used in the context of swarm behaviour forecasting problems.

It is somewhat amazing to analyze animal swarms (like ants, birds, eels, grasshoppers, honey bees, termites, herrings etc.) which self-organize to fulfil the most complex tasks and they have been fascinating scientists and artists for many years. “*Any single insect in a social insect colony seems to have its own agenda, and yet an insect colony looks so organized*” [37]. Agents self-organize through direct (antennation, trophalaxis, mandibular contact, visual contact, chemical contact etc.) or indirect interactions fulfilled through stigmergy [35; p. 14].

We can here draw an interesting analogy to organization and especially teamwork in organizations. Interactions between people self-organizing to achieve a common (higher) goal can be analyzed from a swarm intelligence perspective. “*Perhaps the most powerful insight from swarm intelligence is that complex collective behavior can emerge from individuals following simple rules.*” [37] By studying swarm intelligence and implementing such rules, managers can take advantage of three important characteristics shown by social insect colonies [37]:

1. flexibility (ability to adapt to a changing environment),
2. robustness (even if some individuals fail, the group can still perform),
3. self-organization (work is neither locally supervised nor centrally controlled).

The word stigmergy coming from old Greek *stigma* (sting) + *ergon* (work) and interpreted like “stimulation by work” was first introduced by Grassé to denote task coordination and regulation of a special type of termites (*Macrotermes*) during nest reconstruction. Stigmergy is achieved through indirect agent interaction whereby agents modify the environment which in turn serves as an external memory. Thus work can be continued by any individual depending on the actual state of the environment. On the other hand, the same, simple, behavioural rules can create different designs [35; p. 14].

Stigmergic processes can be an interesting metaphor for knowledge management systems. Especially new Enterprise 2.0 technology can be analyzed from such a perspective. By using insights from stigmergy research, adequate systems can be implemented that will push knowledge sharing and knowledge acquisition [38, 39].

GENESIS AND REPRODUCTION

Genesis coming from the ancient Greek word for birth or origin and reproduction being the biological processes by which new individual organisms are produced seem to be an interesting analogy to contemporary market processes of strategic alliances, joint ventures, spinouts, outsourcing as well as ad-hoc and virtual organizations.

Strategic alliances are formed since contemporary organizations are more and more unable to survive by themselves in a dynamic environment. They understand that they have to focus on what they do best, their core business, and outsource other operations to allies or joint ventures that are more specialized.

Since organizations try to achieve more and more innovation, they realize that there is neither time nor resources to take advantage of all opportunities creative minds can create. To keep their innovative human resources, organizations create spin-out companies for them to undertake entrepreneurship. These spin-outs eventually yield companies for themselves [40; pp. 1-3].

Ad hoc suprastructures are concepts that are built on top of existing organizational structures and they emerge as a response to some problem or change in the immediate environment of the organization [11; p. 119]. Ad hoc organizations are characterized by adaptability, readiness, individual initiative, desire for experimentation, creativity, and outside growth and support [41; p. 7]. They usually disappear when the environment problem is solved.

A virtual organization is a target-oriented suprastructure of geographically separated entities (organizational units) that are specialized for a predefined area of activity, and interconnected through space, time and organizational limitations, mostly using information, communication and network technology for efficient and flexible cooperation and exchange of knowledge. Virtual organization is one of the most widespread examples of ad hoc organization in expert literature. Barnatt [42] says that these organizations exist in cyberspace, that they develop proportionally with the development of information and communication technology and that they can be found in conventional organization structures. Under the term cyberspace he understands the media in which electronic communication and computer programs exist, and he argues that the understanding of the term is essential to the understanding of the virtual organization. Figure 4 shows the concept of a virtual organization [42].

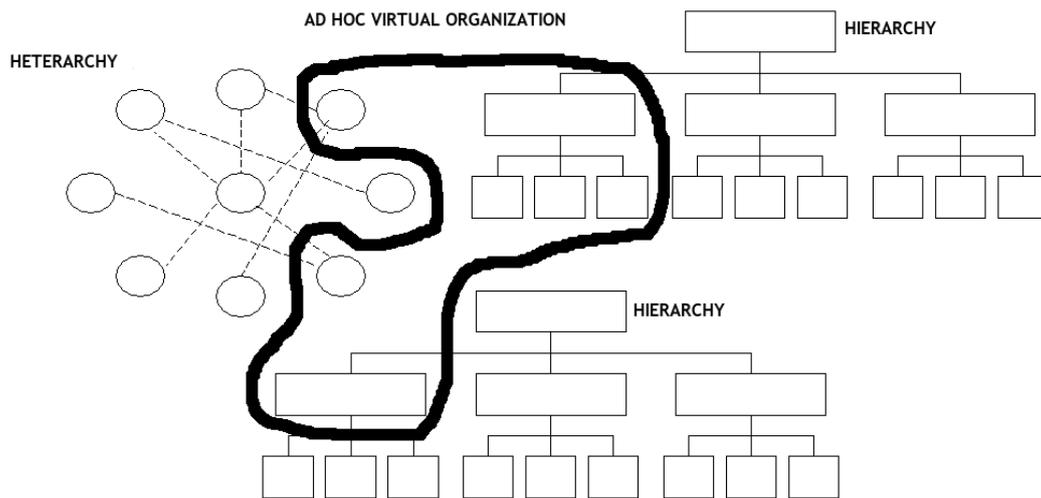


Figure 4. The virtual organization.

If we, for a moment, imagine that organizations are living beings we observe sexual and asexual reproduction depending on the number of entities involved in the creation of new entities. We are even able to observe different reproductive strategies like K-selection (few offspring) and r-selection (many offspring), sexual maturity, allogamy, autogamy and many other terms common in genesis and reproduction. Further conceptualizations are part of our future research.

DISCUSSION – METAPHORS OR COMMON LAWS?

After examining the identified concepts one could conclude that there is a potential application area for biomimetics in organization theory. To clarify our standpoint we analyzed each outlined metaphor for its practical and theoretical implications. From a practical viewpoint we established a descriptive scale of three levels of possible application:

- *Metaphor* – the concept is clearly a metaphor that cannot be directly implemented into practice but could serve other objectives like employee motivation,
- *Analytic* – the concept provides methods that can be applied in practice in order to analyze the current organization (and eventually find inconsistencies, problems, potential opportunities etc.),
- *Systemic* – the concept provides methods that can be applied in practice in order to establish new organizational systems.

From a theoretical viewpoint we established a descriptive scale of three levels of possible use as well:

- *Descriptive* – the concept can be used to describe (possibly metaphorically) some organizational phenomenon,
- *Analytic* – the concept provides actual methods to analyze some (particular) organizational phenomenon,
- *Systemic* – the concept provides (holistic) methods to understand organizational phenomena.

An outline of our findings is given in Table 1.

Table 1. Outline of biomimetic concepts in organizations.

Biomimetic concept	Nature	Organization	Implications for practice	Implications for theory
Amoeba organization	Single cell organism	Small divisional self-organizing unit	metaphor	descriptive
	Changing form	Changing teams and team members	metaphor	descriptive
	Pseudo-hand	Self-establishment of teams	metaphor	descriptive
	Absorption	Taking advantage of opportunity	metaphor	descriptive
	Division	Establishment of new units	metaphor	descriptive
Autopoiesis	Living organization (biochemical processes)	Formal organization (decision making processes)	n/a	analytic systemic
	Reproduction of components (molecules)	Reproduction of components (organizational roles)	n/a	analytic systemic
	Maintenance of boundary	Restriction of communication	n/a	analytic systemic
	Structural coupling (habitat, language, external perturbations etc.)	Structural coupling (organizational culture, cooperation style, market condition etc.)	n/a	analytic systemic
Neural networks & heterarchies	Neurons	People / Organizational units	analytic	analytic
	Axon	Communication channel	analytic	analytic
	Signal	Communication	analytic	analytic
	Parallel processing	Organizational information processes	analytic systemic	analytic systemic
Fractal principles & the fractal company	Self-similarity (geometrical structures)	Self-similarity (organizational units, goals, decisions, process flows etc.)	n/a	descriptive analytic?
Bioteaming	Ant colony (super organism)	Team	metaphor	descriptive analytic? systemic?

Biomimetic concept	Nature	Organization	Implications for practice	Implications for theory
Bioteaming	Autonomy in stimulus – action operations	Autonomy of team members	metaphor	descriptive
	One-way (broadcasting) communication	Team communication optimization	metaphor	descriptive
	Swarm intelligence	“Team intelligence”	metaphor	descriptive
	Self-organization	No central control	metaphor	descriptive analytic? systemic?
	Symbiosis	Trust external partners	metaphor	descriptive
	Clustering	Team member's relationships	metaphor	descriptive
	Tit-for-tat strategy	“What is in for me?”	metaphor	descriptive
	Genetic algorithms	Controlled experimentation	metaphor	descriptive
	Porous membranes	Selection of new team members	metaphor	descriptive
	Emergence	Team growth	metaphor	descriptive
Swarms & stigmergy	Swarm	Organizational unites, teams, divisions etc.	analytic systemic	analytic systemic
	Emergent behaviour	Simple rules	systemic	systemic
	Stigmergy	Knowledge sharing/acquisition systems	analytic systemic	analytic systemic
Genesis & reproduction (continued)	Genesis	Establishment of new organization	n/a	descriptive
	Reproduction	Joint ventures, spinouts, virtual organization	n/a	descriptive analytic?
	Mating	Strategic alliance, mergers, acquisitions	n/a	descriptive analytic?
	Reproductive strategy	Brand management strategies	n/a	descriptive analytic?
	Sexual maturity	Organizational life-cycle considerations	n/a	descriptive analytic?

Most biomimetic concepts are metaphors or not (directly) applicable in practice. Still there are some concepts (neural networks and heterarchies, swarms and stigmergy) that can provide at least analytical methods. On the other hand, from a theory-oriented view there seem to be descriptive, analytical as well as systemic methods more equally distributed. The question marks in the table indicate fields of potential new research that has to be conducted in order to yield adequate methods.

The amoeba organization is a nature-inspired organizational form that allowed organizations to do business without unnecessary bureaucracy in a dynamic environment by using the metaphor of a known single-cell organism. On the other hand, this metaphor provided organization theorists with suitable means to explain and examine such an organizational form.

The theory of autopoiesis gained major attention in the field of biology as well as social and organizational studies. Still there lacks a common foundation between those perspectives outlined in some critics of the theory. Such a foundation needs to be addressed in future research. Due to the fundamental works of Niklas Luhmann [8, 19, 21], partially Milan Zeleny [10, 43] and others, this theory seems very promising in organization theory and the social sciences. Efforts to examine this theory for its practical implications, as well as to formalize it with adequate research methodology, yet have to be done.

The neuropsychological research of the human brain firstly introduced a heterarchical neural network model that was successfully applied to flat, non-hierarchical, networked organizational forms [22; p. 3]. These new forms have become a major trend in modern organizational theory but were applied in practice as well. Network principles have a major role in contemporary science – computers, social systems, information transfer, the human brain, traffic and likewise organizations seem to conform to them.

Fractal geometry is a common law of nature and through the development of complexity theories led to a new revolution in science. The application of fractal philosophy to organizations from a theorist's as well as from a practitioner's view, still needs research and additional efforts. The fractal organization is as yet a metaphor that nevertheless could give interesting insights into the inner laws of organizations.

Bioteaming seems to be a very promising concept, but lacks formal theoretic background. The (over)use of biomimetic metaphors is maybe interesting (and successful) in industry but has to be established scientifically. On the other hand, bioteaming relies on well-established concepts like virtual organizations, social networking and distributed teamwork which of course makes it usable in a dynamic organizational environment.

The potential use of ideas from swarm intelligence as well as stigmergy research could yield new insights into the internal functioning of organizations and especially teamwork. We envision that research in this area will lead to better collaboration policies established upon simple laws and stigmergy that will (hopefully) strengthen productivity and effectiveness of high-performance teams as well as provide foundations for new types of knowledge management systems.

Genesis and reproduction, when put into an organization theory perspective, could give new methods for analyzing contemporary phenomena like strategic alliances, joint ventures, spin-outs, outsourcing as well as ad-hoc and virtual organizations, as outlined before. In this phase of such a conceptualization we are unable to conclude if this biomimetic metaphor will lead to any practical results.

As one can see from this reasoning, in all the analyzed cases some kind of nature-inspired idea was applied to a particular part of organization theory. Biomimetics is applicable to organization theory especially in cases where complex interactive living systems are analyzed

for their organizational characteristics. The mutual interactions between living systems as well as their internal processes seem to have extraordinary similarity to organization in a social context. Due to the turbulent environment contemporary organizations face today, they have to increasingly take the laws of complex non-linear systems into consideration in order to be successful. Nature seems to have found just the right tools to do that, and has additionally millions of years of experience.

CONCLUSIONS AND GUIDELINES FOR FUTURE RESEARCH

Nature was inspiring human beings since the beginning of history. In this paper we outlined several concepts inspired by nature that led to considerable advances in modern organization's theory and practice. We claim that biomimetics, the art and science of imitating nature to achieve solutions, has a major applicative area in contemporary social sciences and especially in modern organization theory. Several cases of biomimetic applications showed gaps that should be filled through future research and practice.

In technology and information systems a biomimetic application is achieved through imitating some (mostly physical) characteristics of some biological system. In modern organizations most biomimetic applications deal with metaphors. Still there are implications in the shown cases that nature's structures replicate themselves in social and organizational systems. The use of metaphors is likely the first step in creating a more tangible biomimetic application in organization theory. The development of such applications can provide us with a suitable backdrop for understanding, analyzing and optimizing modern organizations.

To follow Zeleny [10, 43] who claimed that all living systems are necessarily social systems, it seems obvious that researchers from this field should observe nature in search for new concepts. Nature is a never-ending pool of creative ideas.

On the other hand, one should have in mind that there is still a very big question as to whether these ideas are metaphors (as Morgan's book suggests) or represent something more fundamental about the structures of nature. Very often, the slippage from one position to another has allowed commentators to suggest that because X looks like Y, X has to be like Y, and so the ideological and political implications are quickly naturalized. We take the standpoint that laws obtained from autopoietic theory, network science, swarm intelligence and other fields of research dealing with complex systems are applicable to organizations and can yield insights and methods for their optimization.

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BIOMIMETIKA U MODERNIM ORGANIZACIJAMA – ZAKON ILI METAFORA?

M. Schatten i M. Žugaj

Fakultet organizacije i informatike Sveučilišta u Zagrebu

Varaždin, Hrvatska

SAŽETAK

Biomimetika, umjetnost i znanost imitiranja prirode i života za tehnička rješenja, razmatrana je sa stajališta moderne organizacijske teorije. Temeljna hipoteza članka je kako postoje zakoni prirode koji su primjenjivi u živim, društvenim i drugim organizacijskim sustavima. Kako bi se iskoristilo prednosti tih zakona, predlaže se proučavanje principa prirode i njihova primjena u organizacijama – proces koji je poznat kao bioničko kreativno inženjerstvo. U potrazi za najinteresantnijim konceptom iz prirode, izdvojili smo ameba-organizaciju, teoriju autopoiesisa ili autokreacije, neuronske mreže, heterarhije kao i fraktale i biogrupiranje, što je sve opisano. Dodatno su uvedeni i drugi koncepti, poput inteligencije roja, stigmergije, kao i stvaranje i reprodukcija. Na kraju su navedene ideje izlistane, a smjernice daljnjih istraživanja navedene.

KLJUČNE RIJEČI

biomimetika, teorija organizacije, autopoietika, znanost o mrežama, bioničko kreativno inženjerstvo

COOPERATION AMONG VIRTUAL ANTHROPOIDS IN A COMPLEX ENVIRONMENT

Jakson Alves de Aquino*

Department of Social Sciences/Federal University of Ceará
Fortaleza, Brazil

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ABSTRACT

This paper presents an agent based model of the evolution of cooperation in a complex environment. Anthropoid agents reproduce sexually, and live in a world where food is irregularly distributed in space and seasonally produced. They can share food, form hunting and migrating groups, and are able to build alliances to dispute territory. The agents memorize their interactions with others and their actions are mainly guided by emotions, modelled as propensities to react in specific ways to other agents' actions and environmental conditions. The results revealed that sexual reproduction is extremely relevant: in the proposed model cooperation was stronger between agents of opposite sex.

KEY WORDS

evolution of cooperation, computational model, anthropoids

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*Corresponding author, η : jaa@ufc.br; 55-85-33667419;
Av. Universidade, 2995, Fortaleza, CE, Brazil, 60020-181

INTRODUCTION

Most agent based models of evolution of cooperation are built with simplicity in mind and the models are not intended to be realistic. However, I think that the goal of building realistic models of the evolution of cooperation *in the human species* would also be worthwhile. My goal in this paper is to offer a contribution to this approach by building a model of evolution of cooperation among virtual anthropoids with realistic assumptions about the agents' minds and their ecological environment. My emphasis in this model is on the agents' instinctive propensities to feel emotions, rather than on the evolution of cognitive abilities to make rational decisions.

The knowledge required to make realistic challenges came from many disciplines. Evolutionary psychology was the main source of ideas about evolutionary processes implemented in the model and primatology was the main source of information about real anthropoids.

Models of evolution of cooperation with emphasis on simplicity are not discussed in this paper. In the following sections, I briefly review the literature that most directly contributed to the development of this model¹. I also discuss some advantages and disadvantages of simple and complex models. Then I present my model and the results of some simulations, followed by a brief conclusion.

KIN SELECTION AND RECIPROCITY

The basic natural selection mechanisms are the higher rates of survival and reproduction of the best adapted individuals. When one individual helps another, he is increasing the other's chances of surviving and reproducing. The problem is that, given the natural limitations of resources, as the other's chances increase, the helper's own chances decrease. So, how can we explain why individuals help one another? Biologists have basically found two explanations for the problem: *kin selection* and *reciprocal altruism*.

Dawkins says, metaphorically, that organisms are survival machines owned by their selfish genes [1]. The metaphor is meaningful because an organism which is well adapted to its environment will produce a larger progeny than a poorly adapted one. That is, the genes in its genetic code will yield more copies of themselves than the genes of other organisms, and, thus, their proportion in the genetic pool of the next generation will increase. Genes are simply molecules and, of course, they do not have either selfish or altruist sentiments. However, events take place as if genes were selfish agents manipulating their organisms to yield as many copies of themselves as possible. Metaphorically, we can say that a gene does not have any concern for the organism it lives in, and it will destroy the organism if, for any reason, this is the most efficacious way of producing copies of itself.

Each organism from a given species shares a high proportion of genes, but only close kin share an expressive quantity of some rare genes. Kin selection theory considers these facts while saying that genes will yield a larger number of copies of themselves if their organisms help their close kin to survive and reproduce, even if this help implies a cost for the organism itself. That is, a genuinely altruist organism that sacrifices itself to help close kin may be acting in a way that increases the chances of making copies of its own genes, including the genes of altruism. Returning to the metaphor, the selfish gene can produce an altruistic organism, but only with close kin. Hence, the use of the term *kin selection*.

Political scientists join biologists in the second theory that tries to explain the existence of cooperation. According to this theory, it will be adaptive to an individual to help other if, as a consequence of this action, the probability of receiving help in the future were significantly

higher. In this case, we can say that we do not have a genuinely altruist individual, but a non-myopic selfish one. However, this may not be the complete truth. An individual may help another because his sentiments make him desire to help, without any intention of receiving something as payment. Of course, these sentiments have evolved under natural selection according to the egoistic reasoning explained above. Two individuals who establish a long-term altruistic relationship can be called friends.

The two mechanisms mentioned above may not be enough to explain the cooperation in large groups with hundreds of individuals. In large groups, the majority of individuals are neither close kin nor friends; they are merely strangers. However, some evolutionary psychologists argue that kin selection and reciprocal altruism evolved in the human species over a period of thousands of years when our ancestors lived in small groups. In these circumstances, to help a group member would probably be to help close kin or, at least, someone who would be around for long enough to have many opportunities to reciprocate the favour. Kin selection and reciprocal altruism would be enough to explain the evolution of altruism in these groups. Today, encounters among strangers are ubiquitous, but given that they were rare in our evolutionary past, human beings would have a strong inclination to cooperate and they would be cognitively ill prepared to discriminate between kin, friends or strangers when an opportunity to act altruistically appeared. Evolutionary psychologists argue that our psychological mechanisms lead us to act altruistically in circumstances where helping the other is no longer adaptive.

Henrich and Boyd [2] disagree. They argue that reciprocal altruism and kin selection are not enough to the evolution of cooperation in large groups. Henrich [3] enumerates several reasons that show the implausibility that the cooperation evolved from reciprocal altruism is still practised, despite it is no longer being adaptive. Reciprocity would be a good explanation only for small groups not threatened with extinction. That is, groups where the probability of future interactions is still sufficiently high.

Cooperation will be less difficult if individuals can refuse to have relationships with non-cooperators, that is, if free-riders are ostracised. If there were a permanently high probability of future encounters, ostracism would be enough to account for the evolution of cooperation. However, in our evolutionary past there were probably periods when there was no certainty of future interactions, and, hence, ostracism alone does not seem to have been sufficient to secure the evolution of cooperation [4].

Individuals must take more action than simply ostracising free-riders and restricting their associations to trustworthy friends. Individuals must punish non-cooperators even if there is a cost to themselves, and even if there is no expected future gain [4]. Gintis called this more active attitude *strong reciprocity* [5].

Another type of reciprocity that might be particularly important for the evolution of cooperation among human beings is *indirect reciprocity* [6]. In models that include indirect reciprocity, cooperation and defections are observed by many agents not directly involved in interactions. These observers either add or subtract scores from the images that they have of other agents. In these models individuals cooperate not only in the expectation of direct reciprocation, but to build a good reputation that will increase their chances of benefiting in the future. The flow of information about who usually cooperates and who usually defects will increase if individuals are capable of exchanging information easily, as in the case of human beings.

METANORMS

Axelrod [7] has built in computer a model with 20 agents who could choose to contribute or not towards the production of a collective good. The costs of contributing were smaller than the benefits received, but for a selfish agent the rational action would be to consume the good without contributing towards its production. However, the agents were not rational; they were led by emotions, modelled as genetically inherited probabilities of behaviour.

BETWEEN SIMPLICITY AND COMPLEXITY

On the one hand, sociologists and political scientists often use statistical tools to analyse data, but, for a long time, attempts outside of economics to use mathematics to formalize social theory have not been very successful. Only in the last decades, a branch of theoretical research in social sciences-game theory-has started to build formal explanations of social phenomena. However, the social world is too complex to be easily translated into mathematical formulas.

To be able to elaborate formal explanations, game theorists generally adopt various simplifying assumptions about human behaviour. The two most important of these are that human beings are strictly rational and that they have complete information about their social interactions [8]. Rarely, if ever, is the world as simple as game theory descriptions, and this lack of reality frequently makes the interpretation of the game a difficult task. That is, we frequently cannot say if the way the game evolves adequately resembles what happens in the real world. This is a limitation of any model, but it is particularly visible in traditional game theory models.

On the other hand, the promise of multi-agent models is to build models of complex social phenomena from the actions of multiple and heterogeneous agents [9].

Agent-based models can simulate many phenomena, but we cannot say that they have the same level of formal rigour as equation based models. For example, Taylor's analysis of reiterated the prisoner's dilemma is mathematically rigorous; he *proved* that certain conclusions can be extracted from his model, what is more satisfying than *simulating* the same phenomena. The results found by Axelrod [10] simulating the reiterated prisoner's dilemma were similar to Taylor's conclusions, what is indicative that results reached through simulations are valid, although more difficult to analyse formally. If simulation's sole utility were to replicate results found by equation models, it would be meaningless to do them. However, a simulation can be made with far more complex objects than the reiterated prisoner's dilemma, and as a problem becomes more complex, any attempt to translate it into a mathematical formula becomes impracticable. It is thus expected that multi-agent models are an alternative way of finding explanations to social phenomena [9].

The simulation can be repeated if something apparently strange happens. The events will all be exactly replicated, and it will be possible to examine the minutiae of facts leading up to the phenomenon in question. At least partially, this can compensate for the frequent impossibility of making a rigorous formal analysis of a computer simulated agent-based model.

The basic rule that models must be a simplification of reality is still followed in multi-agent models. A frequently found recommendation is that the model must be kept simple to facilitate the analysis of its results. If the model has a large number of parameters, the numerous variables can interact in a complex way and the role of each parameter can be unclear to the researcher [8].

While a model is kept simple, it is possible to identify the effect of a given agent rule of behaviour. When many strategies are added to a single model, complex results can emerge, and, for instance, a strategy that was previously leading to cooperation, in the presence of other strategies, can begin to inhibit the cooperation [8].

The use of simple models, however, has its own disadvantages. The main one is the risk of building overly unrealistic and empirically irrelevant models. At first, when the basic techniques are being developed, there is no alternative but to build simple models, even if they are too unrealistic. Thus, even recognizing the great usefulness of the above recommendations regarding simplicity, I believe that the opposite approach can also be useful. That is, it is also valid to try to model complex situations, including more than the minimum amount of elements to test a specific kind of relation between variables; also including elements that allow modelling of other social phenomena that one believes are in some way significantly related to the main phenomenon studied.

Usually, multi-agent models are simple, and they are tested by running many simulations with varying values for the different parameters. A model is considered robust when it produces similar results in a broad range of values for its variables [11]. However, a better challenge to the robustness and empirical relevance of a model would be to put it to work in a more realistic environment. The results produced by a complex model can be equivalent to a simpler one. In this case, one strategy would predominate and the variables and other phenomena modelled simultaneously would be only making the result produced by the model more probabilistic.

EMPIRICAL CHALLENGES TO AGENT BASED MODELS

It is advantageous for individuals to solve their problems fast and efficiently. If our ancestors have been confronted with a problem repeatedly over the last million years, it is to be expected that we have the right biological propensities to unconsciously solve the problem (if this is possible). This is advantageous for the individual because he remains free to concentrate his attention in new problems, which can be solved only through improvisation. The identification of commonalities between human beings and apes (bonobos, chimpanzees, gorillas, and orangutans) allows us to create hypotheses regarding our current biological propensities and the biological propensities of our common ancestor with apes. We suppose that our ancestors probably had the cognitive and emotive capabilities currently common among apes and humans. Thus, these abilities should be recognizable in the initial agent characteristics in a model of the evolution of cooperation.

The ability to memorize results of recent interactions with other individuals, for instance, is a pre-requisite for the existence of what Brosnan and de Waal [12] call *calculated reciprocity*, which can also be interpreted as *gratitude*.

Other important ability is the capacity to have a notion of self, that is, the capacity to recognize oneself as an individual distinct from others or, in other words, the capacity to imagine oneself as an object in the world. The notion of self is important to understand the role of other individuals in a cooperative task and, thus, for coordinated action and teamwork. Among primates, macaques (*Capuchin monkeys*) have not shown clear evidence of having a notion of self, but apes have [13].

It is interesting to note that even macaques have an emotional reaction resembling that of individuals who practice strong reciprocity. These monkeys often share food in their natural habitat and, when captive, show what seems to be a certain kind of sense of fairness. They become angry when a mate receives a bigger reward for the same effort from their caretakers [14].

MODEL DESCRIPTION

I was guided by some principles while developing the model presented in this paper. The environment should be interpretable as empirically relevant to the evolution of cooperation among our ancestors and agents should have the potential to evolve and not fixed patterns of behaviour. Global phenomena, like groups and communities should not be directly modelled. Instead, I expected the emergence of these phenomena through the interaction between individuals. These are the reasons why agents have so many genetic features subject to mutation and evolution through “natural” selection.

The model was initially developed using Swarm libraries [15] but latter I translated it into C++, and used GTK and GTKMM to build the graphical user interface². Some ideas were borrowed from the models written by Pepper and Smuts and by Premo, notably the distribution of plants in patches, the possibility of food sharing, predation risk, and territoriality [16, 17]. The agents’ genetic propensities to feel emotions resemble many of the emotions discussed by Trivers [18].

The world is a rectangular grid whose dimensions are defined at the beginning of the simulations. In many agent based models, the world is a torus to avoid edge effects on agents’ behaviour. However, since real anthropoids live in places with borders made by rivers and mountains, I opted for not using a torus world.

In this model time runs in discrete steps, called hours. A day has 4 hours and a year has 50 days.

PREY

The simplest agents in the simulation are the prey hunted by anthropoids. They simply get older and, when reach their maximum age, go back to age zero. At this point, if the number of prey in the world is below the maximum defined before the start of the simulation, the prey gives birth to an offspring. Their behaviour consists in making random movements in the world. When a quarry is hunted, it is not replaced until another one reaches the maximum age. Preys are protected against extinction by over predation: if all of them are hunted, the model creates a new one in a random place. When hunted, prey is converted into an amount of meat proportional to their age.

VEGETATION

Each cell in the grid has either a tree or terrestrial herbaceous vegetation (THV). The THV, as the plants in Pepper and Smutts Pepper [16], grows continuously during the entire year, according to a logistic curve: growth is slower when the plant is near the minimum and maximum values of energy.

The model does not allow the complete consumption of a THV. The plant always remains with an energy level at least equal to its logistic growth rate. The maximum energy of a THV is 1,1 and the logistic growth rate is 0,01.

Trees are capable of producing fruits and the anthropoid agents try to pick as much fruit as is necessary to reach the maximum level of energy. There are three species of trees. The period of fruit production, the number of fruits produced a day, the amount of energy each fruit has, and the time a fruit remains edible are species specific, and all trees of a species share the same features. The fruits are produced once a day, but each anthropoid agent tries to eat either fruits or THV once every hour. In a real tropical forest, anthropoids prefer ripe fruits. Analogously, in this model the first fruits to be eaten are the older ones. The trees are distributed in patches containing only one tree species. The purpose of creating different tree

species and distributing them in patches is to emulate the seasonality and irregularity of fruit distribution in real tropical forests.

Trees and THV do not die, and none of their parameters evolve. Of course prey, trees, THV, and cells are agents, but in this article I will reserve the expression *agent* for anthropoid agents. The Figure 1 shows the world in a simulation before and after the presence of anthropoids, which are only created one year after the vegetation. Thus, when anthropoids are created, the world already has enough vegetation to support them. A single cell may have any number of agents. In the graphical representation of the world, different tree species can be distinguished by the different colours of their borders. The greater the amount of fruit, the more yellowish is the center of the tree. The THV's colour goes from light green (maximum energy level) to almost yellow (minimum energy level). Cells containing agents have their central region coloured with a colour between red (when all agents are female) and blue (when all agents are male).

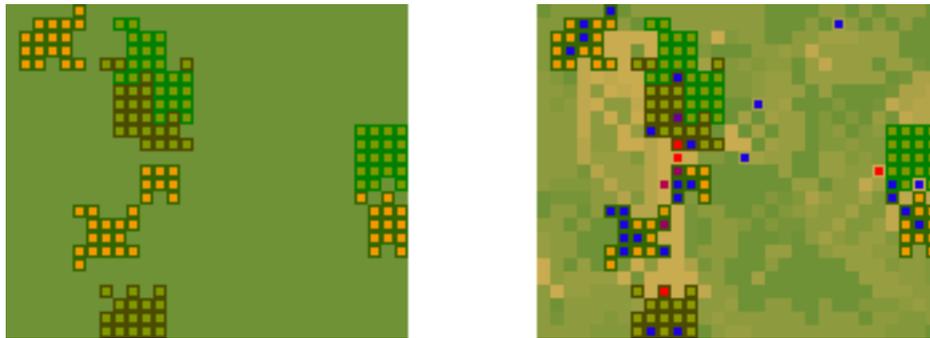


Figure 1. The world before and after the creation of agents.

THE ANTHROPOIDS

Anthropoids are born, grow up, reproduce sexually, and die. A newborn agent receives a name consisting of seven random characters. This name is used during the agent's interactions to identify relatives, friends, and enemies.

Newborn behaviour consists simply of receiving energy from its mother and of following her continuously.

The maximum amount of energy an agent can accumulate, the amount of energy spent hourly (metabolic rate), and the maximum age are fixed for the entire simulation, but the duration of childhood is subject to evolution.

The metabolic rate of adults has a fixed value, 1, but it is possible to define the maximum energy level at the beginning of simulations. These values are used to calculate the duration of childhood for the first population of agents. The duration of childhood has the same value (in hours) as the maximum energy level (in units of energy). The maximum age will be approximately 16 times longer than the initial value for childhood.

Children's metabolic rate is half that of adults and a child receives two times what it spends from its mother. Thus, the childhood duration defined with the above calculation is enough for the first population of children to reach adult age with 50 % of the maximum energy level. An adult dies if its energy falls below 30 % of the maximum. The agents cannot eat more than is required to reach the maximum energy level, and they can consume at the most two times the value of their metabolic rate. The minimum level of energy to stay alive during childhood increases continuously, reaching the adult level when the agent becomes adult.

Most of the agents' actions are guided by emotions, and not by rational calculations. Emotion is here defined as the propensity to behave in specific ways according to the circumstances.

The propensity to feel emotion is genetically inherited, and, in most cases, is represented by real numbers. During reproduction, the propensities are subject to mutation, that is, small increases and decreases in their values.

In this model, almost all of each agent's genetic features is stored in two variables. Both variables are subject to mutation, but during the agent's life only the variable corresponding to its sex is active. During reproduction, for each genetic feature, the agent inherits both variables from either its father or its mother. The aim of this duplication of variables is to give agents the possibility of having different behaviours from the same genetic code. Real animals do not have separate genetic codes for males and females, but a reasonably comparable process exists: many important genes have a different manifestation depending on the presence of masculine or feminine hormones.

MEMORY

Agents can have both positive and negative memories of other agents, and, in many circumstances, they have to elaborate a feeling about another agent from their memories. This feeling will be neutral, positive or negative. There are different ways of calculating this feeling according to the circumstances. If the agent does not have any remembrance of the other agent, the feeling will be neutral. The result will also be neutral if the sum of everything given and the sum of everything received are zero.

When an agent becomes adult, it starts to interact with other agents, including its mother. At this point, it stores in its memory that its mother has given it energy equivalent to $motherValue$, and its mother remembers that has given her child $childValue$.

Agents may follow different strategies to remember others: (a) The most vengeful ones will be vengeful when the last value given is higher than the last value received, (b) the moderately vengeful ones will be vengeful if the last value given is higher than zero and the last value received is below zero, (c) the least vengeful agents will only be vengeful if the sum of all that the agent has given is higher than zero, the sum of all it has received is equal to or below zero, the last time it has received is more recent than the last time it has given, and the last value received is below or equal to zero. When being vengeful, the value recalled is calculated according to the expression:

$$feeling = (-1) \cdot vengefulness \cdot (given \cdot received), \quad (1)$$

where, depending on its vengefulness strategy given and received will refer either to all that was given and received or only to the last event of each kind. The strategy employed is a genetic characteristic of agents.

If not being vengeful, an agent uses gratitude to recall the other, and, there are two ways of remembering with gratitude. In one strategy, only the total value received is remembered, and in the other the calculus considers the difference between given and received, as shown by the expressions:

$$f1 = gratitude \cdot received, \quad (2)$$

$$f2 = gratitude \cdot (received - given). \quad (3)$$

In the model, recent facts may be considered more valuable than old ones. Hence, the calculation of given and received is not a simple sum of everything given and received,

respectively. The age of the event, t , and a factor, f , between 0 and 1, are used to calculate the value of past events. The recall value of each event is defined by the expression:

$$v' = v \cdot f^t, \quad (4)$$

where v' is the recalled value and v is the stored value.

Agents can only store 4 events per known agent, and a new event replaces the least valued one in the agent's memory. If an agent encounters a stranger it will ask its neighbouring friends whether they remember the stranger. To some extent, this is representative of the process of image score discussed by Nowak and Sigmund [6].

Each agent, in almost all circumstances, gives a specific value to unremembered agents. The value differs for female and male strangers and is genetically defined. These values are not used in territory defence, in which the fact of the agent being xenophobic or not prevails.

Agents also memorize the location and the tree species of visited patches as well as whether they were expelled (or not) from the patch in a dispute for territory.

Immediately after being created, the first population of each simulation memorizes the nearby patches of trees as visited and peaceful. They also memorize receiving a small positive value (0,01) from their same cell neighbours. The goal of these memorizations is to deal with the unrealistic fact of all agents being born simultaneously as adults and without social relations or a record of migrations.

BASIC ACTIONS OF AGENTS

Once every hour the agents are activated sequentially and behave according to the algorithm sketched in Figure 2.

Every hour the agent becomes older, has its energy level reduced according to its metabolic rate, and runs a risk of being victim of predation. If the agent has meat, it will eat a bit of it at this time. The probability of being a victim of predation may be defined at the start of simulations, but it will be six times higher in grassland than in a tree patch. The risk will also decrease as the number of agents in a cell increases. If the agent is an infant, it simply follows its mother.

Most of the time the agent either stays put or moves to the best of the eight adjacent cells. If a cell is unoccupied, its value will simply be its energy level. Otherwise, the agent evaluates the adjacent cells using the expression

$$V = \frac{e \cdot e_2}{N} \cdot (1 + m) \cdot (1 + s \cdot N_s) \cdot (1 + o \cdot N_o) \cdot (1 + x \cdot N_x) \cdot (1 + c \cdot N_c) \cdot \left(1 + f \cdot \sum l_i\right), \quad (5)$$

where e_c is the cell energy and e the value that the agent attributes to this energy; N is the total number of agents in the cell, including the future occupant, and N^* is the number of agents of a given type; The types are m , mother; s , siblings; o , opposite sex agents; x , same sex agent; c , son or daughter for females and oestrous females for males. The cell's friendship will also be considered. The agent will multiply its propensity, f , to go to a cell where its friends are by the sum of recalled values of occupants.

When an agent leaves a tree patch, it memorizes information about the patch: localization, tree species, and current time.

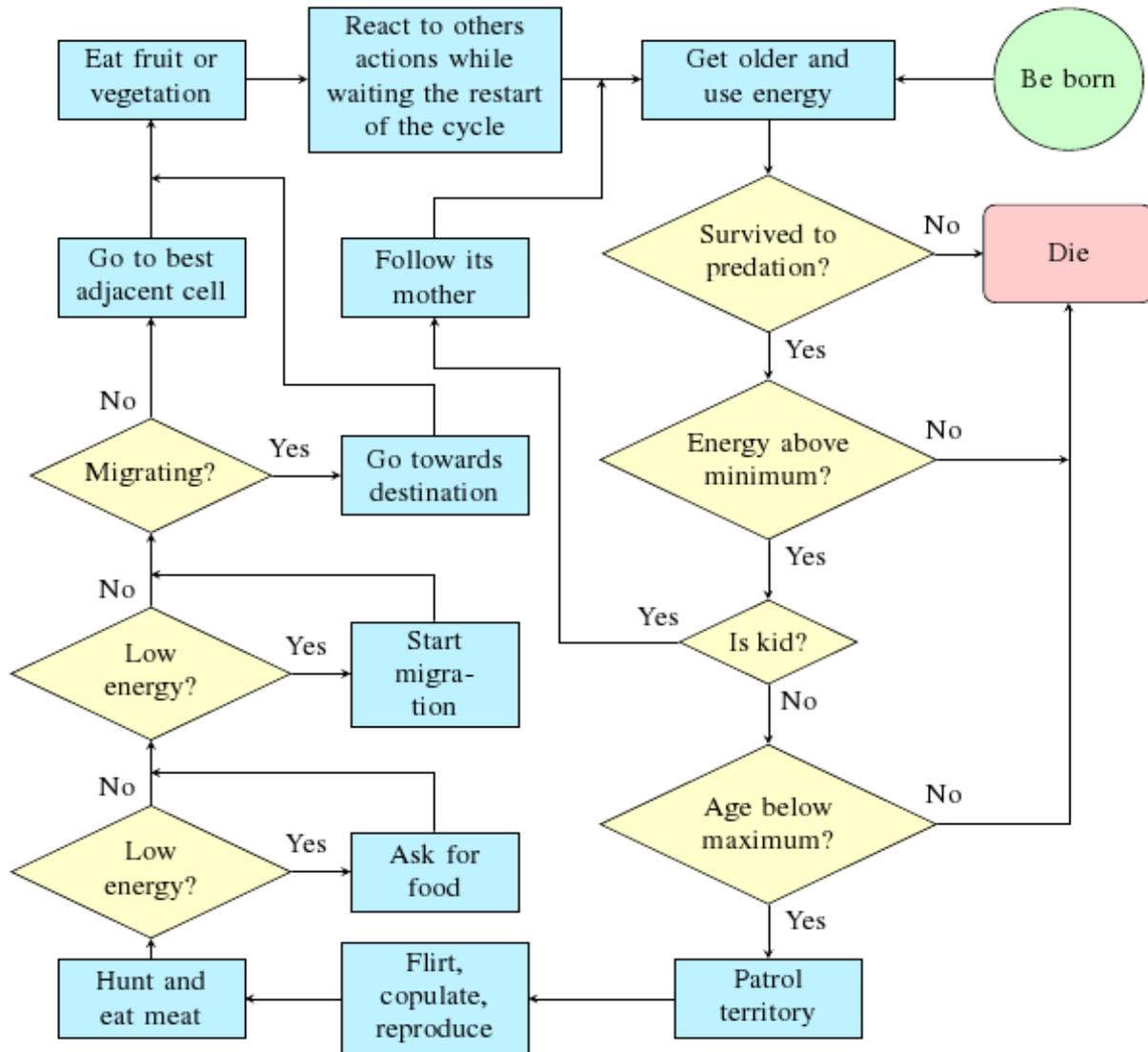


Figure 2. Basic algorithm of the proposed model.

FOOD SHARE

An agent will ask another agent for food if its energy level falls more than lowDeficit since the last step and it will migrate if its energy level drops more than highDeficit.

The agent checks which of its neighbours generates the most positive memories in order to choose the potential donor. However, the agent must evaluate its neighbours with incomplete information. It knows what events involving it the other remembers because all interactions are memorized by all agents involved, but it does not know the other's propensity to be vengeful or grateful, nor does it know the other's recall strategy. Thus, the agent calculates what the other's feeling for it would be using its own propensities and strategy. This equates to saying that the agent is capable of empathy. Because males and females follow different behaviour patterns, agents may also opt to remember past events using average values for vengefulness, gratitude, and the timeFactor that defines the value of old events.

Initially, the probability p of donation is equal to the agent's recall value. To this basic value, it adds its benevolence towards its mother, children, siblings, and, also, its benevolence towards agents of opposite sex or of the same sex. Of course, these benevolence values are only added if the supplicant agent can be classified in such categories. These different

propensities of benevolence are defined by the agent's genetic code. The agent will also add to p the value of its pity if the begging agent has less energy than it has, and subtract from it the value of its envy if the opposite is the case. The program generates a random number between 0 and 1 and, if the number is smaller than p , the agent makes the donation. The donation value depends on two kinds of agent generosity. One refers to the agent's energy level, and the other to the amount of meat that it has. If the agent is carrying any meat and its `meatGenerosity` is higher than zero, it will donate a piece of his meat proportional to its `meatGenerosity`, but always lower than 1,5. If either the agent does not have meat or its meat donation is lower than its metabolism, it will add the value of generosity to the donation, with the donation limited to the value of metabolism. In this second case, the agent's energy level will decrease by the value of donation.

When the process of energy or meat donation finishes, the agents memorize the event. If there was donation, donor and supplicant memorize the value given. If there was no donation, agents memorize the value that they attribute to negative answers to food requests. Each agent has different values for male and female refusals, and, if these values are positive, nothing is memorized.

MIGRATION

Migrations are dangerous because the risk of predation is higher in open land than in tree patches and because trees give much more food than terrestrial herbaceous vegetation. Furthermore, the agent does not know whether its destination will be overpopulated. In any case, the migrations are necessary because fruit production is seasonal. Thus agents may postpone, but cannot avoid migrations. After begging for food, the agent evaluates whether migration conditions are met or not.

The procedure to decide on the migration destination is complex. The agent makes three attempts to decide on a good place to go, and on each attempt it uses a different algorithm.

One of the algorithms consists of going to the best nearest cell, that is, to a cell whose distance is equal or shorter than `MaxVision`. The best cell is chosen using (5).

Another strategy is to remember known tree patches and check which patch is the best in terms of fruit production at the time the agent would be reaching it. More specifically, the patches are evaluated according to the expression:

$$V_{(\text{tree patch})} = N e_f \quad (6)$$

where N is the number of fruits that will be produced by all patch trees from the moment the agent arrives to the end of the tree fruit season, and e_f is the energy value of each fruit.

The third strategy consists of following a nearby agent who has already begun to migrate. In this case, each neighbouring migrant is evaluated according to the expression:

$$V_{\text{migrating}} = \text{remembrance} \cdot V_f + \frac{V_a \cdot a'}{a}, \quad (7)$$

where *remembrance* is the recall value and may be positive, negative or neutral (as already explained), V_f is the value of friendship regarding migration decisions, V_a is the value of age (it may be better to follow an older agent than a younger one because the former probably has a better knowledge of the local geography), a is the agent age, and a' is the migrant's age. The values of V_f and V_a are specific for each individual and are subject to evolution.

The sequence of algorithm activation is genetically determined and subject to evolution. If the three attempts to find a good destination fail, the agent begins the migration to a random

place within a distance between MaxVision and $2 \times \text{MaxVision}$. In this case, once a day the agent tries to find a good place to go using the near good cell search algorithm.

Once the destination is chosen, the agent invites all friends that are nearby to form a migration group, and each agent who accepts the invitation also invites all its neighbouring friends. Each invited agent sums the recalled values of all agents that already joined the group and if the sum is positive, it accepts the invitation, unless its migration strategy is never accepting invitations. Invitations to migrate to random places are refused.

The migration algorithm proper is very simple: at each time step the agent moves one cell towards the destination.

TERRITORIALITY

Each agent has an `enmityThreshold`. If the recalled value of another agent is below this value, it is considered an enemy³. Agents may also be xenophobic towards different types of strangers: males, females and females carrying children.

Once an hour each agent in a tree patch checks whether there is either an enemy or a stranger in the cells as far as `NearVision`. A neighbour is considered an intruder either if it is a stranger from one of the categories towards which the agent is xenophobic or it is an enemy. If any intruder is found, and if the agent's own bravery is higher than a random number between 0 and 1 generated by the computer, it will try to expel the intruder by inviting all nearby friends to join the alliance against it. The intruder will also try to form an alliance. The Figure 3 shows a flow chart of the process.

An agent invites its best friends from its own cell and from the cells within the `AllianceRadius`, whose value is defined before the start of the simulation. Invited agents may follow two different strategies to decide accepting or not the invitation to join an alliance. They may accept invitations coming either from only positively remembered leaders or from strangers and neutrally remembered leaders. If this first condition is met, the agent will accept the invitation if its loyalty is higher than a randomly generated number between 0 and 1. The refusal of the invitation is remembered by both agents as `valueOfNoCT` (value of no in conflict for territory). A neighbour is considered an intruder if the value of the remembrance it triggers is below the `enmityThreshold` of the patrolling agent. The intruder will also try to form an alliance. When the two alliances are formed, agents vote to decide whether their alliance will fight and all agents involved in the conflict register in their memories that they received positive values from their allies and negative values from their enemies.

The agents may follow the norm of punishing others who refused to join the alliance. In this case, the punishment will mean a loss of energy for both groups: punished and punishing agents. Agents that follow the norm of punishing non co-operators may follow the metanorm of punishing those alliance members that did not punish non co-operators. In all cases, the cost c of the punishment process will be proportional to the number of punishing and punished agents, according to the expression:

$$c_1 = \frac{n_2}{2n_1}. \quad (8)$$

The punishment process is memorized by all agents. Punished agents will memorize either the evil that they committed or the penalty that they received, depending on the value of their shame.

The probability of an alliance winning the conflict is proportional to the total energy of its

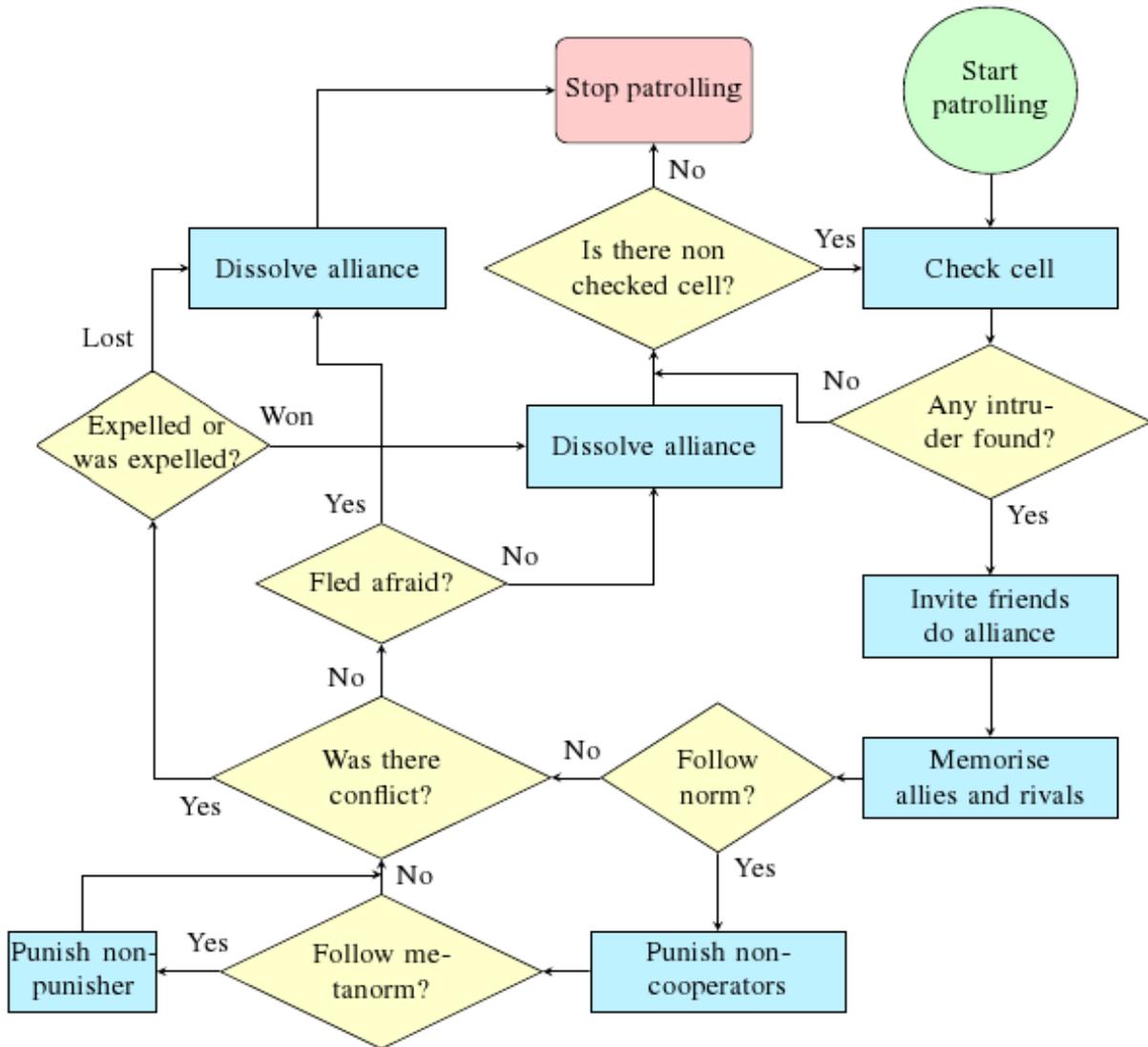


Figure 3. Algorithm of territory patrolling.

allies, and each ally casts a vote favourable to the fight if its audacity is above the probability of its alliance winning the conflict. That is, the rational value for audacity is about 0.5. If the two alliances decide not to fight, nothing happens. If the two alliances decide to fight, the program will generate a random number that will decide the conflict outcome. All agents will lose energy due to conflict, but loss will be inversely proportional to the total energy of the alliance the agent is part of.

Agents of an alliance that voted for peace and agents of alliances that lost the fight will flee from the leader of the winner alliance, running a distance equivalent to NearVision.

HUNT

Once during each cycle of the basic algorithm, the agent decides whether it is time to hunt. The evolution of no-hunting agents is possible because they may follow three strategies: (1) never hunt, (2) hunt only during migrations, and (3) hunt periodically. The interval between hunts is not a genetic variable; it may be considered a cultural one. The agent decreases its interval whenever it participates in a successful hunt and increases it whenever the hunt is unsuccessful. The hunter also increases or decreases its hunt interval according to the average interval of its group members.

When it is an agent's hunting time it invites its best friends to form a group of hunters. The maximum number of invited hunters is defined genetically. A big group has more chances of capturing prey than a small group, but members of successful small groups receive more meat. Thus, the evolution of an optimum group size within some generations is expected.

An agent accepts the invitation to join a group of hunters if it does not follow the strategy of never hunting and if at least half of its hunt interval has elapsed.

The event of refusing the invitation to join a hunting group is remembered, and the members of a group of hunters have their energy level decreased by HuntCost each time they join a group.

Agents seek prey at NearView distance, which is defined at the beginning of the simulation. If prey is found, the probability, p , of it being caught is given by:

$$p = 1 - 2^{(-8n/e)} - \left(\frac{1 - 2^{(-8n/e)}}{3n} \right), \quad (9)$$

where n is the number of hunters and e is the prey's energy. Then, the expected amount of meat, m , that an agent expects is given by:

$$m = pe/n. \quad (10)$$

Figure 4 shows the amount of meat expected according to the number of hunters and the size of the prey.

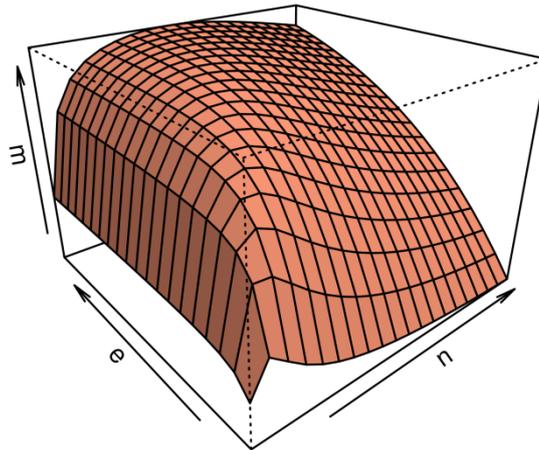


Figure 4. Expected meat reward.

The agent who made the invitation distributes the meat according to its fairness. If its fairness is 1, all agents in the group of hunters receive the same amount of meat. In addition to its own fairness, each agent also expects leaders of groups of hunters to have fairness above a certain threshold (expectedFairness). If the leader's fairness is below this value, the agent who received the meat remembers the event as if the leader has given it

$$\text{valueOfNotFair} \times (\text{expectedFairness} - \text{leaderFairness}).$$

Each agent expects different levels of fairness from male and females leaders.

Agents may carry their meat for some hours before it is spoiled and can consume a maximum of 2 units of the meat's energy at each hour.

REPRODUCTION

Females are solely responsible for nurturing offspring. An adult female enters a five hour oestrous period when her energy level is near the maximum. She then starts to receive mating proposals from nearby males. When the oestrous cycle finishes, the female sorts her suitors

according to the memories that she has of them. The evaluation of a male is also influenced by his energy level and age. Females may consider males more worthwhile if they have high energy and are close to the age she considers ideal. The value of each suitor is defined by the expression

$$V_{suitor} = rememb \cdot \left(\frac{v_a \cdot |\Delta a|}{MaxAge} \right) \cdot \left(\frac{v_e \cdot e}{MaxEnergy} \right), \quad (11)$$

where v_a is the importance for the female of the difference between the male's age and the ideal age; Δ is the difference between the male age and the ideal age; v_e is the value of male energy; and e is the male energy. The necessary adjustments are made to the above expression when a male's value is negative. Another factor that contributes to female's evaluation of males is the distance between them. The more distant the male at the end of the oestrous period, the less worthy he is considered by the female.

With males sorted by values, the female decides how many of them she will copulate with, according to her promiscuity index, which is genetically determined and may be between 0 and 1. The number of sexual partners will be the rounded value of n^f , where n is the number of suitors.

The probability p of a male being the father of the future newborn is proportional to his value to the female in relation to the sum of values of all sexual partners. The males who have the opportunity to copulate, register in their memory $p \times childValue$, where $childValue$ is the value attributed by the male to sexual intercourse. The suitors not chosen as sexual partners memorize the event with the valueOfNoSex. The female also does the corresponding memorization of all these events, but using her own values for $childValue$ and $valueOfNoSex$.

In the real world, many animals, guided by instincts, and humans, guided by instincts and cultural norms, avoid sexual relations with close kin. In this model, males do not have sexual interest in their own mothers.

SETUP OF SIMULATIONS

Due to the model's complexity and limited computational resources, even the simulation of a small world runs slowly. There were 32 different combinations of parameters, but some of them were run more than once and some and were not run (due to either hardware failure or collapse of the population). The total number of simulations was 39. The size of the patches of trees could be either small (just 1 tree) or big (between 4 and 10 trees), the density of trees could be low (0,005 or 0,007) or high (0,05), the maximum density of preys could be either low (0,01) or high (0,03), the world could be shaped as either a strip (20×300) or a square (100×100), and in some simulations there was a period of the year without fruit production (drought).

The average results of some previous simulations were used as initial values for the agent's genetic characteristics. At the beginning of the simulations each agent from the first population received values between 0,2 below and 0,2 above the values shown in Table 1 (all tables are listed in Appendix).

RESULTS

In many simulations, females, males or both developed negative propensities to feel vengefulness, gratitude or both. In only eight simulations, on average, both females and males developed positive propensities to feel both vengefulness and gratitude. The development of negative values for this propensity to feel emotions was unexpected and we

can consider the agents in these eight simulations the normal ones. However, the comparison of the mean values of some other variables reveals that the others may not really be masochistic and ungrateful; it seems that they have developed negative values for vengefulness and gratitude as an adaptation to other unusual values. For example, an abnormal female stores a positive value in memory (on average, 0,33) when other female is not fair to her. In this case, it is adaptive to have an inverted propensity to feel vengefulness. Hence, it was the lack of determination of the model that allowed these unexpected equilibriums between vengefulness and gratitude and other genetic propensities.

I considered as indicators of evolution of cooperation the size of patrol alliances, the size of hunt groups, and the proportion of food shared to food requested. Table 2 in Appendix presents average values of cooperation during the last 1 % of the simulation's steps as well as the average number of generations elapsed. In this table, *N. Hunters* is the average number of agents who formed groups of hunters; *NA 1* is the average number of agents who joined an alliance to defend a patch of trees from an intruder; *NA 2* is the average number of agents who joined the second alliance, formed by the intruder to avoid being expelled. *Food Share* is the proportion of requests for food which were granted; a capital *M* means Male, and *F* means Female. *N. Gen.* is the average generation number of agents. When an agent is born, it receives two generation numbers, a masculine one and a feminine one, which correspond to its parents numbers +1.

Food sharing is highly biased by sex. Females adapted to the exigencies of motherhood by developing the propensity to almost never share food. Males, who need to be positively remembered by females, developed the propensity to be generous towards females in about 60 % of requests, but they also shared food with other males in about 20 % of occasions. As we can see in Table 3, females developed negative values for generosity; an agent with negative generosity never shares food, regardless of who is requesting. Males developed positive generosity when carrying meat, and were generous with females, specially their mothers.

The preference to move and migrate are similar in males and females. Table 4 shows that both sexes prefer to go to cells with agents of opposite sex, but males are more prone to do so, particularly if the cell has an oestrous female. As expected, cells rich in energy are more positively evaluated by females than by males.

On average, the size of alliances to defend territory was not remarkable. The presence of many values below 1 indicates that on many occasions agents not only formed small alliances but also frequently voted for their dissolution. That is, impelled by low audacity, they acted as they would if consciously following a conflict avoidance strategy. It seems that there was no pressure towards or against the evolution of xenophobia or fear of hostile patches as can be seen in Table 5: the values near 0.5 indicate that these variables were changing randomly. The other variables show signs of evolution. Females bravely initiate alliances, rationally decide whether to fight or not and refuse to join alliances initiated by others. Males have a lower propensity to start alliances, but once part of one they are irrationally audacious. They also are more prone to accept an invitation to join alliances than females are. On average, both males and females have the same propensity to follow the norm of punishing agents who refuse to join an alliance, and neither has the propensity to follow the metanorm of punishing the non-punisher agents.

There are some differences between females and males in memorization and recall of events. Both males and females store more negative values when a male refuses to share food than when a female does the same (Table 6). This is equivalent to recognition that females cannot share food because they always need it more than males. Males are less vengeful than females.

Females do not consider it a great favour if an agent joins their alliance to expel an intruder. A male becomes more upset when a female refuses to have sex with him than a female imagines.

Table 7 shows some results related to agents' reproduction. Females developed a propensity to prefer young males. A male's age is more important than his energy because males memorize a high value for the event of being one of the probable fathers of a child. That is, this event makes the male remember a female as his friend for a long time, increasing the chances of food share. Female low promiscuity is correlated with male vengefulness strategy. In simulations with males following more vengeful recall strategies, females are less promiscuous because a male following the most vengeful strategy will consider another agent his friend only if the last value given is higher than the last value received. If a female is promiscuous, the *child value for male* will be divided by many males and, thus, will soon be remembered as a small value. That is, depending on male vengefulness it may be better for females to be either more promiscuous, and, thus, make many male friends and avoid male enemies or less promiscuous and make at least a few male friends.

The burden of children rearing made starvation the most frequent cause of death for females, even in simulation number 27, which had the smallest difference between the number of female and male generations. In no simulation females lived longer than males. The ratio of the number of male generations to the number of female generations, which I have called *fLife* varied from 0,45 to 0,87. Unexpectedly, Table 8 shows that *females clearly fare better when males are vengeful*, particularly when they use the last values given and received while being vengeful. In simulation number 27, females had a low promiscuity (min. 0, mean 0,11, max. 0,22) and males had a high vengefulness (min. 1,10, mean 1,31, max. 1,45). The other most significant variables do not have surprising effects. Females will live less if they join alliances, because conflicts mean loss of energy, and they will live more if males have a high meat generosity.

The abundance of food is the most significant ecological factor in the evolution of cooperation. As shown in Table 9 in Appendix, the summaries of stepwise regression analyses including *patch size*, *tree density*, *prey density*, *world shape*, and the existence of *drought* as independent variables reveal that high tree density is favourable to the formation of larger groups of hunters, and to food share by males. Big patches of trees are favourable to food share from male to females and drought is unfavourable to food share from females to females. High prey density is favourable to food share by females.

One desirable result would be the emergence of fission-fusion societies, similar to real anthropoid societies. The seasonality of fruit production obligates agents to migrate frequently from one patch to another and is responsible for the trend of continuous reshuffling of the population. Although in some of the sociograms of Figure 5 we can identify the existence of big groups of agents who have friendly relations, we cannot distinguish the formation of communities of small interconnected groups. Each sociogram represents the network of friends and was built from the memories of those agents who were alive when the simulation ended; the arrows point to agents remembered with positive values. The sociograms are not sufficient to know which process has caused the formation of big groups: were the agents able to develop strong enough cohesive propensities to cope with the disruptive effects of migration or were the big groups formed as a consequence of the spatial distribution of patches of trees?

The sociograms of neutral relationships would be far denser than the ones shown in Figure 5 since the number of neutral memories was much higher than the number of positive ones. For each simulation, I calculated the proportion of memories corresponding to agents remembered

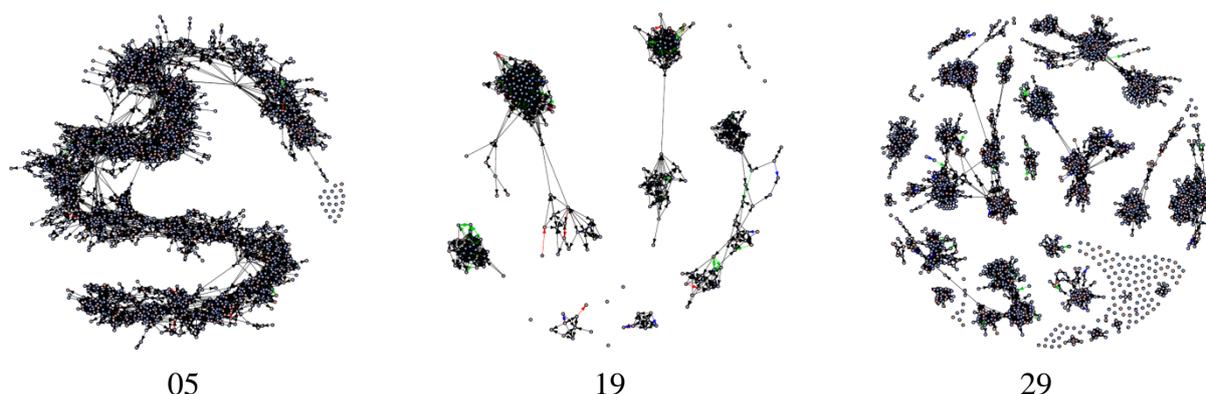


Figure 5. Sociograms of relationships between friends at the end of selected simulations.

as enemies, intractable agents (negatively remembered, but with a recall value above `enmityThreshold`), neutrals and friends. Table 10 in Appendix shows the minimum, mean, and maximum values for all 39 simulations. There is a highly significant correlation between the proportion of friendly relationships and alliance formation for territory defence.

It would be necessary to collect more information from the simulations to know if the agents continuously change from one small group to another while remaining in the same community. However, the data already collected show that cells with friends are not highly evaluated. Agents developed mostly positive values in their selectivity of other agents, that is, the probability of a cell being chosen as destination of either migration or move is higher if it is occupied. Selectivity towards friends is not very high when compared with the selectivity towards other types of agents. The mean value attributed by an agent to a cell with a friend was 0,06 for females and 0,08 for males, far below the values of other variables used to evaluate cells, as can be seen in Table 11 in Appendix. Indeed, past cooperative or conflictive interactions do not seem to be correlated with the distance of agents who know each other. The main factor determining the distance between agents who interacted in the past is the time elapsed since the interaction.

The interpretation of the above results was based on results averaged from all simulations, but there was a great deal of variation between the simulations and each simulation may deserve its own „case study“.

CONCLUSION

No one knows what really goes on the mind of chimpanzees (and possibly other anthropoids) when they form alliances to hunt, fight and remain in power positions within their communities. The algorithm of alliance formation presented herein is a hypothesis of how this happens, testable through virtual experiments.

The high level of food share from male to females is mainly due to the control females have over their sexual life: they choose with whom they have sex. A future work could be the development of an algorithm allowing the evolution of male alliance formation to have sexual access to females, as those existing among real chimpanzees.

Although negative values for vengeance are odd because they imply that agents have a positive remembrance of those who were evil to them, in some simulations this was the path found by the agents to avoid the costs of conflict. However, negative vengeance and gratitude values turn the analysis of the results more complex than they should be. It would not be a strong restraint on the model if the evolution of negative values for these variables were not allowed, because agents would remain free to develop positive values to remember

what real humans commonly agree are bad and negative values to what is usually considered good. They would also remain free to develop negative benevolence.

The model is highly complex, and much more work would be necessary to improve it and fully explore the heuristic potential of this approach. Given the complexity of the model, it was not possible before running simulations to know which variables and strategies would have a meaningful evolution (and, thus, should be kept) and what would vary randomly (and, thus, should be purged from the model). Instead of keeping the model simple, the approach proposed herein consists of starting with a complex model and subsequently simplifying it. This paper should more properly be considered the partial report on ongoing (or interrupted) individual research than the final report of a finished project.

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REMARKS

¹The complete revision of literature done for this research is given in my doctorate thesis, in Portuguese, available at <http://www.lepem.ufc.br/jaa/tese.pdf>.

²The source code is available at <http://www.lepem.ufc.br/jaa/anthropoids.html>.

³This variable was not present in the model that I presented in my doctorate thesis, and it is the most important difference between the two versions of the model. Without *enmity threshold* any negative recall value was highly disruptive to social relations.

APPENDIX

Table 1. Average genetic features of the first population.

Variable	Fem.	Males
gratitude	0.55	0.43
vengefulness	0.42	0.19
time factor	0.37	0.34
f. refusing to share food	0.0	-0.38
f. refusing to join hunt group	-0.68	-0.58
f. refusing no to join alliance	-0.52	-0.35
m. refusing to share food	-0.72	-0.51
m. refusing to join hunt group	-0.43	-0.61
m. refusing to join alliance	-0.59	-0.61
no in sex proposal	-0.58	-0.76
hunt value	1.06	0.85
patrol value	0.37	0.7
value of not fair	-0.50	
generosity	-0.35	0.47
meat generosity	0.48	0.73

pity	0.39	0.73
envy	0.72	0.80
benev. t. agents of oppos. sex	1.13	0.61
benev. t. agents of same sex	-0.14	0.11
benev. t. mother	0.46	0.51
benev. t. sibling	0.51	0.65
benev. t. child	0.38	0.0
importance of migrant age	-0.58	-0.26
importance of migrant friendship	-0.26	0.38
cells with same sex agents	0.19	0.78
the energy of a cell	0.98	0.53
cells with mother	0.45	0.32
cells with sibling	0.55	0.43
cells with friend	0.12	0.24
cells with oppos. sex agents	0.71	0.09
cells with f. in oestrous	-	2.0
cells with child	0.07	-
importance of male energy	0.56	-
importance of male age	0.57	-
promiscuity	0.5	-
child value for male	11.7	13.6
propensity to accept invitation	0.49	0.31
propensity to accept move invitation	0.47	0.47
xenophobia towards males	0.52	0.53
xenophobia towards females	0.56	0.49
xenophobia towards f. with child	0.42	0.50
bravery	1.09	0.09
audacity	0.95	0.7
loyalty	-0.29	0.0
fear of hostile patch	0.49	0.62
fear of hostile patch when has child	0.42	-
propensity to follow Norm	0.4	0.4
propensity to follow Metanorm	0.01	0.02
fairness in meat distribution	1.1	
value of stranger	0.1	
enmity threshold	-0.9	
meat value	0.26	

Table 2. General results of all simulations.

Simulation	No. of hunters	NA 1	NA 2	Food Share				N. Gen.
				M. to M.	F. to F.	M. to F.	F. to M.	
01	1.34	1.22	0.65	0.484	0.000	0.882	0.000	38483
01a	1.15	1.31	1.20	0.000	0.041	0.003	0.000	13431
01b	1.28	2.14	1.80	0.000	0.000	0.000	0.000	41350
02	1.02	1.12	1.06	0.000	0.000	0.000	0.000	43273
02a	1.05	0.24	0.08	0.063	0.000	0.028	0.000	66043
02b	1.02	1.03	1.03	0.014	0.004	0.101	0.005	44309
03	1.00	1.00	0.07	0.007	0.000	0.011	0.000	25154
03a	1.72	3.00	1.45	0.847	0.000	0.924	0.000	17771
04	1.00	1.00	1.00	0.000	0.007	0.000	0.003	22905
04a	1.17	0.00	0.00	0.779	0.000	0.928	0.000	24558
05	1.00	1.00	1.00	0.719	0.000	0.939	0.007	1923
05b	1.00	0.98	0.96	0.513	0.007	0.018	0.032	2084
06	1.58	2.87	3.22	0.543	0.001	0.999	0.007	3260
06b	1.00	1.00	0.89	0.000	0.000	0.163	0.003	3668
07	1.67	2.64	1.55	0.260	0.023	0.552	0.063	994
07b	1.11	1.32	1.09	0.108	0.049	0.169	0.105	1092
08	2.10	0.50	0.00	0.067	0.001	1.000	0.003	1908
10	1.77	1.99	3.03	0.197	0.000	0.731	0.000	35112
11	1.36	1.62	1.62	0.048	0.130	0.000	0.078	23460
12	1.22	2.59	0.44	0.001	0.000	0.152	0.040	24485
13	1.44	2.64	0.08	0.009	0.080	0.352	0.308	2115
14	2.97	7.60	3.72	0.252	0.019	0.999	0.010	3368
15	1.73	4.69	1.73	0.364	0.048	0.029	0.069	954
16	1.86	1.75	0.58	0.214	0.013	0.999	0.154	1724
17	1.00	0.84	0.19	0.000	0.064	0.000	0.112	25320
19	1.10	1.16	1.06	0.674	0.034	0.996	0.000	10375
20	2.33	13.10	5.14	0.483	0.000	0.998	0.000	6821
21	2.51	4.80	5.40	0.037	0.011	0.996	0.036	932
22	1.48	1.76	1.82	0.085	0.013	0.998	0.100	1720
23	2.13	3.39	1.38	0.100	0.003	0.993	0.025	522
24	2.10	1.02	0.37	0.151	0.000	0.999	0.064	888
26	1.72	2.09	2.24	0.000	0.000	0.004	0.000	6181
27	1.00	0.94	0.88	0.971	0.000	0.926	0.000	10985
28	1.00	1.00	1.00	0.055	0.000	1.000	0.000	9286
29	1.64	1.00	0.35	0.112	0.005	1.000	0.041	883
30	2.33	3.49	1.94	0.048	0.017	0.999	0.112	1733
31	1.86	1.38	0.49	0.104	0.025	0.994	0.113	542
32	1.30	2.56	1.02	0.047	0.041	1.000	0.105	874
32a	1.71	3.87	2.26	0.077	0.019	0.997	0.018	743
mean	1.51	2.25	1.38	0.216	0.017	0.587	0.041	13365

Table 3. Average genetic propensity to share food of last populations.

Variable	Females	Males
generosity	-1.00	-0.34
meat generosity	-0.07	0.19
pity	0.99	0.85
envy	0.59	0.36
benev. t. opposite sex	1.39	1.05
benev. t. same sex	-0.49	-0.69
benev. t. mother	0.43	0.58
benev. t. sibling	0.56	0.21
benev. t. child	-0.03	-

Table 4. Average genetic propensity to move and migrate of last populations.

Variable	Females	Males
importance of migrant age	-1.49	-1.01
importance of migrant friendship	1.09	0.93
cells with agents of the same sex	0.28	0.49
the energy of a cell	1.92	1.16
cells with mother	0.70	0.67
cells with sibling	1.07	0.74
cells with friend	0.06	0.07
cells with agents of opposite sex	0.93	1.39
cells with females in oestrous	-	2.46
cells with child	0.62	-

Table 5. Average genetic propensities related with territory conflict of last populations.

Variable	Females	Males
xenophobia t. males	0.50	0.54
xenophobia t. females	0.48	0.48
xenophobia t. females with child	0.46	0.53
bravery	1.66	0.78
audacity	0.57	1.56
loyalty	-0.68	0.38
fear of hostile patch	0.48	0.44
fear of h. patch when has child	0.49	-
propensity to follow Norm	0.40	0.40
propensity to follow Metanorm	0.03	0.04

Table 6. Average genetic propensities related with memorization and recalling of last populations.

Variable	Females	Males
gratitude	0.48	0.50
vengefulness	0.50	0.04
time factor	0.42	0.49
female refusing to share food	-0.34	-0.57
female refusing to join hunt group	-0.91	-0.68
female refusing no to join alliance	-0.72	-0.82
male refusing to share food	-0.73	-0.94
male refusing to join hunt group	-0.41	-0.17
male refusing to join alliance	-0.70	-0.71
no in sex proposal	-0.75	-1.27
hunt value	1.09	0.97
patrol value	0.07	0.82
unfair meat distribution by female	-0.29	-0.49
unfair meat distribution by male	-0.75	-0.74

Table 7. Average genetic propensities related with reproduction of last populations.

Variable	Females	Males
importance of male energy	0.22	-
importance of male age	0.88	-
promiscuity	0.48	-
child value for male	10.05	13.10

Table 8. Regression Summary for *fLife* as dependent variable.

Coefficient	Est.	SE	p
(Intercept)	0.472	0.040	0.000
Male gratitude	-0.015	0.010	0.144
Male vengefulness	0.069	0.013	0.000
Male benev. t. opp. sex	-0.012	0.008	0.169
Male benev. to sibling	-0.013	0.008	0.130
Male veng. strategy 2	0.140	0.070	0.056
Male meat generosity	0.028	0.009	0.004
Male audacity	0.019	0.008	0.028
Male loyalty	-0.024	0.007	0.003
Female bravery	0.025	0.011	0.032
Female loyalty	-0.052	0.010	0.000
Multiple R ² : 0.7438, Adjusted R ² : 0.6523.			

Table 9. Regression summaries for *Number of Hunters* and *Food Share* as dependent variables.

	Coefficient	NHunters	FS-MF	FS-FM	FS-FF
(Intercept)	1.15**	0.24*	0.01	0.02**	
	(0.13)	(0.11)	0.02)	(0.01)	
Patches	0.22	0.40**			
	(0.15)	(0.13)			
Tree Density	9.61**	6.85*	1.13**		
	(3.30)	(2.77)	(0.39)		
Prey Density			0.04*	0.02*	
			(0.02)	(0.01)	
Drought			-0.03	-0.02**	
			(0.02)	(0.01)	
Adjusted R ² :	0.212	0.308	0.289	0.219	

* p < 0.05; ** p < 0.01.

Table 10. Minimum, mean, and maximum proportion of memories representing different kinds of relationship.

	enemies	intractable	neutrals	friends
Min.	0.0000	0.0000	0.7195	0.0056
Mean	0.0078	0.0159	0.9238	0.0525
Max.	0.1295	0.0844	0.9892	0.2643

Table 11. Mean value of some variables used to evaluate cells.

Variable	Female	Male
cells with friend	0.063	0.075
cells with children	0.625	-
cells with mother	0.698	0.666
cells with opposite sex agents	0.927	1.395
cells with sibling	1.072	0.738
the energy of a cell	1.922	1.158
cells with females in oestrous	-	2.459

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KOOPERACIJA VIRTUALNIH ANTROPOIDA U KOMPLEKSNOJ OKOLINI

J.A. de Aquino

¹Odsjek za sociologiju, Federalno sveučilište Ceará
Fortaleza, Brazil

SAŽETAK

Članak prikazuje model agenata za simulaciju evolucije kooperacije u kompleksnoj okolini. Antropoidni agenti spolno se razmnožavaju i žive u svijetu gdje je hrana prostorno nejednoliko raspoređena, a sezonski generirana. Agenti mogu dijeliti hranu, formirati grupe za lov i za migraciju, a sposobni su sklapati saveze za podjelu teritorija. Agenti pamte svoja međudjelovanja s drugim agentima, a njihova djelovanja prvenstveno su upravljana emocijama, modelirana kao težnje specifičnom načinu reagiranja na akcije drugih agenata i uvjete okoline. Rezultati pokazuju kako je spolno razmnožavanje vrlo bitno – u predloženom modelu, kooperacijaje intenzivnija između agenata suprotnog spola.

KLJUČNE RIJEČI

evolucija kooperacije, komputacijski model, antropoidi

THE GYULA FARKAS MEMORIAL COMPETITION IN THE CONTEXT OF THE HUNGARIAN SCIENTIFIC COMPETITIONS

Dezső Gurka*

Institute of Pedagogics and Social Sciences, Szent István University
Szarvas, Hungary

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ABSTRACT

Gyula Farkas (1847-1931) became a well-known scientist in his age due to his thermodynamic achievements, but today – after rediscovering his articles in 1950 – he is also noted as one of the founders of operation research. On the occasion of the 150th anniversary of his birth, his name became known beyond scientific circles.

In this article, brief introduction into his life is given. The emphasis is put onto his achievements which provides modern context for efficient introduction of younger generations into the scientific world, and especially scientific methodology and interdisciplinary approaches.

KEY WORDS

Gyula Farkas, sciences, thermodynamics, scientific competitions

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*Corresponding author, η: gurka.dezso@gmail.com; +36 66 311511;
Institute of Pedagogics and Social Sciences, Faculty of Education, Szent István University,
H-5540 Szarvas, Szabadság str. 4, Hungary

INTRODUCTION

Gyula Farkas was born on 28th March 1847 in Pusztasárosd (now Sárosd) near Lake Balaton, where his father was an estate supervisor on an Esterházy property there. During his secondary school years in Győr he got acquainted with Ányos Jedlik, one of inventors of dynamo and it was Jedlik's encouragement which directed him towards physics. Farkas was interested in music at a young age. He was devoted to music later in his life, too: he wrote several articles in music, played the piano and gave performances also outside Hungary.

In 1874, still as a secondary school teacher, he had the opportunity to read one of his papers at the Hungarian Academy of Sciences, which was given a criticism by Loránd Eötvös. The following years in Gyula Farkas's life were marked by Eötvös's demands: he could obtain widespread scientific knowledge ability and was able to deepen his mathematical awareness.

Farkas got a job as tutor of the Batthyány counts, who played an important role in the beginnings of his scientific career. They built a laboratory of physics in one of their castles, and Farkas, escorting his aristocratic students, had the opportunity to make some professional acquaintances.

Although his first remarkable works were in the fields of algebra published, from 1880 he became the privat-docent of function at the University of Budapest. In 1887 he was appointed the professor of the mathematics and physics department at the University of Kolozsvár (now Cluj-Napoca, Romania). His state is special because at the beginning of his scientific career he was noted more as a mathematician, later more as a theoretical physicist, yet his scientific oeuvre looks homogeneous became the most important feature of his articles in physics had a strict mathematical background.

In 1893 Gyula Farkas was delegated by University of Kolozsvár at the Galilei celebrations in Padoa, where he was appointed honorary professor. Focal articles of his oeuvre were connected to this event, as his article titled *A virtuális sebességek elve Galileinél* (eng. *The theory of virtual speed at Galilei*) was written after this celebration. After this the main area of his research became this branch of mechanics.

Between 1893 and 1926 Farkas wrote nine articles about virtual speed and the mathematical problems relating to it, whose effect on the theory of optimalization was first valued by András Prékopa [1]. The Farkas Theorem was first determined in [2] and was first used to describe the mechanical balance. His achievements in mathematics became known by his article [3], and the rediscovery of this article made him the often cited classic of the theory of optimalization.

Another important publication of his preceded the thermodynamic theory of Caratheodory. Latest research has found that the foundations of thermodynamics by Farkas were described fourteen years earlier than those of Caratheodory and they were completely different from those, but followed a much simpler way [4].

Gyula Farkas was appointed a member of the Hungarian Academy of Science in 1898. He was the Dean of the University of Kolozsvár seven times and in the academy year of 1907/1908 he was the Rector of it. He played an important role in the development of the traditions of mathematics in Kolozsvár, namely that Frigyes Riesz, Alfréd Haar and Lipót Fejér taught at the university.

The results of modern physics also appeared in his university talks, he was the first in Hungary who gave lectures about the special theory of relativity¹ [5]. Gyula Farkas resigned because of his eye problems and lived in Budapest from 1915 until his death in 1930.

The basic principle of homogenous linear inequalities, published in the Crelle Journal, became part of the history of mathematics as the Farkas Theorem. Albert W. Tucker rediscovered it in the 1950s and used it in his proofs² [6]. Later Farkas was recognized as the predecessor of several areas of modern science (e.g.: linear programming, economic and mathematical optimization). One of the latest synthesis of mathematical history thinks that the Farkas Theorem is one the most important thesis in the historical precedent of linear programming [7].

THE BEGINNINGS AND THE CHARACTERISTICS OF THE GYULA FARKAS MEMORIAL COMPETITIONS

THE EVENTS OF THE FARKAS-ANNIVERSARY

Commemorating the 150th anniversary of the Birth of Farkas the periodical *Fizikai Szemle* published six, and the *Természet Világa* two articles about Gyula Farkas' life and work. The book titled *Új utak a magyar operációkutatásban* (eng. *Alternative Ways in Hungarian Operation Research*) contains two lectures given at the Institute of Mathematics. A sixty page book was published (titled *Farkas Gyula élete és munkássága* (eng. *Gyula Farkas' life and work*)) in 2003 [8]. The most important event of the fortunately growing Farkas cult was the international scientific conference held in Kolozsvár (Cluj-Napoca) in Aug 2004.

The beginning of the Gyula Farkas Memorial Competition in Sárosd is also connected to the anniversary of his birth. Farkas's name thanks to a local historical was already known in Sárosd. The private initiative to erect a memorial plate and a similar intention by the Loránd Eötvös Physical Society and the Bolyai Society made the decision by the local authorities faster. Farkas's birthplace was marked by the memorial plate in 1997.

The next step in building the Farkas cult was that the local primary school took up Gyula Farkas' name. On this occasion László Filep, the author of the first biography presented the school with the photos which he received from the relatives of Gyula Farkas. They have been commemorating the locally born scientist with a memorial competition since 2000.

THE SCIENTIFIC FEATURES OF THE COMPETITION

The Gyula Farkas Memorial Competition, which commemorates the intricate work of the eponym, is a complex science competition, which contains musical, art and drama tasks, too.

The participants of the competitions

There are 10-12 teams at the competition in two age groups pupils in the 5th–6th grade and pupils in the 7th-8th grade make up four member teams. Apart from the Sárosd region two forcing Hungarian schools take parts. The relationship with the Báthory Lycée was justified by the fact that Gyula Farkas was a professor in Kolozsvár, the teams from Zenta (Senta, Serbian Republic) applied for the invitation. This way it is possible for the Hungarians to keep contact with Hungarian minorities living in bordering countries in an informal way, too. At the same time both the students and the teachers can have a closer look at the characteristics of the teaching methods in the different countries (it is a striking fact that the team from Kolozsvár has a precise apparatus in solving a mathematical problem, whereas the Hungarian teams are more flexible in the reacting to situations outside the curriculum).

Diversity of the exercises

The students in the 5th–6th grade and in the 7th–8th grade get two tasksheets relevant to their knowledge. These tasksheets do not demand the reproduction of the knowledge typical in

primary school testpapers, but the creative use of mathematical terms outside curriculum. At the beginning of the competition each group has to fill in a 13 + 1 quiz question sheet about Gyula Farkas's life. The playfulness of the competition and the mobilisation of the multiform creativity is encouraged by the performance of a short play. The teams make and exhibit drawings, watercolours and collage on a pre-given topic beforehand and these can be seen before and during the competition. The 10–15 minute, which is based on a preset theme, is directed by the students and performed between the two rounds of the competition. Pongrác Kacsóh, who took his doctorate at Gyula Farkas, composed music for Petőfi's *János vitéz* epic poem. The jury also evaluates these performances.

Direct connection between the universal-scientific sphere and the primary school

The teachers at the primary school and the university lecturers make the preparations for the competition together. Thus the lecturers can follow the basic scientific terms of knowledge of students and can perceive the one-sidedness of primary school coursebooks (being stuck to patterns or distortion of certain terms e.g.: in case of the concepts of work or energy). The primary school students can get a notion of a different point of view in an informal way and they can experience that the terms used in scientific thinking can be reflected and can be thought over. The presence of the university lecturers and researchers as private people and voluntary helps entails the productive operation of the network of personal relationships several institutions (Eötvös Loránd University, Budapest University of Technology and Economics, College of Nyíregyháza) and disciplines (mathematics, physics, history of science and philosophy) take part in the organisation of the competition, and organizers and members of juries of other competitions take part or took part in this process. Thus students can get a wider scale of information, which can help them in career orientation. (The direct helping touch with the universities can be seen only in few examples now, but hopefully it will contribute to the general growth in the number of future graduates.)

The growth of the operation area of the organizing school

The Gyula Farkas Primary School in Sárosd joined directly into the fostering of the Farkas traditions became determining in the school's image. The new name of the institution, the memorial plate dedicated to the eponym strengthens the cohesion of the institutions, at the same time the board of teachers and the leaders of the school are present at scientific events related to eponym. Their delegation took part at the conference at the Babes-Bolyai University and they donated a painting of Gyula Farkas for the university, which is placed in the hall named after him. The costs of the publishing of the book *Farkas Gyula élete és munkássága* (eng. *Gyula Farkas' life and work*) [9] were mostly covered by the financial benefit from the county authorities for the primary school in Sárosd.

THE PLACE OF THE GYULA FARKAS MEMORIAL COMPETITION AMONG THE HUNGARIAN SCIENTIFIC COMPETITIONS

In Hungary the secondary school competitions have a longer history and among these too the mathematics competitions have a traditionally important role. The *KÖMÁL* (shorthand for *Secondary School Mathematics Journal*) has been carrying out a mission in taking care of talented students since 1912, and many of the prize-winners (who have been recorded since 1926) have later become internationally noted like the mathematician Pál Erdős and the Wolf-prize winner László Lovász but also the philosopher of science Imre Lakatos, the Nobel-prize winner economist János Harsányi.

The most important focus point of these competitions is problemsolving, which has traditionally been emphasized in Hungarian education of mathematics, too. This concept gives the background to György Pólya's book titled *How to solve it?*, which is the best known interpretation of his heuristical method. The Hungarian mathematical reforms in the 1950s made a similar view significant. Tamás Varga, who developed the theoretical basis of the reform in the education of mathematics, together with László Kalmár and Rózsa Péter represented the empirical mathematical view, and originally all three of them (together with Imre Lakatos) were Sándor Karácsonyi's students at the University of Debrecen [10]. Certain elements of the empirical view can also be found in the works of Árpád Szabó, who is the most characteristic representative of the Hungarian research of history of mathematics [11].

This tradition in education and competitions put a significant effort on Hungarian mathematical and science competitions, too (such as the National Secondary School Competition or the Pál Bugát Natural Competition). New phenomena in the 1990s are those primary school competitions in mathematics, which became nationwide events organized by one single school, for example Ilona Zrínyi Competition in Kecskemét and the Bátaszék Competition in Mathematics.

A common feature of the above listed competitions is that they work within the existing educational structure (which is true for the structure of competitions in higher education, too). The competition in Sárossd is not a nationwide one, it is a regional competition, but it is irregular in several ways. There are also university lecturers in the organisation and jury in the above mentioned secondary school and primary school competitions, but compared to these, the number of lecturers from universities is a lot higher at the Gyula Farkas Memorial Competitions.

The place of the Gyula Farkas Memorial Competition is not defined by the number of participants or its importance in the structure of competitions in Hungary, but by its focused character, which comes from the cooperation of the local authorities, the public educational authorities and the higher educational spheres. Its true importance is in its value being an example it gives a model for recognizing and keeping the local traditions and how these can be connected to the propagation of relevant knowledge informally and taking care of the talented students in a way which encourages competitive skills.

REMARKS

¹László Filep found the then living relatives of Farkas in the 1970s, according to whose memories Gyula Farkas was corresponding with Einstein.

²András Prékopa writes about the rediscovery of the articles this way: Albert W. Tucker was working on one of the proofs of the nonlinear programming with his Ph.D. student Harold W. Kuhn. They got stuck and they needed the results in connection with the linear inequalities. Tucker sent his student down to the library to search and Kuhn found Gyula Farkas's article then, which contained exactly what they need.

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THE GYULA FARKAS MEMORIAL COMPETITION IN THE CONTEXT OF THE HUNGARIAN SCIENTIFIC COMPETITIONS

D. Gurka

Institut za pedagogiju i sociologiju, Sveučilište sv. Ivana
Sarvaš, Mađarska

SAŽETAK

Gyula Farkas (1847-1931) postao je poznati znanstvenik svog vremena zbog dostignuća u termodinamici. U današnje vrijeme – nakon ponovnog otkrivanja njegovih članaka tijekom 1950-ih godina – smatra ga se začetnikom operacijskih istraživanja. Prigodom 150. obljetnice njegovog rođenja njegovo ime postalo je poznato izvan znanstvenih krugova.

U ovom radu ukratko je opisan njegov životni put. Težište je stavljeno na dostignuća koja su omogućila suvremeni okvir za učinkovito uvođenje mladih generacija u svijet znanosti, a posebno znanstvene metodologije i interdisciplinarnih pristupa.

KLJUČNE RIJEČI

Gyula Farkas, prirodne znanosti, termodinamika, natjecanja iz znanosti

MANUSCRIPT PREPARATION GUIDELINES

Manuscript sent should contain these elements in the following order: title, name(s) and surname(s) of author(s), affiliation(s), summary, key words, classification, manuscript text, references. Sections acknowledgments and remarks are optional. If present, position them right before the references.

SUMMARY Concisely and clearly written, approx. 250 words.

KEY WORDS Not more than 5 key words, as accurate and precise as possible.

CLASSIFICATION Suggest at least one classification using documented schemes, e.g., ACM, APA, JEL, PACS.

TEXT Write using UK spelling of English. Preferred file format is Microsoft Word. Provide manuscripts in grey tone. For online and CD-ROM versions, manuscripts with coloured textual and graphic material are admissible. Consult editors for details.

Use Arial font for titles: 14pt bold capital letters for titles of sections, 12pt bold capitals for titles of subsections and 12pt bold letters for those of sub-subsections.

Include figures and tables in the preferred position in text. Alternatively, put them in different locations, but state where a particular figure or table should be included. Enumerate them separately using Arabic numerals, strictly following the order they are introduced in the text. Reference figures and tables completely, e.g., “as is shown on Figure 1, y depends on x ...”, or in shortened form using parentheses, e.g., “the y dependence on x shows (Fig. 1) that...”.

Enumerate formulas consecutively using Arabic numerals. In text, refer to a formula by noting its number in parentheses, e.g. formula (1). Use regular font to write names of functions, particular symbols and indices (i.e. \sin and not *sin*, differential as d not as *d*, imaginary unit as i and not as *i*, base of natural logarithms as e and not as *e*, x_n and not *x_n*). Use italics for symbols introduced, e.g. $f(x)$. Use brackets and parentheses, e.g. $\{[()]\}$. Use bold letters for vectors and regular GoudyHandtooled BT font (for MS Windows) or similar font for matrices. Put 3pt of space above and below the formulas.

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Denote footnotes in the text by using Arabic numerals as superscripts.

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