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# INTERDISCIPLINARY DESCRIPTION OF COMPLEX SYSTEMS

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# INTERDISCIPLINARY DESCRIPTION OF COMPLEX SYSTEMS

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## CONFERENCE PAPERS

# EDITORIAL I

Dear readers,

you are reading the first issue of the second volume of INDECS - *Interdisciplinary Description of Complex Systems*. It differs from the first volume both substantially and formally. Substantially, the Journal council includes Advisory Board, interdisciplinary and international in character, the members of which are Professors Vjekoslav Afrić, Aleksa Bjeliš, Marek Frankowicz and Katalin Martinás. In addition, the new member of the Editorial Board is Professor Karin Šerman. Formally, some details of the Journal format are improved in order to contribute to texts' content readability, and structure recognisability. An underlying contribution to the improvement regarding the previous issue is the emphasising the INDECS' contribution to the scientific community, as operationalised in the INDECSA - the Annual award for the best published article, the details of which are found in another page.

The content of this issue was framed during the first Editorial Board meeting, on which it was concluded that Prof. Katalin Martinás is responsible for its guest-editing. Conclusively, Prof. Martinas and Prof. Michel Moreau are guest-editors of this issue. They formulated its content as the collection of representative papers presented during the International Workshop *Complex Systems in Natural and Social Sciences*, which was held in Budapest, 24-25 October 2003.

Zagreb, 16 June, 2004 Editors

*Interdisciplinary Description of Complex Systems* 2(1), iii, 2004

# EDITORIAL II

The purpose of the CSNSS'03 workshop was to bring together multidisciplinary groups of scientists working on applications of complex systems and nonlinear dynamics in physics, chemistry, mathematics, economy and future studies. The workshop was a continuation of the series of similar meetings that took place in Hungary (Mátrafüred 1995, Tata 1996, Budapest 1997, Mátrafüred 2002) and in Poland (Kazimierz Dolny 1999, Zakopane 2000, Torun 2001). It was intended to provide a forum to report researches, discuss emerging topics and gain new insights into: complex system approaches in biology, astrophysics, thermodynamic constraints and thermodynamical studies of socio-economic systems.

Key motivation was to provide a common ground for an open dialogue.

We hope that this purpose was fulfilled at least partially, since definitive success cannot be expected in this everlasting process of interchange between different fields of Science and Life.

The articles for the workshop were accepted after affirmative evaluation conducted by the program committee.

Budapest and Paris, June 2004

Katalin Martinás and Michel Moreau

# INDECSA

In accordance with the conclusions of the 1st Meeting of INDECS Editorial Board, the annual award for the best published article of the Journal INDECS has been established. The propositions for its implementation are stated below.

INDECSA is the annual award of the Journal INDECS for the best article published in one volume.

The purpose of the award is additional accentuation of the selected article, on the basis of significant and widely recognised contribution to interdisciplinary description of complex systems, both scientifically and methodically.

The award consists of the plaque and an appropriate monetary amount, given to the author or authors' representative.

The best article is determined after voting of INDECS Council members and authors of all articles published in the year before the one for which the award is given. Each person contributes one vote to determination of the best article. Voting is performed at least one month after publication of the last issue of the volume for the corresponding year, and ends not later than one month before publication of the first issue of the next volume. The Commission for choosing the best article regulates the process.

The best article is the one that obtains the largest number of votes. If two articles are tied for the first place, the Commission for choosing the best article evaluates whether one of these stands out, in which case it is denoted as the best article. If the Commission determines that none of the articles stands out for that year the award is not given. If after the voting three or more articles share the largest number of votes the award is not given.

The Commission concludes the process with the decision about the best article which is announced on the web pages of the INDECS and in the next printed issue.

The Commission consists of three members of INDECS Council and all guest editors in the issues of the year considered. It is established by the editors in accordance with the previously stated elements. The establishing document specifies the monetary amount included in the award.

The articles in which at least one author is a member of the INDECS Council are excluded from the selection. The INDECSA is not awarded if there are no more than five articles fulfilling the process requirements.

Zagreb, 8 March 2004 Editors

*Interdisciplinary Description of Complex Systems* 2(1), 1-11, 2004

# A KINETIC MODEL OF THE MUSCULAR CONTRACTION

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## SUMMARY

In this article, we build a self consistent mean field deterministic model for the muscular contraction. The two main variables are the number of free myosin heads and the number of myosin heads attached to the actin, just after attachment. The model is natural in the sense that it respects the physico-chemical natural constraints. We calculate the stationary state, prove that it is stable and calculate the efficiency.

## KEY WORDS

muscular contraction, chemical kinetics, efficiency

## CLASSIFICATION

PACS: 82.20.-w, 87.10.+e, 87.19.Ff

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## INTRODUCTION

The metabolic process of a cell transforms chemical energy stored in bonds of various nutrients, either into other form of chemical energy, or into various forms of mechanical energy for transport of metabolites inside a cell, or communication between cells. Many forms of transport take place through membranes, or along special structures inside the cytoplasm. The muscular contraction is of the last category: it transforms the chemical energy stored in the phosphate bond of ATP in mechanical energy of the motion of a large protein called actin. The general character of this transformation is now well understood, at least in a qualitative manner, and is described in many text books (see [1, 2]). The first mathematical treatment of this process was given by Hill (see [3], for the first model, as well as [4], [5] and Hill's textbook for a more general theory of the conversion of chemical free energy into other forms of free energy [6]). More recently, there has been a renewed interest for mathematical models of molecular motors, as they are now called. These models follow the fundamental idea of Hill, namely that a certain degree of freedom can transit between two different form of free energy through a chemical reaction (see [7] for a recent review and references, as well as [8], [9], and also [10] for other type of mesoscopic motors like thermal ratchets). Nevertheless, certain of these models present difficulties of a mathematical nature, or difficulties concerning biochemical rate constants or of statistical nature. In a previous publication [11], we have introduced a detailed microscopic model, taking into account the actual fluctuations of the number of myosin heads which are attached to the actin filament. We have studied, in particular, the correlation between the number of heads which are attached to the actin filament and the actual force which is exerted on the actin molecule.

In this article, we define a new and simple model: this model is a self-consistent mean field theory of the muscular contraction. It can be described by three processes, two of them being of chemical nature, one of them being of a mechanical nature describing the motion of the actin. The total work and the efficiency can be calculated exactly. This model describes a different regime from [11], namely the case of an intermediate regime where the muscle is loaded and starts to contract, but not enough so that the spring reaction is important. It is much simpler than our previous model [11], but it also takes into account, although schematically, the chemical reactions of attachment and detachment of a myosin head in a plausible way.

The contents of this article are as follows: in section 2, we recall the biochemical description of the muscular contraction, in particular, we distinguish four phases. Only one of them will be the subject of this article. In section 3, we describe the self consistent kinetic model. We prove that it is natural, in the sense that it respects the natural physico-chemical constraints, calculate its stationary state and prove that it is stable (see section 4). We compute the work and the efficiency in section 5 and finally we discuss the various assumptions and intrinsic limitations of our model in the conclusion.

## DESCRIPTION OF THE MUSCULAR CONTRACTION

A muscular cell is a specialized cell which expresses certain types of proteins which are able to transform chemical free energy into mechanical energy. The two essential proteins species which allow this transformation are a large rigid protein called actin and a shorter one called myosin which contains two articulate parts. The actin is attached to the wall of a sarcomer which is a compartment of the muscular cell. The moving arm of the myosin can attach to the actin and then exerts a dragging force on the actin inducing the contraction of the sarcomer. The actin molecules and the fixed parts of the myosin molecules are arranged in separate parallel bundles. The moving arms of the myosin molecules spring out of the bundles of myosin. The arms are constituted of a linear peptidic chain surrounded by a global protein called the head of the myosin, which can attach to the actin. Many myosin heads can attach to a given bundle of actins (see Fig. 1 and ref. [1, 2]).

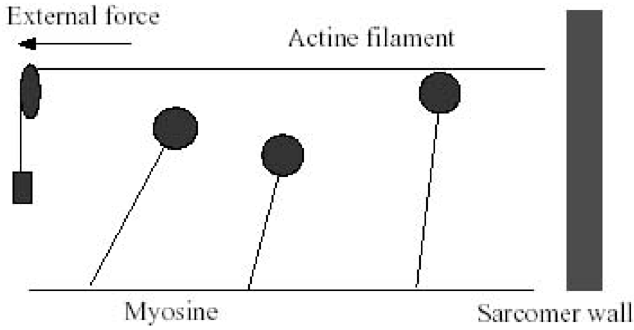


**Figure 1.** The interaction between the actine and the myosine heads molecules.

The myosin head has also a catalytic function for the hydrolysis of ATP (adenosine triphosphate) in ADP (adenosine diphosphate) + P (phosphate) with the release of an important amount of energy when the phosphate bond is broken (at normal temperature and neutral pH, the free energy released is about 30 kJ/mol). The molecule ATP and its phosphate bond are the essentially universal storage of energy which is used in the metabolism of all living organisms (see ref. [1, 2]).

We describe now the various states and phases of the contraction of a muscular cell.

### 1st phase. The unloaded cell at rest.

At rest, the myosin heads cannot attach to the actin molecules. Indeed, there is another protein called the troponine which blocks the sites of attachments on the actin, preventing the attachment of the myosin heads. The myosin arms can rotate and when the corresponding head is not attached, the angle $\theta$ between the fixed part of the myosin and the moving part takes its equilibrium value which is about $\pi/2$. Moreover, in this phase, the myosin head carries on a special site a dissociated ADP+P.

### 2nd phase. The effect of a nervous impulse.

The excitation of a muscle cell by a nervous impulse induces a release of the neurotransmittor acetylcholin, which allows ions $Ca^{2+}$ to enter the cell, diffuse and inhibit the troponine which was blocking the attachment sites of the actin molecules for the myosin heads. The details of this process do not concern us here. But as a consequence, the myosin heads can now attach to an attaching site of the actin molecules.

### 3rd phase. The cycle of the myosin head (see Fig. 2).

Let us consider now a free myosin head equipped with its ADP+P which is in its equilibrium position, the angle between the fixed part of the myosin and the arm being $\pi/2$. This is step 1.

The myosin head together with its ADP+P attaches to a site of the actin forming a strong covalent bond, while the ADP+P detaches from the complex (step 2). Now, the

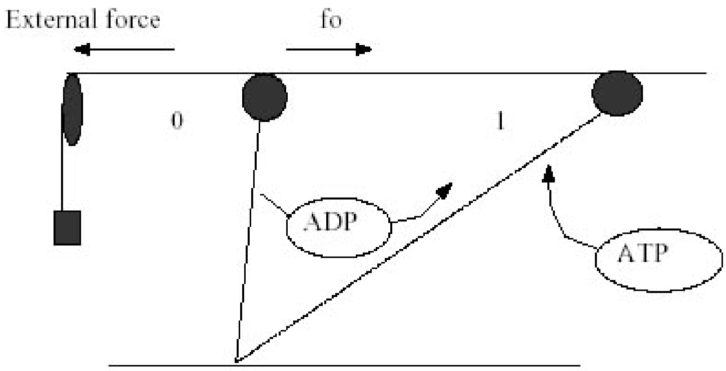


**Figure 2.** A myosine head has attached in position 0 to the actine and exerts a dragging force $f_0$. The ADP leaves the myosine head, and the myosine head reaches its new equilibrium position 1. An ATP attaches to the myosine which is then detached from the actine.

arm of the myosin is no more in its equilibrium position. The potential acting on the angle $\theta$ is such that the new equilibrium position of this angle, when the myosin head is attached to the actin, is $\pi/6$. So the myosin arm starts to rotate to reach this new equilibrium value. But as it is rigidly attached to the actin, it drags the actin inducing a contraction of the cell (step 3). During this motion of the myosin head coupled to the actin, an ATP molecule can attach to the myosin head and destabilize the bond between the actin and myosin head so that the myosin head is detached from the actin (step 4) and comes back to its free equilibrium position, while catalyzing the hydrolysis of the ATP molecule in ADP+P coming back to step 1. The myosin head equipped with the ADP+P molecules is ready for another cycle.

In each cycle, the actin moves by about 10 nm. One molecule of ATP is consumed, one molecule of ADP and a phosphate residue P are released.

### 4th phase. Coming back at rest.

Finally, this cyclic motion of the myosin head stops when the neural firing stops: the neurotransmitter is no more released, the influx of the ions $Ca^{2+}$ stops, and the troponine which was inhibited, is disinhibited and blocks again the site attachment of the myosin head on the actin filaments.

In this article, we are interested in the third phase, when the attachment sites of the myosin heads on actin filaments are not blocked. On a given actin filament, there are many attachment sites (of the order of $10^3$) and a corresponding number of myosin heads can reach the attachment sites, and when attached, can drag the actin filaments.

The cyclic motion of a myosin head is converted in the linear motion of the actin filament (and the contraction of the muscle), exactly as in a standard engine, where the cyclic motion of the piston is converted to a linear motion.

The main difference with a standard engine is that there are many "pistons" dragging the actin filament and causing the mechanical motion.

We can consider the attachment times of the various myosin heads, as well as the detachment times of the myosin heads as independent random variables, essentially exponentially distributed. On the other hand, the myosin heads which are attached to the actin filament have, while they stay attached, the same velocity, which is the velocity of the center of mass of the actin filament.

Following the analysis of Hill [1, 6], we assume that the potential energy of the angle $\theta$ between the fixed part of the myosin and the moving arm is

1. a given function $V^{(0)}(\theta)$ with a minimum at $\theta^{(0)} \approx \pi/2$ when the myosin head is not attached to the actin.
2. another given function $V^{(1)}(\theta)$ with a minimum at $\theta^{(1)} \approx \pi/4$, when the myosin head is attached to the actin (see Fig. 3).

The potential energy $V^{(1)}(\theta)$ is the potential energy of the angle $\theta$ of an attached myosin head, if it was alone. Its derivative is essentially the force exerted by the attached myosin head on the actin, if that myosin head were alone.

If we assume that all the free energy of the phosphate bond is released in mechanical energy, the force that a myosin head exerts on an actin filament is about

$$F \approx \Delta G/d \approx 0{,}5\cdot 10^{-19}/10^{-8} \approx 0{,}5\cdot 10^{-11} \text{ N/molecule.}$$

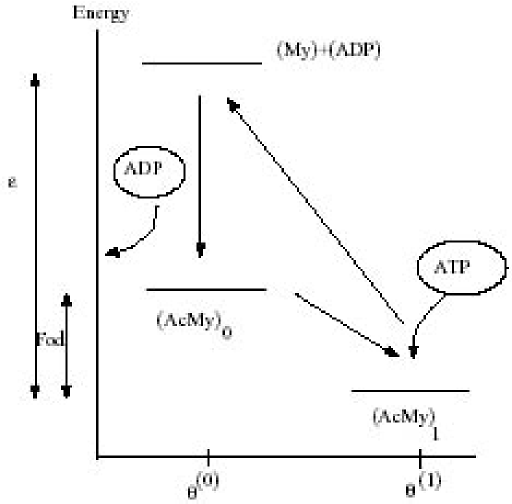


**Figure 3.** The cycle of the myosine head. This displays also the levels of energy with $\varepsilon > f_0 d$.

## A SELF-CONSISTENT MODEL FOR THE ACTIN MOTION

We denote by $M$ the total number of myosin heads. We simplify the description by assuming that the given myosin head can be in three different states (see Fig.3).

(i) unattached myosin heads, the number of which is denoted [My]

(ii) attached myosin heads with an angle $\theta$ close to the angle $\theta^{(0)}$; The number of these heads is denoted $[\text{AcMy}]_0$. When a head is in this state, it exerts a dragging force $f_0$ on the actin filament.

(iii) attached myosin heads with an angle $\theta$ close to the equilibrium value $\theta^{(1)}$. The number of these heads is $[\text{AcMy}]_1$. When the head is in this state, it exerts dragging force $f_1$ on the actin filament.

We assume that, when the myosin head is detached, it relaxes to equilibrium instantly in the potential $V^{(0)}$.

Obviously, one has the conservation law

$$[\text{My}]+[\text{AcMy}]_0+[\text{AcMy}]_1 = M. \tag{1}$$

One can describe the cyclic motion of the myosin head using three types of transitions.

(i) a reaction of attachment of the myosin head (with the ADP+$P_i$ complex to the actin at an angle close to $\theta^{(0)}$, and the corresponding reaction of detachment of the myosin head which has received an ATP. These reactions are written

$$(\mathrm{My}) \underset{k_1}{\overset{k_0}{\rightleftarrows}} (\mathrm{AcMy})_0. \tag{2}$$

Notice that $\bar{k}_0$ is essentially proportional to the concentration of ATP and we assume that $\bar{k}_0 << k_0$.

(ii) a reaction of detachment of the myosin head which is attached to the actin at an angle close to $\theta^{(1)}$ (the myosin head has just received an ATP molecule) and a corresponding reaction of attachment of the free myosin head to the actin at an angle close to $\theta^{(1)}$

$$(\mathrm{AcMy})_1 \underset{\bar{k}_1}{\overset{k_1}{\rightleftarrows}} (\mathrm{My}). \tag{3}$$

Notice here that $k_1$ is essentially proportional to the concentration of ATP and that $\bar{k}_1 << k_1$.

The notations are chosen so that $\bar{k}_{\mathrm{j}} << k_{\mathrm{j}}, j = 0, 1$.

(iii) a mechanical transition, when the attached myosin heads transits from an angle close to $\theta^{(0)}$ to an angle close to equilibrium $\theta^{(1)}$ or vice versa

$$(\mathrm{AcMy})_0 \underset{\omega_{01}}{\overset{\omega_{10}}{\rightleftarrows}} (\mathrm{AcMy})_1. \tag{4}$$

Now, each attached myosin head has the same velocity $v$ which is the velocity of the center of mass of the actin filament. So, the rates of the transitions in (4) are given as follows (see Fig. 3):

a) if $v > 0$, the $(\mathrm{AcMy})_0$ is converted to $(\mathrm{AcMy})_1$ and the corresponding rate is

$$\omega_{10} = \frac{\mathrm{d}}{\mathrm{d}t}([\mathrm{AcMy}]_1)_{\mathrm{mech}} = \frac{v}{d}[\mathrm{AcMy}]_0. \tag{5}$$

where $d$ is an average distance of displacement of the center of mass of the actin in this transition (see Fig 3).

b) if $v < 0$, the $(\mathrm{AcMy})_1$ is converted back to $(\mathrm{AcMy})_0$ and the corresponding rate is

$$\omega_{01} = \frac{\mathrm{d}}{\mathrm{d}t}([\mathrm{AcMy}]_1)_{\mathrm{mech}} = \frac{v}{d}[\mathrm{AcMy}]_1. \tag{6}$$

Notice that $\omega_{01} < 0$. We can summarize both equations (5) and (6) by defining

$$\begin{aligned}\omega &\equiv \frac{\mathrm{d}}{\mathrm{d}t}([\mathrm{AcMy}]_1)_{\mathrm{mech}} \\ &= \frac{v}{d}\Theta(v)[\mathrm{AcMy}]_0 + \frac{v}{d}\Theta(-v)[\mathrm{AcMy}]_1.\end{aligned} \tag{7}$$

where $\Theta(u)$ is the Heaviside function

$$\Theta(u) = \begin{cases} 0, & \text{if } u < 0, \\ 1, & \text{if } u > 0. \end{cases}$$

We still have to determine the law of motion of the actin filament. The total force on the center of mass is given by

$$F + f_0[\mathrm{AcMy}]_0 + f_1[\mathrm{AcMy}]_1, \tag{8}$$

where $F$ is the total exterior force, which includes the load of the muscle and a spring-like force which tends to bring back elastically the muscle (or the walls of the sarcomer) to their positions in the absence of neural firing and of external load.

We assume a high friction limit for the motion of the center of mass of the actin filament, namely the velocity $v$ of the center of mass (and consequently of the attached myosin heads) is proportional to the total force given by Eq.(8).

The equation of motion is thus

$$\alpha \cdot v = F + f_0[\mathrm{AcMy}]_0 + f_1[\mathrm{AcMy}]_1, \tag{9}$$

where $\alpha$ is a friction coefficient.

The state of the myosin evolves according to the following (non linear) differential equations deduced from Eq. (2 - 4)

$$\frac{\mathrm{d}}{\mathrm{d}t}[\mathrm{My}] = \quad (k_0 + \bar{k}_1)[\mathrm{My}] + \bar{k}_0[\mathrm{AcMy}]_0\,, \tag{10}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}[\mathrm{AcMy}]_0 = k_0[\mathrm{My}] - \bar{k}_0[\mathrm{AcMy}]_0 - \omega\,, \tag{11}$$

together with Eq. (9) and the definition of $\omega$ in Eq. (7).

Here we have used the obvious result that

$$\left.\frac{\mathrm{d}}{\mathrm{d}t}[\mathrm{AcMy}]_0\right|_{\mathrm{mech}} = -\left.\frac{\mathrm{d}}{\mathrm{d}t}[\mathrm{AcMy}]_1\right|_{\mathrm{mech}} = -\omega\,.$$

Moreover, we can eliminate $[\mathrm{AcMy}]_1$ using the conservation law (1).

$$[\mathrm{AcMy}]_1 = \mathrm{M} - [\mathrm{My}] - [\mathrm{AcMy}]_0. \tag{12}$$

Eq. (11) is non linear, due to the term $-\omega$ and Eq. (7) for $\omega$, when we eliminate $v$ in term of the concentration $[\mathrm{AcMy}]_j$, using the equation of motion Eq. (9). Nevertheless, because $\omega$ is 0 if $v$ is 0, the second member of Eq. (11) is a continuous function of the concentration, although its derivatives are discontinuous for $v = 0$.

In the following calculations, we take

$$f_1 = 0. \tag{13}$$

We eliminate $v$ from Eq. (9) with $f_1 = 0$ and we determine $[\mathrm{AcMy}]_1$ using Eq. (12), then

$$\omega = (\alpha \cdot d)^{-1}(F + f_0[\mathrm{AcMy}]_0)\{\Theta(v)[\mathrm{AcMy}]_0 + \Theta(-v)(\mathrm{M} - [\mathrm{My}] - [\mathrm{AcMy}]_0)\}. \tag{14}$$

Define

$$x = [\mathrm{AcMy}]_0; \qquad y = [\mathrm{My}], \tag{15}$$

$$\frac{\mathrm{d}x}{\mathrm{d}t} = -\left(\frac{F}{\alpha d} + \frac{f_0 x}{\alpha d}\right)[\Theta(v)x + \Theta(-v)(M - x - y)] + k_0 y - \bar{k}_0 x \tag{16}$$

$$\frac{\mathrm{d}y}{\mathrm{d}t} = \quad -(\mathrm{k}_0 + \bar{k}_1 + k_1)y + (\bar{k}_0 - k_1)x + k_1 M \tag{17}$$

$$\Theta(v) = \Theta\ \ \frac{F}{\alpha d} + \frac{f_0}{\alpha d}x \quad . \tag{18}$$

We can renormalize these equations using

$$K = k_0 + k_1 + \bar{k}_1 \qquad t^* = Kt$$

$$k_j^* = k_j/K \qquad \bar{k}_j^* = \bar{k}_j/K$$

$$F^* = \frac{F}{\alpha d K} \qquad f_0^* = \frac{f_0}{\alpha d K}$$

so from Eq. (16) and (17), one deduces

$$\frac{\mathrm{d}x}{\mathrm{d}t^*} = -(F^* + f_0^* x)\{\Theta(v)x + \Theta(-v)(M - x - y)\} + k_0^* y - \bar{k}_0^* x \tag{19}$$

$$\frac{\mathrm{d}y}{\mathrm{d}t^*} = \quad - y + (\bar{k}_0^* - k_1^*)x + k_1^* M \tag{20}$$

$$\Theta(v) = \Theta(F^* + f_0^* x)\,. \tag{21}$$

Then,

$$0 \leq k_0^* + k_1^* \leq 1, \tag{22}$$

and we shall assume that

$$F \leq 0, f_0 \geq 0, \tag{23}$$

(see Fig 2. for the sign convention).

## STATIONARY POINTS AND STABILITY

In this section, we study the stationary points of the system of Eqs. (19) and (20). The discussion is standard except for the presence of the Heaviside function. We also suppress the * in Eqs. (19) and (20). Whatever is the sign of $v$, the equation Eq. (17) gives

$$\hat{y} = \bar{k}_0 x + k_1 (M - x)\,, \tag{24}$$

for a stationary point ($\hat{x}$, $\hat{y}$).

First, we assume that the corresponding velocity $\hat{v}$ is positive. Then, the stationary solution ($\hat{x}$, $\hat{y}$) satisfies Eq. (24) and the stationary equation corresponding to the equation Eq. (20) for $v > 0$, namely,

$$(F + f_0\hat{x})\hat{x} + k_0 y \quad \bar{k}_0\hat{x} = 0\,. \tag{25}$$

Combining with Eq. (24), one sees that there is only one positive solution for $\hat{x}$. We assume that the velocity $\hat{v}$ is positive or

$$F + f_0\hat{x} > 0\,. \tag{26}$$

A standard analysis shows that *the stationary point* ($\hat{x}$, $\hat{y}$) *is an attractor*.

It can also be proved that, under the natural hypothesis of Eq. (25), if one assumes the condition (26), *there is no stationary solution with a negative velocity*, and that *condition* (26) *is equivalent to the inequality*

$$|\,F\,| \leq M f_0\,. \tag{27}$$

This condition is natural: it means that the external force $-|F|$ (which is negative) has its modulus less than the maximal force $Mf_0$ which can be exerted by all the myosin heads on the actin filament. This maximal force is exerted when all the myosin heads are attached to the actin filament, in configuration 0, so that the force is $Mf_0$ in this case.

Finally we have proved that the stationary points satisfies the physical condition

$$\hat{x} + \hat{y} \leq M\ , \tag{28}$$

and that, during the evolution, the state of the system stays in the physical region

$$x \geq 0, y \geq 0, x + y \leq M,$$

and it is attracted towards the stationary state ($\hat{x}$, $\hat{y}$).

## WORK AND EFFICIENCY

The work per unit time, which can be extracted from the system is $w = |F|\,\hat{v}$ in the stationary state, which can be written as

$$w = -(F + f_0\hat{x})\hat{v} + f_0\hat{x}\hat{v}\,.$$

Now the stationary velocity $\hat{v}$ is given by Eq. (9)

$$\hat{v} = \frac{1}{a}(F + f_0\hat{x})\,, \tag{29}$$

so

$$w = f_0\hat{x}\hat{v} - \alpha\hat{v}^2\,. \tag{30}$$

Now the work $w_0$ per unit time of the force exerted by the myosin heads is

$$w_0 = f_0\hat{v}\widehat{[\mathrm{AcMy}]}_0 = f_0\hat{v}\hat{x}\,. \tag{31}$$

From the first equation (1) for the stationary state, one has

$$(F^* + f_0^*\hat{x})\hat{x} = k_0^*\hat{y}$$

so that restoring normal units and using Eq. (29)

$$\hat{v}\hat{x} = dk_0\hat{y}$$

and thus from Eq.(31)

$$w_0 = f_0 dk_0\hat{y}\,. \tag{32}$$

On the other hand, the consumption of ATP's energy per unit time is the rate of detachment $k_1$[AcMy]$_1$ multiplied by the energy of one molecule of ATP, say $\varepsilon$, so the consumption of ATP's energy per unit time is

$$e = k_1\widehat{[\mathrm{AcMy}]}_1\varepsilon.$$

We use the fact that in the stationary state, Eq. (10) gives

$$k_1\widehat{[\mathrm{AcMy}]}_1 = (k_0 + k_1)[\widehat{\mathrm{My}}]\,,$$

so

$$e = (k_0 + k_1)\hat{y}\varepsilon\,. \tag{33}$$

The efficiency is thus the quotient of $w$ by $e$

$$e = (k_0 + k_1)\hat{y}\varepsilon\,. \tag{33}$$

Notice that in our approximation $f_0{\cdot}d$ is the work of the force $f_0$ of an individual myosin head when it transits from configuration 0 to configuration 1, and thus it is obviously less than $\varepsilon$ (see Fig 3.), so in Eq. (34), the term $(f_0d/\varepsilon){\cdot}k_0/(k_0 + k_1)$ is less than 1.

The second term of Eq.(34) represents the loss of efficiency due to friction. Thus, Eq. (34) gives the following, simple upper bound for the muscle efficiency:

$$R < \frac{k_0}{k_0 + k_1}\,.$$

## DISCUSSION AND CONCLUSION

The model of muscular contraction that we have presented in this article is extremely simple: it is a deterministic kinetics with two degrees of freedom, essentially the number of unattached myosin heads and the number of attached myosin heads before they release to their equilibrium position. Nevertheless, this model respects the obvious physicochemical constraints, reaches a unique stationary state, and captures the main features of the biochemistry of muscular contraction. The parameters in the model are control parameters which depends of other parts of the metabolism of the cell and its environment, namely

(i) the concentration of ATP which is assumed to be given in our model and is the main control parameters for the state of detachment of the myosin heads and provides the energy,

(ii) the level of neural firing, and then the concentration of $Ca^{2+}$ ions which is the main control parameters of the rates of detachment of the myosin heads on the actin filament.

In particular, the level of firing controls the stationary velocity $\hat{v}$ of the actin filament, through the parameter $k_0$ (rate of attachment) and the total number of sites of the actin which are available for an attachment of a myosin heads, so that this is a control of the number $M$ of "effective" myosin heads.

The number $M$ can be such that $F + f_0 \cdot M$ is very small, so that in this case, although $M$ can be large, the resulting velocity $\hat{v}$ is negligible: this is the case of a concentration with no net work of the force $F$.

We have neglected many components of the metabolism of the muscular cell. Firstly, we have neglected the global spring force on the muscle, so that our model can represent a muscle starting to contract after being loaded and reaching quickly an asymptotic velocity, which obviously cannot be maintained for ever and is counteracted by the spring force tending to bring back the muscle to its rest conditions. A fully microscopic model was introduced in [11] and solved using a Markovian approximation. However, in order to include specific chemical reactions in the model, all fluctuations effects have been neglected in the present paper.

Another fact is that ATP is the universal energy source of the cell. As a consequence, it is also used to get rid of the waste products of the contraction of the muscle, including lactate, and also to keep the pH in physiological bounds. These two chemical components are at the origin of the muscular fatigue and should be taken into account in more refined calculations.

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# KINETIČKI MODEL KONTRAKCIJE MIŠIĆA

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## SAŽETAK

U ovom radu izgrađujemo samosuglasni, deterministički model srednjeg polja za opis kontrakcije mišića. Dvije glavne varijable su broj glava miozina i broj glava miozina pričvršćenih za aktin, neposredno nakon pričvršćenja. Model je prirodan u smislu da zadovoljava prirodne fizikalno-kemijske uvjete. Određujemo stacionarno stanje, dokazujemo da je stabilno i određujemo učinkovitost.

## KLJUČNE RIJEČI

kontrakcija mišića, kemijska kinetika, učinkovitost

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# CONCEPTUAL STEPS TOWARDS EXPLORING THE FUNDAMENTAL NATURE OF OUR SUN

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Motto: "*The purpose of life is the investigation of the Sun, the Moon, and the heavens.*" - Anaxagoras 459 BC

## SUMMARY

One of the basic questions of solar research is the nature of the Sun. We show here how the plasma nature of the Sun leads to the self-generation of solar activity. The release of magnetic, rotational, gravitational, nuclear energies and that of the gravity mode oscillations deviate from uniformity and spherical symmetry. Through instabilities they lead to the emergence of sporadic and localized regions like flux tubes, electric filaments, magnetic elements and high temperature regions. A systematic approach exploring the solar collective degrees of freedom, extending to ordering phenomena of the magnetic features related to Higgs fields, is presented.

Handling solar activity as transformations of energies from one form to another one presents a picture on the network of the energy levels of the Sun, showing that the Sun is neither a mere "ball of gas" nor a "quiescent steady-state fusion-reactor machine", but a complex self-organizing system. Since complex self-organizing systems are similar to living systems (and, by some opinion, identical with them), we also consider what arguments indicate the living nature of the Sun. Thermodynamic characteristics of the inequilibrium Sun are found important in this respect and numerical estimations of free energy rate densities and specific extropy flows are derived.

## KEY WORDS

solar physics, degrees of freedom, self-organizing complex systems, non-equilibrium thermodynamics, astrobiology

## CLASSIFICATION

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## INTRODUCTION

Solar physicists would like to know as much from the Sun as possible, as thoroughly as possible, as validly as possible. Following this aim, the solar physicists' community looked forward to find new windows for the Sun. The entrance of helioseismology or neutrino detectors resulted in a significant improvement in the study of the Sun. Regarding theoretical models, a common fundamental assumption contrasting with present day approaches is to regard the Sun as a mere gaseous body. The Sun is the nearest star, and a "star" is "a luminous ball of gas" [48]. At the same time, we know that the Sun is not in a gaseous, but in a plasma state. In the solar interior, the temperature is so high that matter is ionized and therefore the whole interior of the Sun is in a plasma state, including the solar core. Plasma consists of electrically charged particles that respond collectively to electromagnetic force. Because of their strong interaction with electromagnetism, plasmas display a complexity in structure and motion that far exceeds that found in matter in the gaseous, liquid, or solid states. The electromagnetic interaction is 39 orders of magnitude stronger than the gravitational one, and, correspondingly, it is enormously richer in nonlinear interactions. The collective plasma processes are associated in particular with various plasma instabilities. As a rule the development of instability is accompanied by an increase in the electric field strength, which can attain large values. Consequently, even in the absence of intense external fields, relatively strong fields can still occur spontaneously in a plasma due to the growth of instability [61]. Plasma microinstabilities are localized, usually high frequency phenomena that cannot be described in MHD but in the kinetic models. In general, the plasma can support electric currents (e.g. [26]). Plasmas are extremely complicated physical systems fundamentally different from classic neutral gases, especially when there is a magnetic field present, and even more so when gravitational and nuclear energy sources liberate energies in a strong dependence on temperature.

Moreover, the main body of the Sun, the radiative interior of this “luminous ball of gas,” is regarded as being quiet, with no other changes occurring beside the slow transmutation of elements due to nuclear reactions. Bahcall [2] characterized a general view with the following sentence: “The Sun's interior is believed to be in a quiescent state and therefore the relevant physics is simple”. On the other hand, the “plasma diagram” showing the ranges of temperature and number density of natural and man-made plasmas posits the solar core in line with terrestrial lightning, but at higher density and temperature (see http://fusedweb.pppl.gov/CPEP/chart.html).

The idea that the solar core may show dynamism is an old one; but recently it has received theoretical and observational support (see in [30, 32]). There is a whole range of interactions liberating energies in the solar radiative interior, but it was assumed that these energies are negligible. Within the most important energy sources, we mention here the nuclear, gravitational, rotational, magnetic, oscillatory energies, p-mode, g-mode, r-mode waves and tidal waves. In the actual solar radiative interior a wide range of magnetic, rotational, tidal and oscillatory instabilities are present and the solar core is changing on a wide variety of timescales. Magnetohydrodynamic calculations (e.g. [58, 60]) indicated the general presence of MHD instabilities in the solar radiative zone. Electric conductivity in the solar plasma is very high. Solar core is widely penetrated by dynamic influences that generate movements within it. Such motions are the electric currents, tidal waves, g-mode oscillations, as well as the ones triggered by different instabilities like e.g. the magnetic, rotational [56], and baroclinic [57] ones. Any slight hydrodynamic change of the plasma generates electromagnetic disturbances. Plasma instabilities have a local and nonlinear character. When the magnetic field is unstable, the magnetic energy is transformed into other energy forms like into the electric energy of currents. Since the initial time development of magnetic instabilities has an exponential character in general, the related electric currents grow exponentially until they reach intensity where the pinch-effect contracts the currents and filamentary structures will be formed. These current filaments in the solar core may stabilize themselves and lead to significant local heating. Filamentation is a general, well-known property of plasma [11, 43].

Despite of its plasma state, the solar core is widely regarded as being in a gaseous state. Plasma nature of the solar core has been ignored because of the general assumption that the solar core is quiescent and, therefore, being static, the solar core does not show any peculiar plasma behaviour. In the solar core a lot of different types of motions set up [30]. Therefore plasma processes will also set up and they will lead to significant dynamic phenomena. In the solar core the gaseous pressure ($\sim 10^{12}$ N/m$^2$) is much larger than the magnetic pressure since the average toroidal field has a helioseismic upper limit of $3\cdot10^3$ T [62]. Nevertheless, the criterion for neglecting magnetic effects in the treatment of a problem in gas dynamics is that the Lundquist parameter $L_u = \mu^{1/2}\sigma B l_c/\rho_m^{1/2}$ (measuring the ratio of the magnetic diffusion time to the Alfven travel time, where $m$ is the magnetic permeability $4\pi\cdot10^{-7}$ H·m$^{-1}$, $\sigma$ is the electric conductivity in siemens/m, $B$ is the strength of the magnetic field in Tesla, $l_c$ is a characteristic length of the plasma in meter, and $\rho_m$ is the mass density in kg/m$^3$) is much less than unity, $L_u << 1$ [43, p. 19]. Now for the solar core $\sigma \sim 10^7$ S/m, $B >> 10^{-7}$ to $3\cdot10^3$ T, $l_c \sim 10^8$ m, $\rho_m \sim 10^5$ kg/m$^3$, and so $L_u \sim 10^3$ to $3\cdot10^{13}$. Therefore, plasma effects may play a dominant role in the dynamism of the solar core. We note that even when $L_u << 1$, the hydrodynamic movements may amplify the magnetic fields to values to $L_u >>1$ later on.

The nature of solar rotational instabilities is far from being understood (see e.g. [56]). Solar rotation during the last $4{,}6\cdot10^9$ years has been spun down from $E_{rot,\,0} \sim 10^{38}$ J to the present one, representing $E_{rot,\ present} \sim 2{,}4\cdot10^{35}$ J [1]. Charbonneau and MacGregor [12, 13] calculated the solar spin-down from the zero-age main sequence. From their Fig. 2a, one can read that the present rate of solar spin-down corresponds to $(\Delta E_{rot}/\Delta t)_{present} \sim 2\cdot10^{27}$ J/year. Although Couvidat et al. [16] obtained a flat rotation profile down to $0{,}2\cdot R_{Sun}$, the uncertainties in the rotation rate are still quite large below $0{,}3\cdot R_{Sun}$. It is widely thought that the deceleration of the solar core is due to magnetic breaking. The flat rotation curve at 430 nHz in the solar radiative interior lends support for a magnetic field strong enough to suppress any differential rotation that might arise from angular momentum redistribution through the gravity waves [59]. It is well known that the dissipation of rotational energy is used to drive the dynamo, and, in general, solar activity in the solar envelope. At the same time, the main part of the solar rotational energy is dissipated in the core as it is decelerated. It may seem plausible that the rotational energy is dissipated in the solar core, too, in a form suitable to drive activity phenomena.

Gravitational energy liberation in the solar core deviates from perfect uniformity and homogeneity since the solar core does not show perfect spherical symmetry. Asphericity may lead to the development of sites where the gravitational energy liberation is enhanced relative to the environment, and so a local heated region may develop, which will expand and become lighter.

All aspects of solar activity (Ellerman bombs, bright points, flares, particle acceleration etc.) are self-similar and their statistical behaviour follows well-defined power laws. This last point reinforces the belief that the solar atmosphere is coupled, through the magnetic field, with the convection zone [66]. Regarding that the solar atmosphere is widely different from the interior of the Earth, and despite this difference similar catastrophic events occur, we have to allow that similar events may occur in the solar core, too, where all the ingredients are given. Namely, nonlinear plasma with its collective modes, magnetic field, and even a highly nonlinear energy source are present.

Based on a dynamical model of two-fluid equations with energy generation and loss, recently Li and Zhang [39] pointed out that, due to nonequilibrium of the solar core, coherent structures may develop and survive the destroying effects of frequent collisions and avoid decoherence at the high temperatures. Nuclear reactions go through inelastic collisions between ions and the accelerated ions transfer energy and momentum only subsequently via elastic collisions. The electrons lose energy and momentum through emitting photons via inelastic collisions with ions. On average, the direction of the energy and momentum flux in the nuclear fusion region is therefore: ions → electrons → photons. This implies that electrons do not reach thermodynamic equilibrium with ions ($T_i > T_e$), nor do photons with electrons in the fusion plasma. The non-equilibrium effect also shows itself in the two-fluid dynamical equations, and Li and Zhang have shown that the collision terms have been cancelled out by the non-equilibrium effect within general conditions. The reduced nonlinear two-fluid equations have been solved and it was shown that the self-organization of the stochastic thermal radiation field is in a close relation with the self-generated magnetic field: if one of them is absent, the other is very weak. Solving the model equations with a standard second-order explicit quasispectral method, they obtained that a magnetic field of at least $4 \cdot 10^4$ T may be generated at the centre of the Sun. Such a strong field shows that the self-organizing behaviour of the stochastic radiation field does occur. The growth time scale of the self-generated magnetic field is about $10^{12}$ s ($\approx 3 \cdot 10^4$ year).

Chang et al. [11] demonstrated that the sporadic and localized interactions of magnetic coherent structures arising from plasma resonances are the origin of 'complexity' in space plasmas. Dynamics of a plasma medium under the influence of a background magnetic field are characterized by coherent structures like convective cells, propagating nonlinear solitary waves, pseudo-equilibrium configurations and other varieties. They pointed out that MHD and kinetic (linear and nonlinear) instabilities result in fine-scale turbulences and trigger localized chaotic growth of a set of relevant order parameters. For typical MHD turbulence, the arising coherent structures are generally flux tubes. For our present purposes, it is important to notice that plasma interactions in general lead to sporadic and localized energy concentrations, and we suggest that the anisotropic dissipation of e.g. rotational energy of the solar core may enhance the energies of these sporadic and localized coherent structures significantly.

The localization of nuclear energy liberation needs a heating timescale $\tau_{nucl} = C_p T/(\varepsilon\nu)$ to be shorter than the timescale of the cooling processes $\tau_{expansion} = 5\ H_p/\mathrm{v}$, $\tau_{adj} = \kappa\rho^2\ C_p R^2/(16\sigma T^3)$ [30], where $C_p$ is the specific heat at constant pressure, $T$ the temperature of the heated region, $\varepsilon$ is the rate of energy liberation by nuclear reactions, $\nu$ is the exponent in the $\varepsilon \sim T^\nu$ relation, $H_p$ is the pressure scale height, 'v' the velocity of the heated region, $\kappa$ is a mean absorption coefficient, $\rho$ and $R$ is the density and the radius of the heated region, $\sigma$ is the Stefann-Boltzmann constant ($\sigma = 5{,}67 \cdot 10^{-8}$ W·m$^{-2}$·K$^{-4}$). With typical values ($\kappa = 0{,}2$ m$^2$·kg$^{-1}$, $\rho \sim 10^5$ kg·m$^{-3}$, $C_p = 30$ J·K$^{-1}$·mol$^{-1}$, $T = 10^7$ K,

$R$ = $10^4$ m, $H_p \sim 7 \cdot 10^7$ m, v ~ 10 - $10^4$ m/s), $\tau_{adj} \sim 7 \cdot 10^6$ s, $\tau_{expansion} \sim 3 \cdot 10^4 - 10^7$ s, $\tau_{nucl} \sim 10^{16}$ s, while for $T = 10^8$ K, $\tau_{adj} = 7 \cdot 10^3$ s, $\tau_{expansion} \sim 3 \cdot 10^4 - 10^7$ s, $\tau_{nucl} \sim 1$ s. It is clear that when the timescales of the cooling processes are comparable to or longer than the timescale of the rising motion of heated bubbles, the bubbles may travel significant distances. When the sporadic and localized energy enhancements heat a small macroscopic region above $10^8$ K, nuclear energy liberation will make the region explosive.

For the localization of the gravitational waves, Burgess et al. [7, 8] indicated the presence of density fluctuations in the deep solar core as a result of a resonant process similar to coronal heating. Energy is transferred from the g-modes into magnetic Alfven modes with density fluctuations corresponding to $\Delta T/T \sim 1{,}1$, dissipated heating energy is $Q_0 \sim 10^{28}$ J. Now our calculations [30] had shown that a much lower heating of $Q_0 \sim 10^{20}$ J is enough to produce a bubble rising a distance larger than its linear size.

Rotational, magnetic and thermal instabilities, gravitational g-mode oscillations, tidal effects and metastabilities make the solar core a dynamic, active system [27, 28, 30, 63]. The simple "ball of gas" concept, and the standard solar model based on this concept starts to lose its exclusive dominance in our picture of the Sun, and the emphasis may shift towards the dynamic phenomena of the Sun. A discrepancy between the old concept of the Sun and the accumulated results of the last decades makes it timely to present a revision of our concept of the Sun, and work out a deeper, more proper picture that may be useful for the paradigm shift from the "ball of gas" picture into the dynamic Sun framework.

In this paper, we present an approach, based on the concept that Sun has an astronomically large number of degrees of freedom (d.o.f.). There are mathematical methods worked out already to describe these dynamic collective modes offered by quantum field theories (e.g. [17, 18]); synergetics (e.g. [35]); self-organized criticality [3]; and so the approach suggested in this paper also opens up perspectives to new branches of solar sciences. We will shed some light on fields where the usefulness of this approach is indicated, and we will also propose some experiments to obtain measurable data on the nature of the Sun.

Sun is a self-organizing complex system. There are also some similarities to the most fundamental characteristics of terrestrial living organism. These lifelike characteristics correspond to the fact that the Sun shows a pronounced *activity, sensitivity, homeostasis, self-governance, integrality, and even a special type of "metabolism"* (obtaining energy from transforming materials into different compounds). Our aim is not to argue that the Sun is a living system or organism. Instead, our aim is to initiate a research to explore the most relevant facts, methods, and approaches suitable for the consideration of the nature of the Sun. We would like to make some initial steps in order to facilitate the exploration of the most important data, concepts and treatments necessary to work on this new field. To decide what is important for this aim we have to know what is a self-organising system, and what is life. In this introduction, we present a short preliminary consideration on the harder, and more fundamental question: on the lifelike nature of the Sun.

Three spectacular, easy-to-recognize signs of life are *activity, sensitivity and government from the level of the organism as a whole*. An exact study would necessitate a definition of the terms "activity", "sensitivity", and "government from the level of the organism as a whole". Instead, since our aim at present is only a stimulation of interest, we will postpone this more exact study to a later, more philosophical paper.

(i) Is the Sun active? Yes, and its activity is known under the name: solar activity. The persistence of this activity adds a special emphasis on the significance of this activity, since a persistent activity is self-regenerating.

(ii) Is the Sun a sensitive object? Yes. Every star is fundamentally sensitive, as nuclear energy production is an extremely sensitive function of temperature. Energy producing mechanisms are dependent on the high power of temperature ($\varepsilon_{pp} \sim T^4$ for the proton-proton cycle, and $\varepsilon_{CNO} \sim T^{20}$ for the CNO-cycle), a small amount of heating may lead to an acceleration of nuclear energy production and to further, increased amount of heating, which in turn may accelerate the heating process in a positive feedback cycle – if the negative feedback (heat loss processes) is weaker. This fundamental stellar sensitivity may be responsible for the development of local heated regions in stellar interiors and generating stellar activity from the radiative interior [30, 32].

(iii) Is solar activity regulated from the global level? Yes. "The prime cause of the solar cycle is a quasi-periodic oscillation of the SOLAR MAGNETIC FIELD." [42]. Solar cycle involves the sunspots, solar irradiance, surface flows, coronal shape, oscillation frequencies, etc. Sun is governed by a subtle agent (the magnetic field) that has a relatively small energy.

The Sun seems to govern its own behaviour from a high level of organization, and this would be a realization of a downward causation. The macroscopic degrees of freedom related to solar activity have significant energies even in comparison to the microscopic ones.

We note that the "bottom-up" approach building up the Sun from mass points or elementary particles is only one of the possible, physically sound approaches. For example, Eakins and Jaroszkiewicz [21, 22, 38] pointed out that a "top-down" approach offers a better description of our universe as a quantum universe, containing the bottom-up approach as a special, simplistic case. The quantum entanglement of the Sun to its global level and to the universe as a whole makes the Sun an even more highly complex system.

In this short paper we consider the nature of the Sun in an approach based on a consideration of the solar d.o.f., namely how the macroscopic d.o.f.s become excited, how the collective modes develop, and how they become organized by the magnetic field. The macroscopic degrees of freedom related to solar activity have significant energies even in comparison to the microscopic ones. The relative energy budget of solar activity to the average luminosity reaches an amplitude of 0,1 % [67, 68]. A whole series of phenomena related to intermediate collective degrees of freedom might play a role in the dynamics of the Sun that has yet escaped attention in the MHD approach.

## THE COLLECTIVE MODES OF THE SUN

Sound waves, MHD waves, p-mode, f-mode, g-mode, r-mode etc. oscillations, tidal waves, rising flux tubes etc. represent a continuous and self-regenerating activity extending throughout the whole body of the Sun and, in time, to a period comparable to the whole lifetime of the Sun. At a higher level of the solar collective modes, there appear the active regions, differential rotation, meridional circulation, giant, supergranular and granular activity, faculae, flares etc. At an even higher level we find the magnetic cycle with global collective modes and quasi-regularly repeating complex patterns of activity that represent such a long-lifetime and permanent self-initiating activity that they, apparently, do not have their counterpart in the realm of terrestrial physical self-organizing systems like sandpiles [3], lasers, Bénard-cells [35], phase transitions like ferromagnetism or superconductivity etc.

Appearance of Bénard cells is due to sharp temperature gradient. Different boundary conditions (rigid or free boundaries [10]) lead to different structural patterns of Bénard cells. The appearance of order is related to the macroscopic boundary conditions, which – being macroscopic - themselves represent macroscopic order that they can distribute to the system which they delimit. In that context, the phenomenon of Bénard cells is a member in the set of collective modes triggered by macroscopic physical influences. The phenomenon of generation of macroscopic order by the boundary conditions is a strange phenomenon of organizing remote control, organizing an astronomical number of microparticles into a coordinated behaviour to develop a coherent macroscopic order, in accordance with the boundary conditions. Del Giudice [19] pointed out that it is the electromagnetic radiative field, a long-range messenger indeed, that is responsible for such macroscopic organization. The quantum field formalism is also capable of describing the dynamism of the collective degrees of freedom [65].

In solid state physics collective phenomena found their description through the appearance of phonons and other quasiparticles. Plasma is very rich in collective phenomena, and our Sun consists largely from plasma. Actually, plasmons are suggested to describe collective plasma processes [44]. In addition to the haphazard individual fluctuations of electrons, Bohm saw there was a collective motion involving the electron sea as a whole, 'an electron plasma'. In such collective modes, the movement of individual electrons might appear to be 'random', but the cumulative effect of minute fluctuations in an enormous number ($10^{23}$) of electrons combined to produce an overall effect. Such collective effects representing a deeper order [6] were eventually well established experimentally and called 'plasmons' or, more generally, quasiparticles or excitons.

We know that the development of macroscopic modes received a rigorous foundation in the quantum theory of collective phenomena [53]. The macroscopic wave function gives a global collective description of the dynamical evolution in terms of a classical (but complex) wave field with a well-defined quantum phase. This is exactly what Saniga [49, 50] applied to describe the order represented in solar activity. He introduced a complex scalar Higgs field interacting with the electromagnetic gauge field in a modified Ginzburg-Landau theory. We suggest that the physical basis of the solar Higgs-fields is the development of collective modes of microscopic polarization effects, of electromagnetic quasiparticles contributing to "macromolecular dipoles" in the form of macroscopically polarized filaments. The solar Higgs field is a manifestation of quantum field changes related to dipole ordering, manifested also at the macroscopic degrees of freedom.

## IS THE SUN A SELF-ORGANIZING COMPLEX SYSTEM?

"Self-organized, non-equilibrium system … is a distinguishable collection of matter, with recognizable boundaries, which has a flow of energy, and possibly matter, passing through it, while maintaining, for time scales long compared to the dynamical time scales of its internal processes, a stable configuration far from thermodynamic equilibrium. This configuration is maintained by the action of cycles involving the transport of matter and energy within the system and between the system and its exterior. Further, the system is stabilized against small perturbations by the existence of feedback loops which regulate the rates of flow of the cycles.” [55, p. 155].

Examples of natural self-organizing complex systems/phenomena are phase transitions like glaciation, magnetism, crystallization, pattern formation of snowflakes [25], avalanches of sandpiles [3], Benard-cells of convective flows, the generation of laser light [35], earthquakes in the mantle of the Earth. Applying the formulation of Bak [3, p. 5], we find that the Sun is a complex system, since it shows a definite and rich variability. By the concept of Haken [35, p. 11] the Sun is a self-organizing system, since a significant part of its collective modes are developing without a specific, impressing interference from the outside. Certainly, the Sun is able to change its internal structure through the homeostatic process of self-stabilization through its expansion and contraction, or otherwise. The Sun is a non-equilibrium system, which has a significant flow of energy passing through it while maintaining a stable configuration, having also a cyclic activity transporting energy and matter within the system and between the system and its exterior. The Sun is stabilized against small perturbations by the existence of negative feedback loops, since e.g. a heating perturbation generates expansion, and expansion causes cooling and return to the equilibrium, therefore fulfilling the criterion of Smolin [55, p. 155], too.

The solar surface is much more ordered than our present physical knowledge recognizes. Schwarzschild noticed in 1959 that granular structure should be turbulent instead of the observed cellular pattern. Reynolds number (the ratio of the inertial force of the motion to the decelerating drag force) characterizing the degree of turbulence is enormous – $Re \sim 10^{14}$. According to laboratory experiments, above $Re{\sim}10^6$ the flow becomes chaotically turbulent, losing all its remaining regularities. Now the range $Re>10^7$ is not yet reached experimentally. The extremely high Reynolds-number $Re \sim 10^{14}$ seems to indicate the necessity of a completely and extraordinarily chaotic turbulence of the solar granules. On the other hand observations show a quite different picture of an almost complete regularity, reminiscent to the cells of the beehives.

Solar activity is an expression of energy transfers from one mode to another, and to understand solar activity it is fundamental to keep in mind what are the relevant energy sources and actual modes of energy transfers.

**Table 1.** Estimated energies, luminosities and activity-related luminosity change amplitudes.

| Type | Energy, J | Luminosity, $J{\cdot}s^{-1}$ | Luminosity change amplitude, ($J{\cdot}s^{-1}$ in an ~ 11 year cycle) |
|---|---|---|---|
| Nuclear | $2{\cdot}10^{44}$ | $4{\cdot}10^{26}$ | $4{\cdot}10^{23}$ |
| Gravitational | $4{\cdot}10^{41}$ | $3{\cdot}10^{22}$ | ? |
| Rotational | $2{\cdot}10^{36}$ | $6{\cdot}10^{19}$ | ? |
| Convective | $10^{31}$ | ? | ? |
| Magnetic | $5{\cdot}10^{27}$ | $2{\cdot}10^{19}$ | ? |
| Tidal | small | $< 10^{15}$ | $< 10^{15}$ |

The Earth [24, 40], galaxies [55] and the Universe [37, 54, 69] are already recognized to be complex self-organizing systems. Moreover, a comprehensive picture is proposed on cosmic evolution as the rise of complexity in nature [9]. There were attempts to apply self-organization in solar physics too. Li and Zhang [39] pointed out that coherent structures may be present in the solar core due to non-equilibrium processes.

Due to the self-organization of the stochastic radiation field, a self-generated magnetic field will develop in the solar core, the magnitude of which may reach $6{\cdot}10^4$ T.

Vlahos [66] regards the surface solar active regions as open dynamical systems away from equilibrium, driven by the turbulent convective zone. He has shown that all aspects of solar surface activity share one common characteristic, they are self-similar and their statistical behaviour follows well-defined power laws. Chang et al. [11] reviewed complexity, forced and/or self-organized criticality and topological phase-transitions in space plasmas.

## IS THE SUN A LIVING SYSTEM?

Living systems are such self-organizing systems that display high degree of functional self-governance of each organizational level [34]. The Sun is much more complex than ice, snowflake, sandpile, magnet, a Benard-cell, or a flame. *There is a significant difference between the most complex terrestrial complex systems (like Benard-cells or flames) and the Sun showing a lifelike activity involving thermodynamical, electromagnetic and gravitational behaviour on a wide range of spatial and temporal scales, degrees of freedom and energetic levels.* The special type of complexity of the Sun is related to dielectric macroscopic filaments and magnetic flux tubes, in a remarkable similarity to the terrestrial living organisms which are organized through the order of their polarized filamentary macromolecules also by electromagnetic fields [4]. The Sun is in a permanent state of activity and produces high-quality order in the patterns of solar activity [15], and in coherent sunlight [5, 45].

Ervin Bauer formulates three key marks of living systems [4, p. 32]. The first key mark says: "In order that a system could be alive, it should be able to show spontaneous changes even in an unchanging environment. Therefore it needs to have accumulated energy, which may be used within the conditions prevailing within the system and at unchanging outer conditions. This means that potential differences should set up within the system." The second key mark says: "The living systems show changes which are not due only to the effects of the outer changes but also to internal, non-mechanical factors…It is not necessary that the living systems react to every outer effect in every case with a work modifying the arising processes; our claim is only that they should not show only passive changes that can be determined unequivocally on the basis of the initial state of the system and the outer effect…The living systems show a sensitivity that is very wide-ranged, present to almost all outer effects, in the case of the repeated action of the outer effects as well. The reaction of the system is not a direct consequence of the outer effect, regarding its strength, too, and frequently the topographic agreement is also missing, when a stimulus acting on one place of the system corresponds to a reaction process occurring in a distant place of the system … the sensitivity of the living system is the ability to show processes that reacts to the equilibrating processes elicited by the outer effects by other processes using energy to recharge the potential differences" [4, pp. 36-42]. Therefore, the persistence of such sensitivity involves a self-regenerative activity, recharging the most important living potentials in the most suitable way. Such a self-regeneration assumes the presence of free energy available for such a work. Now if the sensitivity is present in most of the places of the system, and if it may act non-locally, this requirement apparently necessitates a free energy reservoir that is available by many or most parts of the system. Therefore, the free energy supply of almost any part of the system at any time assumes the presence of an activity that mobilizes and directs the free energy to the proper place in due time. This governing activity should consume much less energy than the system's "real activity" that concerns to the outer effects and the corresponding internal changes. In this way the global sensitivity of living systems seems to involve the presence of a subtle free energy field that is able to govern the processes developing from the stimulus until the answer in a functionally reasonable manner. Now the question is how is it that such a governing subtle energy field is present in the Sun, and how it is able to govern from "above", from the global level of the living system.

Such a governance is enlightened by Ervin Bauer with his third requirement: "The work of the living system, independently of the environmental conditions, is used against the equilibrium towards which the system would proceed by the physico-chemical laws at the actual outer conditions and the initial state of the system." Ervin Bauer formulated the life principle: "Living systems and only living systems are never in a state of equilibrium; to the debit of their reserves of free energy they continually perform work against the setting in the equilibrium state which should, according to the laws of physics and chemistry, be established under the actual external conditions" [4, p. 44].

The fact that life is intimately related to collective phenomena is an inevitable necessity. Microparticles have only individual degrees of freedom. Propensities [47] act as generalized determinations. They are situation-dependent collective phenomena developing in many-sided, dynamic, changing situations. Propensities are already related to collective degrees of freedom. Living systems are possible only above a certain level of complexity because the appearance of collective modes depends critically on the level of complexity. The higher the complexity, the richer and more field-like the propensities will be. Living systems may develop when propensities are so complex that they develop a field-like character that coheres with an energy reservoir available for this field. Of course, this statement is true only together with its dual: living systems may develop only when the life principle meets with a system complex enough that a field-like causative structure may develop with a field-like energy reservoir.

Regarding the electromagnetic nature of the solar cycle, it is important to be aware to the work of Del Giudice [19]. He recognized that a missing ingredient of liquid water formation as condensed matter from water vapour is the electromagnetic (e.m.) radiative field. In the process of water condensation, water density increases abruptly by a factor of 1600 at the condensation point of 373 K, and this process occurs remarkably fast regarding the fact that more than $10^{23}$ individual water molecules have to be hooked together almost instantaneously. Although the contribution of the e.m. radiative field to the interaction between two particles is exceedingly small with respect to the static forces, but, when we collect a very large number $N$ of components, it is possible to realize [20] that at a density exceeding a threshold the radiative contribution becomes very large (superradiance). In the solar interior, the plasma and its filamentary structures interacting with the strong radiative field may produce a coherent phase (in the context of radiative field) or collective mode (in the context of the plasma constituents), similarly to water. The coherent phase represents only a fraction of the solar plasma, and so a two-fluid picture emerges, again resembling the picture of the superfluid helium. At the same time, the coherent field is able to arrange an astronomical number of plasma particles almost instantaneously when suitable conditions develop. We know that the electrodynamic properties of water depend on the coherent phase, and, similarly, we can expect that the electrodynamic properties of the solar plasma also depend on the coherent collective mode. In the process of formation of coherent collective modes, a sizeable polarization field develops, which may contain a significant amount of information [19], and hooks together an astronomical number of particles by the coupling of quantum electrodynamic fields. Indeed, it is well-known that water may show a complex behaviour, it has memory, structure, and information (e.g. [14]). Similarly, the formation of a filamentary basic plasma structure in the solar core is indicated by Li and Zhang [39]; and in the solar convective zone [49, 52] and in space plasma by Chang et al. [11]. On this basis, we think that the detailed calculations of Del Giudice and his group may substantiate that the solar plasma may be rich enough in information to make the Sun capable of maintaining its lifelike organisation.

The fellow systems of the Sun, the Earth (e.g. [40, 64]), the Galaxy [33] and the Universe [22] were already considered as living systems/organisms. Recently, Grimm [34] concluded that Gaia System is an authentic living system. The idea that a galaxy is a self-organized system – more an ecology than a nonliving clump of stars and gas – has become common among astronomers and physicists who study galaxies [55]. Some regards galaxies as literally alive: "I have argued that our Galaxy is alive – literally alive, in the full biological meaning of the term. … The striking feature of the way in which spiral galaxies maintain a steady state, far from equilibrium … has been produced by a process of evolution and competition" [33, p. 214]. We note that these approaches are merely physical ones, and as such, they may miss the most substantial points of living organisms. "From the standpoint of the traditional physical sciences a living organism appears as a complex aggregation of separable units of matter associated causally with one another in separable events. From the biological standpoint, on the other hand, the apparently separable units of matter and events are seen not to be actually separable, but, in their relationships to one another, to be taking part in the manifestation of the co-ordinated and persistent whole which is called a life, and which has no spatial limits. Thus the separable units and events of physical interpretation are seen to be illusory, but the same phenomena become intelligible in so far as they can be interpreted as phenomena of life" [36, p. 62]. "Physical interpretation, in so far as we adhere to it, is applicable to the whole of our perceived experience. But so is biological interpretation … Inasmuch, however, as in biological interpretation we are taking our experience more fully into account than in physical interpretation, biological interpretation is on a higher level, and represents reality less incompletely than physical interpretation." [36, p. 64]. The biological standpoint is worked out in our books [29, 31].

## THERMODYNAMIC CHARACTERISTICS OF THE INEQUILIBRIUM SUN

The Sun has much more degrees of freedom and much higher energy flux than the surface of the Earth, therefore the Sun shows much higher versatility, plasticity and inner drive towards autonomous activity than systems at the surface of the Earth. An important quantitative characteristic of any complex and living system is the distance from thermodynamic equilibrium. The distance from the thermodynamic equilibrium can be measured with extropy.

Martinás [41, p. 39] calculated the extropy flow $J_\Pi = L_2/T_2 - L_1/T_1$ (where $L$ is the luminosity, $T$ is the temperature, index 1 refers to the incoming and index 2 to the outgoing values) for the Earth as being $J_\Pi(\text{Earth}) = 4{\cdot}10^{14}$ J K$^{-1}$ s$^{-1}$. We calculated the extropy flow for the Sun: $J_\Pi(\text{Sun}) \sim L(Sun)/T_{\text{eff}}(\text{Sun}) = 7 \cdot 10^{22}$ J K$^{-1}$ s$^{-1}$. This number indicates that the Sun is a strongly nonequlibrium system. Regarding that the numerical values of extropy flows are generally not really familiar, we calculated also some representative values for comparison. For an (unmoving) human the heat output is $L \sim (2$ J·kg$^{-1}$ s$^{-1}$ 7 $10^5)\cdot g$ = 1,4·10$^3$ J s$^{-1}$ as estimated on the rate of metabolism. Therefore, for an unmoving human: $J_\Pi(\text{human}) \sim L/T$ = 4 J K$^{-1}$ s$^{-1}$. The extropy flow for unit masses ($j_\pi$) is $j_\pi$(Sun) = $3{,}5 \cdot 10^{-14}$ J $K^{-1}$ $s^{-1} \cdot kg^{-1}$, $J_\pi$(Earth) = $6{,}7 \cdot 10^{-17}$ J $K^{-1}$ $s^{-1} \cdot kg^{-1}$, and $J_\pi$ (human) = $5{,}7 \cdot 10^{-2}$ J $K^{-1}$ $s^{-1} \cdot kg^{-1}$. In the solar emitting layer, the photosphere, $J_\pi$(photosphere) ~ 14 · J $K^{-1}$ $s^{-1} \cdot kg^{-1}$. We do not think that one can immediately draw definite conclusions on the basis of these numbers. Nevertheless, if other facts will point to the same direction, these results may indicate that solar photosphere is more favourable for lifelike complexity than the surface of the Earth.

**Table 2.** Some estimated specific extropy flows.

| Generic structure | Average $j_\pi$, J $K^{-1}$ $s^{-1} \cdot kg^{-1}$ |
|---|---|
| Stars | $10^{-8} - 10^{-4}$ |
| Earth | $7 \cdot 10^{-11}$ |
| Prebiotic material | $3 \cdot 10^{-5}$ |
| Human body | $6 \cdot 10^{-2}$ |
| Solar photosphere | 10 |

Chaisson [9, p. 139] presented the free energy rate for the modern society a $\Phi_m$ value 50 $J \cdot s^{-1} \cdot kg^{-1}$, that is $j_\pi$ = 2 J $K^{-1}$ $s^{-1} \cdot kg^{-1}$, this number arises if we count all the energies used by man but the related mass is the mass of mankind. When all the mass of these equipments (and the mass of the equipments producing these ones etc.) is involved, then the value decreases by some orders of magnitude. In this way, modern society loses its 'top position'.

## EXPERIMENTS SUGGESTED TO TEST THE NATURE OF THE SUN

The Sun has a life favouring effect through the negentropy (extropy) it carries, transporting free energy available for living organisms to do work. The Sun plays a life-inducing role in the earth [45, p. 143]. Popp and Yan [46] demonstrated (see their Figs. 8a and 8b) that spontaneous emission of biological systems may also originate from squeezed states as it is shown by their emissions, a significant part of which had fallen below the Poissonian statistics $p(0) < e^{-<n>}$. In case of artificial light sources, the emitted radiation never had fallen below the Poissonian photocount statistics. We suggest that this method may be applied to test the nature of solar electromagnetic radiation. If the solar radiation contains non-classical squeezed light, the photocount statistics may be similar to the spontaneous emissions of biological systems, and this would be an important element to understand the emergence of life. The apparent fact is that greenhouse vegetables have less natural aroma and nutritive, vitalizing power than the same vegetables grown on open air and sunshine.

Our study proposes to consider if there are any life-enhancing solar effects besides the extropy carried in solar radiation. We propose that one candidate from the wide range of solar effects is the information content of solar radiation. Recently, Consolini et al. [15] have shown by means of the normalized information entropy measure that the regularities of granular pattern present evidence of a spatial-temporal organization in the evolution of convective pattern. We point out that this and/or other types of information present in solar phenomena (e.g. in the Higgs-field [51, 52]) may also carry life-enhancing effects. We suggest the experimental study of the growth of different organisms (bacteria, plants, eggs) on the influence of different types of light: (i) room-temperature artificial light sources; (ii) high-temperature (visible, UV, EUV) artificial light; artificial light with the same temperature as that of the sunlight $T$ = 5 778 K (S1); artificial light with the same spectra as sunlight (S2); artificial light with the same spectra, time and incidence angle variation as that of sunlight (S3)

(iii) artificial electromagnetic waves like the waves of radio-broadcasts and television-broadcast; informatically modulated artificial lights (like S1, S2, S3); (iv) and light from living organisms, biophotons. In comparison, one may study (v) the biological influence of natural solar light. These experimental possibilities would give a better understanding of the nature of Sun.

## CONCLUDING REMARKS

The present approach aims to build up a systematic picture on the network of collective and coherent modes of the Sun, and offers a higher resolution of the physical and possible lifelike nature of the Sun. The obtained results draw some methods and formalisms into solar physics like complexity science, quantum field theory, information theory, theoretical biology, biophoton research, synergetics, condensed matter physics, self-organization and non-linear sciences etc., some of which actually play a central role in the dynamism of modern sciences.

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# KONCEPTUALNI KORACI PREMA ISTRAŽIVANJU PRIRODE NAŠEG SUNCA

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## SAŽETAK

Jedno od temeljnih pitanja u solarnim istraživanjima je o prirodi Sunca. U ovom radu pokazujemo da stanje plazme Sunca dovodi do samorazvijanja solarne aktivnosti. Oslobađanje magnetske, rotacijske, gravitacijske, nuklearne energije i energije gravitacijskih vibracija uzrokuje odstupanja od uniformnosti i sferne simetrije. Putem nestabilnosti to dovodi do nastajanja sporadičnih i lokaliziranih područja poput cijevi toka, električkih ispuna, magnetskih elemenata i područja visokih temperatura. Prikazan je sustavni pristup istraživanju solarnih kolektivnih stupnjeva slobode, do uključivo pojave reda zbog magnetskih svojstava povezanih s Higgsovim poljima.

Razmatranje solarne aktivnosti kao pretvorbe oblika energija vodi na sliku mreže energetskih razina Sunca, pokazujući kako Sunce nije ni obična kugla plina, niti stacionarni fuzijski reaktor, nego složeni, samoorganizirajući sustav. Budući da su složeni, samoorganizirajući sustavi slični živim sustavima (a po nekim shvaćanjima identični njima) također razmatramo argumente koji ukazuju na živu prirodu Sunca. Termodinamička svojstva neuravnoteženog Sunca su u tom smislu značajna. Numerički su procjenjene gustoće stope slobodne energije i specifične eksergije.

## KLJUČNE RIJEČI

solarna fizika, stupnjevi slobode, samoorganizirajući složeni sustavi, neravnotežna termodinamika, astrobiologija

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# OPTIMAL PROCESSES IN IRREVERSIBLE THERMODYNAMICS AND MICROECONOMICS

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## SUMMARY

This paper describes general methodology that allows one to extend Carnot efficiency of classical thermodynamic for zero rate processes onto thermodynamic systems with finite rate. We define the class of minimal dissipation processes and show that it represents generalization of reversible processes and determines the limiting possibilities of finite rate systems. The described methodology is then applied to microeconomic exchange systems yielding novel estimates of limiting efficiencies for such systems.

## KEY WORDS

finite-time thermodynamics, minimal dissipation process, optimal exchange processes in microeconomics

## CLASSIFICATION

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## LIMITING POSSIBILITIES OF HEAT ENGINES

One of the basic results in thermodynamics, obtained by Sadi Carnot, is the limiting value of heat engine's efficiency. Efficiency understood as the ratio of the mechanical work $A$ to the amount of heat energy $Q_+$ removed from the hot source [1]. This limit turns out to be equal to

$$\eta^0 = \frac{A}{Q_+} = 1 - \frac{T_-}{T_+}, \tag{1}$$

where $T_+$ and $T_-$ are absolute temperatures of the hot and cold sources in heat engine cycle.

The value of $\eta^0$ was found by Carnot essentially intuitively, because he did not know the energy conservation law and believed in the thermogen theory. Note that the value $\eta^0$ does not depend on such characteristics of the engine as its size, the material of heat-exchange surfaces, the equation of state of the working body, etc. If Carnot were to consider this problem from the viewpoint of modern thermodynamics he would cast it as the problem of finding the optimal dependence of working body's temperature on time $T(t)$ subject to the cyclic changes of the working body's state and the optimal cycle's period $\tau$ (Figure 1). He would arrive at the following optimal control problem:

$$\eta = \frac{\int_0^{\gamma\tau} q_+(T_+, T)\mathrm{d}t - \int_{\gamma\tau}^{\tau} q_-(T, T_-)\mathrm{d}t}{\int_0^{\gamma\tau} q_+(T_+, T)\mathrm{d}t} \to \max_{\tau,\gamma,T(t)}, \tag{2}$$

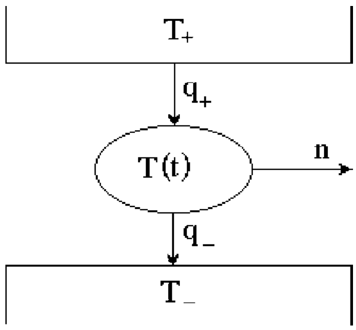


**Figure 1.** The structure of thermodynamic system (heat engine).

where the time of contact between the working body and the hot reservoir is $\gamma\cdot\tau$ and the time of contact between the working body and the cold reservoir is denoted as $(1 - \gamma)\tau$; $q_+$ and $q_-$ are the heat fluxes from the hot and to the cold reservoirs correspondingly. From the energy conservation and cyclic changes of working body's state it follows that the denominator in (2) is equal to the obtained work $A$. Because of the same cyclic condition the maximum in (2) is to be found subject to constraint

$$\Delta S_\mathrm{p} = \int_0^{\gamma\tau} \frac{q_+(T_+, T)}{T}\mathrm{d}t - \int_{\gamma\tau}^{\tau} \frac{q_-(T, T_-)}{T}\mathrm{d}t = 0, \tag{3}$$

where $\Delta S_\mathrm{p}$ is the change of the working body's entropy during a cycle and $0 \le \gamma \le 1$.

The problem (2) and (3) does not have a solution, that is, for natural laws of heat transfer $q_+$ and $q_-$, $\eta$ increases monotonically when $\tau$ increases, and the optimal temperature of the working body over the interval $\gamma\tau$ tends to $T = T_+$, and over the interval $(1 - \gamma)\tau$ to $T = T_-$. Meanwhile, the value of $\eta$ is bounded and its limit (supremum) turns out to be equal to $\eta^0$.

Thus, Carnot's intuition helped him to bypass succesfully these mathematical difficulties and to obtain the correct result. This result is valid for any $q_+$ and $q_-$, which obey the natural requirement that the heat flux is directed from the body with the higher temperature to the body with the lower temperature.

A number of other problems can be formulated for the system, shown in Figure 1. Namely:

1. What is the maximal power, that can be obtained in a heat engine?

$$n = \frac{1}{\tau}\left[\int_0^{\gamma\tau} q_+(T_+, T)\mathrm{d}t - \int_{\gamma\tau}^{\tau} q\ \ (T, T\ \ )\mathrm{d}t\right] \to \max_{\tau,\gamma,T(t)}, \tag{4}$$

   The maximum in (4) is to be found subject to constraint (3).

2. What is the maximal value of a heat engine's efficiency $\eta$, when its power $n_0$ is fixed?

If the solution of the Problem 1, $n_{\max}$, is found then the fixed power $n_0$ must obey inequalities

$$0 \le n_0 \le n_{\max}, \tag{5}$$

If the left inequality is violated then the cycle is already not a cycle of a heat engine and if the right inequality is violated then the solution does not exist.

The first of these problems was solved by Novikov [2], and then independently and much later by Curson and Albborn [3] for the Newton law of heat transfer

$$q_+ = \alpha_+(T_+ - T), \quad q_- = \alpha_-(T - T_-). \tag{6}$$

The coefficients $\alpha_+$ and $\alpha_-$ in these expressions implicitly describe the size of the heat engine. Problem 2 was solved for the Newton law and other laws of heat transfer in [4, 5].

Mathematical features of the Problems 1 and 2 are due to the averaging operations in their formulations. Indeed, in the maximal power problem it is required to choose a temperature of the working body $T(t)$, such that the average value of the heat flux $q$ (after taking into account its sign), which is supplied to it, is maximal, subject to zero average change in the working body's entropy. In the maximal efficiency problem it is required to minimize the average value of the flux $q_+$ subject to constraints on the entropy of the working body and the fixed average power. Such problems are called averaged nonlinear programming problems [6]. As a rule, they have an infinite set of solutions, each of which switches between not more than $k + 1$ so-called "basic" values, where $k$ is the number of averaged conditions. For example, since in the maximal power problem there is only one averaged condition (3), the temperature of the working body in the optimal cycle takes not more than two values $T_1$ and $T_2 < T_1$. Thus, for any law of heat exchange the optimal cycle includes two isotherms and the instant (adiabatic) temperature switches between them. Here $T_1 < T_+$, and $T_2 > T_-$. The basic values $T_1$ and $T_2$ are determined jointly with the fractions $\gamma$ and $(1 - \gamma)\tau$ of the cycle's period $\tau$ (when $T(t) = T_1$ and $T(t) = T_2$ and the working body makes contact with the hot and cold reservoir correspondingly) by solving the auxiliarly nonlinear programming problem (without averaging).

In the maximal efficiency problem with the fixed power $n = n_0$ there are two averaged conditions – one on the average entropy rate of the working body and the other on the average power. Therefore the number of isotherms in the optimal cycle does not exceed three. But for the Newton law of heat exchange (6) this number is two and the cycle has the same form as the maximal power cycle (two isotherms and two adiabats) but with different values of $T_1$ and $T_2$ and with different time fractions $\gamma$ and $1-\gamma$.

Let us write down the solution of the limiting power problem

$$n_{\max} = \alpha_0 \left(\sqrt{T_+} - \sqrt{T_-}\right)^2, \tag{7}$$

where

$$\alpha_0 = \frac{\alpha_+ \alpha_-}{\left(\sqrt{\alpha_+} + \sqrt{\alpha_-}\right)^2}, \tag{8}$$

The efficiency that corresponds to this power is

$$\eta_{n_{\max}} = 1 - \sqrt{\frac{T_-}{T_+}} < \eta_0. \tag{9}$$

In the limiting efficiency problem with fixed power $n_0 < n_{\max}$ this value is

$$\eta_n = 1 - \frac{1}{2T_+}\left[T_+ + T_- - \frac{\eta_0}{\alpha_0} - \sqrt{(T_+ - T_-)^2 + \left(\frac{\eta_0}{\alpha_0}\right)^2 - 2\frac{\eta_0}{\alpha_0}(T_+ - T_-)}\right], \tag{10}$$

and $\alpha_0$ corresponds to (8). The optimal fraction $\gamma$ of the cycle period when the working body stays in contact with the hot reservoir is the same in both problem

$$\gamma^* = \frac{\sqrt{\alpha_-}}{\sqrt{\alpha_+} + \sqrt{\alpha_-}}. \tag{11}$$

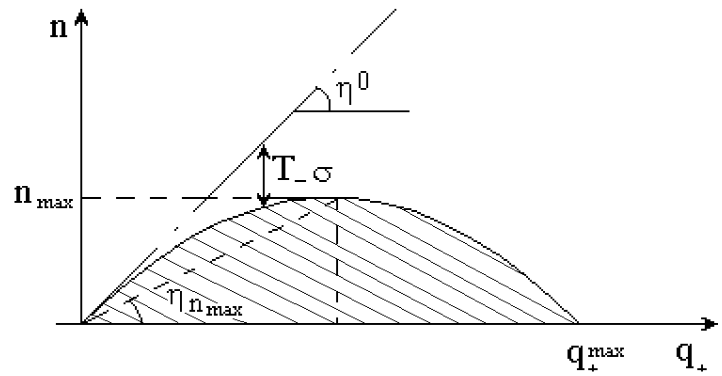


**Figure 2.** The area of the feasible regimes of the heat engine.

It is interesting to note, that if the power of the heat engine is fixed then it is possible to find not only its maximal but also its minimal efficiency. Here it is possible to construct the feasible area of the heat engine in the 2-D space where the coordinates are $\overline{q}_+$ (the average per cycle value of $q_+$) and the average power $n$. This is the dashed area in Figure 2. Its boundary, which is denoted here with the solid line, corresponds to cycles that include two isotherms and two adiabats. The dependence between $n$ and $\overline{q}_+$, which corresponds to the infinite heat transfer coefficients (that is, to an infinitely large engine) is denoted with the dotted-dashed line. Here the processes approach reversible ones and the efficiency (the tangent of the slope of dotted-dashed line) is equal to $\eta^0$. The efficiencies, given by the expression (10), correspond to the slopes of the limiting power curve for the point that is located to the left of the maximum. The difference between the dotted-dashed curve and the boundary of the dashed area characterizes the irreversibility of the processes in the heat engine. Later we will show that this difference is equal to the product of the entropy production in the system $\sigma$ on the temperature $T_-$. Thus the problem of efficiency maximization corresponds to the minimization of the entropy production (dissipation) in the system

$$\sigma = \frac{\Delta S}{\tau} = \frac{1}{\tau}\left[\frac{1}{T_-}\int_0^{(1-\gamma)\tau} q_-(T,T_-)\mathrm{d}t - \frac{1}{T_+}\int_{(1-\gamma)\tau}^{\tau} q_+(T_+,T)\mathrm{d}t\right], \tag{12}$$

## MINIMAL DISSIPATION PROCESSES

The study of the limiting possibilities of heat engines led to the development of the new branch of thermodynamics - finite-time thermodynamics (optimizational thermodynamics). This branch of thermodynamics studies the limiting possibilities of thermodynamic systems of various types where the average rates of heat and mass fluxes are fixed. One of the ways to fix these fluxes is by fixing the duration of the process when the values of all or some of the state variables are fixed. Let us describe the general schema of solving the problem of determining the feasible area in the space of parameters of the thermodynamic system.

The state of a system is described by its internal energy $U$, the amount of mass (vector) $N$ with components $N_i$, (i = 1, …, $m$) and the entropy $S$. In the general case, the system can be open, that is, an exchange of mass, energy and entropy between the system and the environment can takes place.The changes to $U$, $N$ and $S$ are determined by the mass, energy and entropy balances:

$$\dot{U} = \sum_j g_j h_j + \sum_j g_{\alpha j} h_{\alpha j} + \sum_j q_j - n, \tag{13}$$

$$\dot{N}_i = \sum_j g_j x_{ij} + \sum_j g_{\alpha j} x_{\alpha ij} + \sum_\nu k_{i\nu} W_\nu , \tag{14}$$

$$\dot{S} = \sum_j g_j s_j + \sum_j \frac{g_{\alpha j}}{T_{\alpha j}}\left(h_{\alpha j} - \sum_i \mu_{\alpha ij}\right) + \sum_i \frac{q_j}{T_j} + \sigma, \tag{15}$$

Here $g_j$ and $g_{\alpha,\, j}$ are the fluxes of mass that are driven by diffusion and conduction; $h_j$ and $h_{\alpha,\, j}$ are the specific enthalpy of these fluxes; $q_j$ are the heat fluxes; $n$ is the produced work ; $x_{ij}$ is the concentration of the i-th component in the j-th flux; $k_{ij}$ is the stoihiometric coefficient of the i-th component in the $\nu$-th reaction; the rate of this reaction – $W_\nu$; $s_j$ is the specific enthalpy of the j-th flux; $\mu_{\alpha,\, ij}$ is the chemical potential of the i-th component in the j-th diffusion flux.

If the state of the system does not change, then the right-hand sides of the balance equations (13) – (15) are equal to zero for any $t$. If the state of the system changes cyclically with the period $\tau$, then the integrals over the time interval [0, $\tau$] of the right-hand sides of equation (13) – (15) are equal to zero, because

$$U(\tau) = U(0), \quad N(\tau) = N(0), \quad S(\tau) = S(0).$$

Let us emphasize that the last of the balance equations includes the entropy production $\sigma$, which is non-negative according to the second law of thermodynamics. Only such trajectories and such stationary states in the state space for which $\sigma \geq 0$ can be realized. This limits the possible states of the system. For example, for a heat engine with two reservoirs of infinity heat capacity, the condition $\sigma \geq 0$ singles out the area below the dashed-dotted line in Figure 2, and thus limits the efficiency to below $\eta^0$. Indeed, if there are no exchange fluxes between this system and the environment then the entropy increment is equal to the change of the sources' entropies during the cycle

$$\frac{Q_-}{T_-} - \frac{Q_+}{T_+} = \int_0^\tau \sigma \mathrm{d}t = \Delta S \,, \tag{16}$$

The first term here is the entropy increment of the cold reservoir when the heat is supplied to it; the second term is the reduction of the hot reservoir's entropy when heat is removed from it; and $\sigma$ is the entropy production in the system. From the energy balance it follows that

$$Q_+ - Q_- = A. \tag{17}$$

After elimination of $Q_-$ from (16) and (17), and denoting the ratio $A/Q_+$ as $\eta$, from the condition $\Delta S \geq 0$ it follows that

$$\frac{A}{Q_+} = \eta \leq \frac{T_+ - T_-}{T_+}. \tag{18}$$

If the state of the system is described by the equations (13) – (15) and some additional constraints are imposed on the initial and final states of the system and on the duration of the process $\tau$, then it is possible to find such phase trajectories among all feasible trajectories for which the average entropy production (dissipation) is minimal and equal to $\overline{\sigma_{\min}} > 0$.

The condition

$$\int_0^\tau \sigma \mathrm{d}t \geq \tau \overline{\sigma_{\min}} \,, \tag{19}$$

narrows down the area of the system's feasible phase trajectories. Thus, the condition of the fixed power of the heat engine leads to the inequality

$$\Delta \mathrm{S} \geq \tau \overline{\sigma_{\min}}(n_0) \,,$$

and instead of the inequality (18) we get

$$\frac{\mathrm{A}}{\mathrm{Q}_+} = \eta \leq \frac{T_+ - T_-}{T_+} - \frac{\tau \overline{\sigma_{\min}}(n) T_-}{Q_+} \,, \tag{20}$$

Thus, the estimate of the limiting possibilities of a thermodynamic system is reduced to finding the minimal dissipation in the system subject to given constraints.

In order to find an estimate of the minimal dissipation in the system with the fixed rate of the processes in it, it is reasonable to solve the minimal dissipation problem for each of the possible processes (heat exchange, mass transfer, chemical reactions, throttling, etc.). Then the dissipation in a complex system can be estimated by decomposing its internal processes into a set of minimal dissipation processes. In some sense the class of such processes extends the class of reversible processes by taking into account the non-zero rate of their processes. Let us first describe how the conditions of minimal dissipation are derived for the heat exchange and then we will generalize this derivation to other processes. A heat-exchange process between two bodies with the temperatures $T_1$ and $T_2$ is accompanied by entropy production

$$\sigma = q(T_1, T_2)\left(\frac{1}{T_2} - \frac{1}{T_1}\right), \tag{21}$$

where $q$ is the heat exchange law.

Assume that $T_2$ is the control and that $T_1$ changes according to the equation

$$\dot{T} = -\frac{q(T_1,T_2)}{C_1(T_1)}, \tag{22}$$

where for simplicity we assume that the heat capacity $C_1$ is constant. The duration of the process is fixed and it is required to change the temperature $T_1$ from $T_{10}$ to $\overline{T_1}$ in such a fashion that the system's entropy increment is minimal

$$\Delta S = \int_0^\tau \sigma \mathrm{d}t = \int_0^\tau q(T_1,T_2)\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\mathrm{d}t \to \min_{T_2(t)}, \tag{23}$$

The problem (22) and (23) is an optimal control problem. Its conditions of optimality can be easily derived by using the fact that the sign of the function $q$ coincides with the sign of the difference $T_{10} - \overline{T_1}$ and does not change over the interval [0, $\tau$]. After transformation which replaces the time with the temperature of the first flux, that is, d$t$ with d$T_1 = -[C_1(T_1)/q(T_1, T_2)]$d$t$, the problem takes the following form

$$\int_{T_{10}}^{\overline{T_1}} C_1(T_1)\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\mathrm{d}T_1 \to \min, \tag{24}$$

subject to the constraint

$$\int_{T_{10}}^{\overline{T_1}} \frac{C_1(T_1)}{q(T_1,T_2)}\mathrm{d}T_1 = \tau\,. \tag{25}$$

The condition of optimality for the problem (24), (25) has the following form

$$\left[\frac{q(T_1,T_2)}{T_2}\right]^2 \frac{\partial q}{\partial T_2} = M\,. \tag{26}$$

That is, the optimal temperature $T_2$ has to depend on $T_1$ in such a way that for any instance of time the left-hand side of the equation (26) is constant. The value of the constant $M$ is to be found after substitution of the dependence $T_2^*(T_1, M)$ from (26) into the equation (25).

From (26) it follows that for the linear heat exchange (6) in the minimal dissipation process the temperatures ratio $T_1/T_2$ must be constant. Let us note that in a counter-flux heat-exchanger the minimal dissipation process can be realized, that is, here it is possible to choose a ratio of the fluxes' input temperatures and rates such that for the heat exchange law (6) the heat exchange operates with the minimal dissipation (26) [6].

Let us generalise the above-described approach to the abstract thermodynamic process where there is a key flux $J$, which depends on intensive variables (temperatures, pressures, chemical potentials, etc) denoted as $U_1$ and $U_2$ for the 1st and 2nd contacting systems correspondingly. It is assumed that $U_1$ and $U_2$ are scalars that vary over time or over the length of the apparatus. The function $J(U_1, U_2)$ is such that

$$\left.\begin{aligned} &\mathrm{sign}J(U_1,U_2) = \mathrm{sign}(U_1 - U_2),\\ &J(U_1,U_2) = 0 \quad \text{for} \quad U_1 = U_2\,. \end{aligned}\right\} \tag{27}$$

The difference between the values of $U_1$ and $U_2$ generates driving forces $X(U_1, U_2)$, which obey the conditions (27). For example, the driving force in a heat exchange process is the difference $(1/T_2 - 1/T_1)$, and in mass transfer process the driving force is

$$X = \frac{1}{T}\left[\mu_1(C_1) - \mu_2(C_2)\right],$$

where $C_i$ is the concentration of the key component and $\mu_i$ is the chemical potential, which depends on this concentration. The dissipation here is

$$\bar{\sigma} = \frac{1}{\tau}\int_0^{\tau} J(U_1, U_2)X(U_1, U_2)\mathrm{d}t \to \min. \tag{28}$$

Because $J$ and $X$ obey the conditions (27), $\bar{\sigma} \geq 0$. Here the equality holds only if $U_1(t) = U_2(t)$.

The minimal dissipation process is defined as a process with the given average rate of flux

$$\frac{1}{\tau}\int_0^{\tau} J(U_1, U_2)\mathrm{d}t = \bar{J} \tag{29}$$

where $\bar{\sigma}$ is minimal. Here it is assumed that $U_2(t)$ is the control variable and $U_1(t)$ changes in accordance with the properties of the thermodynamic system as

$$\frac{dU_1}{dt} = C(U_1)J(U_1, U_2), \quad U_1(0) = U_{10}. \tag{30}$$

The right-hand side in this equation is sign definite.

Derivations similar to the ones used above yield the following optimality conditions for the problem (28) – (30)

$$\frac{J^2(U_1, U_2) \cdot \partial X / \partial U_2}{\partial J / \partial U_2} = \text{const.} \tag{31}$$

The value of the constant in (31) is to be found from (29).

The conditions of minimal dissipation in heat exchange (26) follow from (31). In particular if the ratio $\partial X/\partial U_2$ to $\partial J/\partial U_2$ is constant then the conditions of minimal dissipation require the dependence $U_2^*(U_1)$ such that the flux is constant.

The minimal dissipation problem can be also solved for vector fluxes, vector driving forces and vector variables $U_1$ and $U_2$. In the vicinity of equilibrium the fluxes and driving forces relate to each other via the Onsager equation

$$J = AX^{\mathrm{T}},$$

where $A$ is a positively definite matrix of phenomenological coefficients. It is easy to see that in this case the solution of the minimal dissipation process corresponds to constant driving forces. Note that in vector case it is possible that the averaged values of not all but only some of $J$ components are fixed.

Separation process are among the largest energy consumers. The dependence of the energy consumption for separation of one mole of a binary (two-component) mixture without losses into the environment, in an infinitely large apparatus and in infinitely long time (that is, in a separation process that is close to reversible) on the concentration $X$ of the first component is shown in Figure 3 with the solid line.

The calculations [5] give the characteristic dependence of minimal energy consumption in separation over finite time (which corresponds to the minimal dissipation process) that is shown in Figure 3 with the dashed line. Thus, for poor mixtures ($X \to 0$, $X \to 1$) the condition of the non-zero rate of separation leads to the jump of the lower bound on energy consumption. This is consistent with the fact that the energy consumption for uranium isotope separation exceeds the reversible estimate by a factor of hundreds of thousands [8].

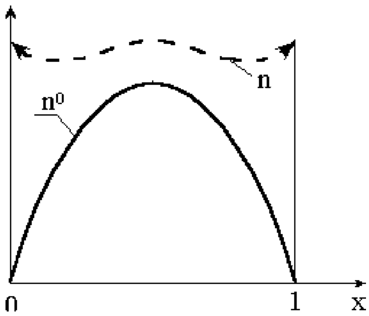


**Figure 3.** The characteristic dependencies of the reversible and irreversible energy consumption of separation on key component concentration.

## OPTIMAL PROCESSES IN MICROECONOMICS

Economic systems, where exchange of commodities and capital between consumers and producers takes place, are in many respects similar to the thermodynamic systems. As in thermodynamics, the system's variables can be divided into two categories: the extensive variables, which are proportional to the system's size, and intensive variables, that do not depend on the size of the system. The capital and stocks of commodities are extensive variables and the prices that describe how valuable the commodities are for the system (commodity estimates) are the intensive ones.

In thermodynamics one considers three classes of systems: systems with finite capacities, reservoirs and working bodies. In a system with finite capacity and constant size the intensive variables depend on its extensive ones. For example, temperature is determined by energy. In reservoirs the amount of energy is so high that their intensive variables can be considered constant (the heat capacity is infinite). And finally the intensive variables of the working bodies can be controlled, for example, by controlling their size. Similarly in economics one can define systems with finite capacities, with infinite capacities and intermediaries. For the finite capacity system the commodity estimate is determined by its current stock; for infinite capacity system this estimate is constant and finally an intermediary itself determines the price it is offering for buying and selling.

The analogy between reversible thermodynamics and economics was emphasised by Samuelson [9], Lihnerowicz [10], Rozonoer [11]. We will consider irreversible process in microeconomics [12, 13] and their optimization.

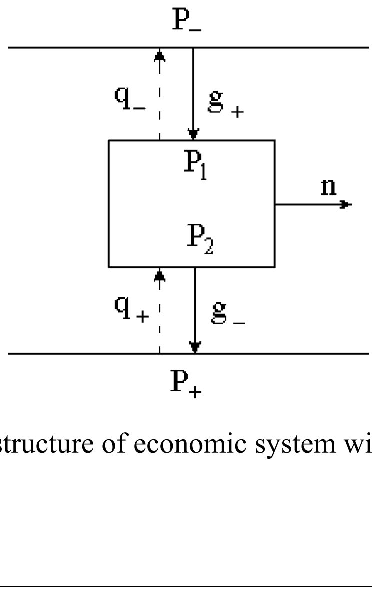


**Figure 4.** The structure of economic system with intermediary.

## LIMITING POSSIBILITIES OF AN INTERMEDIARY

We consider a system (Figure 4) that consists of two markets and an intermediary, which buys commodity on the first market and sells it on the second. The commodity estimates on these markets are $P_-$ and $P_+ > P_-$ correspondingly. $P_1$ and $P_2$ denote the prices of purchasing and selling that are offered by the intermediary. $q_-$, $q_+$, $g_+$ and $g_-$ denote the fluxes of capital and commodity. Subscript (+) corresponds to the fluxes that enter the intermediary and (–) to these that leave it. $n$ denotes the flux of the capital produced.

The fluxes $g_+$ and $g_-$ depend on the relative values of the commodity price and the commodity estimate such that

$$\left.\begin{aligned} \operatorname{sign}[g_+(P_1, P_-)] = \operatorname{sign}(P_1 - P_-), \\ \operatorname{sign}[g_-(P_+, P_2)] = \operatorname{sign}(P_+ - P_2), \end{aligned}\right\} \tag{32}$$

and the capital fluxes are

$$q_- = P_1 g_+, \quad q_+ = P_2 g_-. \tag{33}$$

Let us find the limiting possibilities of the intermediary, that is, the maximal amount of capital per unit of the initial investment and the maximal rate of profit (rate of flux $n$) that can be achieved in this system. The schema of the solution process here is similar to the one used to solve heat engine's maximal efficiency and maximal power problems.

The balances on the commodity and capital of the intermediary are

$$\left.\begin{aligned} g_+ - g_- = \frac{q_-}{P_1} - \frac{q_+}{P_2} = 0, \\ q_+ - q_- - n = 0. \end{aligned}\right\} \tag{34}$$

After elimination of $q_+$ we get the profit per unit of expenses

$$\eta = \frac{n}{q_-} = \frac{P_2}{P_1} - 1 . \tag{35}$$

$\eta$ attains its maximum $\eta^0$ at $P_2 = P_+$, $P_1 = P_-$, so

$$\eta^0 = \frac{P_+}{P_-} - 1 \tag{36}$$

However the fluxes of commodities and therefore the rate of profit $n$ here are infinitely small.

Let us find out the limiting value of the profit flux $n_{\max}$ for the linear dependencies

$$g_+ = \alpha_-(P_1 - P_-), \quad g_- = \alpha_+(P_+ - P_2). \tag{37}$$

The problem that determines $n_{\max}$ takes the following form

$$n = q_+ - q_- = \alpha_+ P_2(P_+ - P_2) - \alpha_- P_1(P_1 - P_-) \to \max_{P_1, P_2} . \tag{38}$$

subject to constraint

$$\alpha_-(P_1 - P_-) = \alpha_+(P_+ - P_2). \tag{39}$$

The solution of this problem leads to the following result

$$n_{\max} = \frac{\alpha_+ \alpha_-}{4(\alpha_+ + \alpha_-)}(P_+ - P_-)^2 . \tag{40}$$

$$P_1 = \frac{P\,\alpha \;\; + (P_+ + P\;)\alpha_+ /2}{\alpha_+ + \alpha}, \quad P_2 = \frac{P_+\alpha_+ + (P_+ + P\;)\alpha \;\; /2}{\alpha_+ + \alpha}$$

According to (35)

$$\eta = \frac{(P_+ - P\;)(\alpha_+ + \alpha_-)}{2P_-\alpha_- + (P_+ + P_-)\alpha_+} < \eta^0,$$

The characteristic dependence $n(q_-)$ is shown in Figure 5.

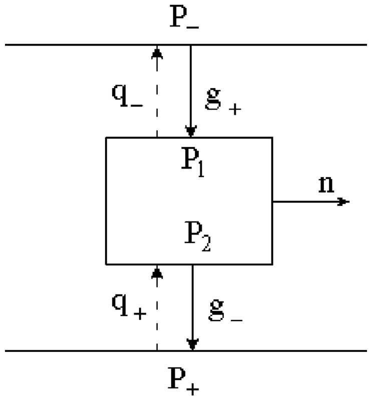


**Figure 5.** The dependence of the limiting profit on the expenses of the intermediary.

Let us introduce the notion of capital dissipation as the expenses of the intermediary caused by establishing the commodity flux $g$. Indeed, if the price that is paid by the intermediary for the commodity is $P_-$ then its expenses are $g_+ \cdot P_-$ and in reality the intermediary spends $g_+ \cdot P_1$ for buying and the difference

$$\sigma_1 = g_+(P_1, P_-)\,(P_1 - P_-).$$

represents the trading expenses during buying. Similarly

$$\sigma_2 = g_-(P_+, P_2)\,(P_+ - P_2).$$

describes the trading expenses in a selling process. Because the fluxes of commodity are the same $g_1 = g_2 = g$ the profit is

$$n = g(P_+ - P_-) - (\sigma_1 + \sigma_2) = g(P_+ - P_-) - \sigma. \qquad (41)$$

If $\alpha_+$ and $\alpha_-$ tend to infinity then the dependence of $n$ on $q_-$ tends to the dashed line in Figure 5. For finite $\alpha_+$ and $\alpha_-$ an increase in $q_-$ leads to an increase in dissipation $\sigma$.

## EQUILIBRIUM IN OPEN ECONOMIC SYSTEMS

Exchange fluxes emerge in a non-uniform economic system, which include subsystems with different commodity estimates,. If a non-uniform system is insulated then these fluxes lead it to an equilibrium, where the commodity estimate in all subsystems are the same. If commodity exchange between the system and the environment takes place then in a stationary regime this estimate differs from the estimate at equilibrium. Here the commodity is re-distributed between subsystems so that a new distribution is established. This new distribution is determined by the commodity stocks, the commodity estimates (determined by the stocks) and the commodity fluxes (which are in turn determined by these estimates).

In irreversible thermodynamics the well-known Prigogine theorem [14] states that *in an open thermodynamic system in a stationary state in the vicinity of equilibrium the entropy production is minimal*.

That is, the extensive variables (internal energy, amount of mass, etc) are re-distributed inside the system in such a fashion that the dissipation caused by the fluxes inside the system is minimal. The condition of being near equilibrium is essential because here the dependence of the fluxes on the driving forces can be linearized.

A similar statement is valid for an economic system, namely: *in an equilibrium in an open economic system, where the commodity fluxes linearly depend on the differences in their estimates, the stocks of commodities are distributed between subsystems is such fashion that the dissipation of capital $\sigma$ is minimal* [15].

Because any non-uniform system can be decomposed into elementary units, which contain sequentially and parallel connected subsystems, we will demonstrate the validity of this statement for such units, as shown in Figure 6.

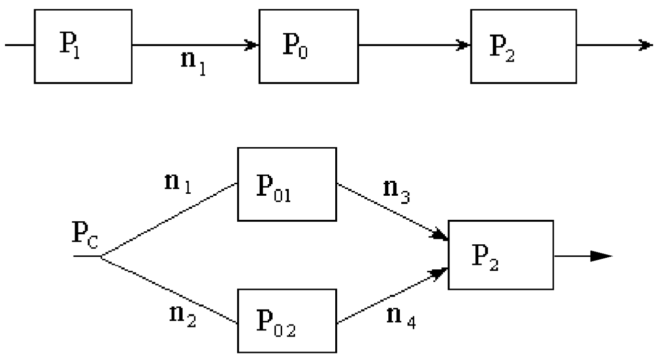


**Figure 6.** The simplest structures of open microeconomic systems.

For the sequential chain (Figure 6 (a)) the fluxes are

$$n_1 = \alpha_1(P_0 - P_1), \quad n_2 = \alpha_2(P_2 - P_0).$$

and the dissipation is

$$\sigma = \sigma_1 + \sigma_2 = \alpha_1(P_0 - P_1)^2 + \alpha_2(P_2 - P_0)^2 = \frac{n_1^2}{\alpha_1} + \frac{n_2^2}{\alpha_2}. \tag{42}$$

The conditions of $\sigma$ minimum with respect to $P_0$, which in turn is determined by the stock of commodity in the middle subsystem, lead to the equation

$$n_1(P_0, P_1) = n_2(P_2, P_0) = n.$$

Thus, the stationarity condition of the system and the condition of minimum of $\sigma$ coincide.

For the parallel connection (Figure 6 (b)) we get

$$n_1 = \alpha_1(P_{01} - P_c), \quad n_2 = \alpha_2(P_{02} - P_c),$$

$$n_3 = \alpha_3(P_2 - P_{01}), \quad n_4 = \alpha_4(P_2 - P_{02}).$$

Similarly to (49) the dissipation is $\sigma = \sum_{i=1}^{4} n_i^2/\alpha_i$ . The conditions of its minimum on $n_1$ and $n_2$ for $n_1 = n_3$, $n_2 = n_4$, $n_1 + n_2 = n$ lead to the equation

$$\frac{n_1}{n_2} = \frac{(\alpha_2 + \alpha_4)\alpha_1\alpha_3}{\alpha_2\alpha_4(\alpha_1 + \alpha_3)}. \tag{43}$$

On the other hand, from the stationarity conditions $n_1 = n_3$ and $n_2 = n_4$ it follows

$$P_{01} = \frac{\alpha_1 C + \alpha_3 P_2}{\alpha_1 + \alpha_3}, \quad P_{02} = \frac{\alpha_2 C + \alpha_3 P_2}{\alpha_2 + \alpha_4},$$

and the fluxes are

$$n_1 = \frac{\alpha_1\alpha_3}{\alpha_1 + \alpha_3}(P_2 - C), \quad n_2 = \frac{\alpha_2\alpha_4}{\alpha_2 + \alpha_4}(P_2 - C).$$

Their ratio coincides with the equation (43), which is obtained from the condition of minimal dissipation.

## CONCLUSION

The optimal processes in thermodynamic systems (from the viewpoint of energy consumption) correspond to the minimum entropy production. The thermodynamic quality of the processes with given productivity (rate) can be evaluated not by the value of $\sigma$ but by the difference between the actual and the minimal-feasible entropy production.

The irreversible processes in microeconomics are in many respects similar to the thermodynamic processes. The role of entropy production here is played by the capital dissipation, whose minimum corresponds to the stationary state of an open economic system.

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# OPTIMALNI PROCESI U IREVERZIBILNOJ TERMODINAMICI I MIKROEKONOMICI

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## SAŽETAK

U ovom radu razmotrena je opća metodologija koja omogućuje proširenje Carnotove učinkovitosti u klasičnoj termodinamici za beskonačno spore procese na termodinamičke procese konačnog trajanja. Defnirana je klasa procesa minimalen disipacije i pokazano da ona predstavlja poopćenje reverzibilnih procesa i određuje krajnje mogućnosti sustava u kojima se odvijaju procesi konačnog trajanja. Opisana metodologija je primijenjena na mikroekonomske sustave izmjene što dovodi do novih procjena graničnih učinkovitosti takvih sustava.

## KLJUČNE RIJEČI

termodinamika u konačnom vremenu, procesi minimalne disipacije, procesi optimalne izmjene u ekonomiji

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# LIMITING POSSIBILITIES OF RESOURCE EXCHANGE PROCESS IN COMPLEX OPEN MICROECONOMIC SYSTEM

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## SUMMARY

A problem on extreme performance of microeconomic system with several firms is considered. Each firm aspires to increase the profit. Flows of the good between the firms determine the structure of the system. So, sequential structure corresponds to intermediaries (dealers) operating in the market, parallel structure corresponds to competition in the market. The system at issue is an open economic system because of presence of external flows from the sources described by a distribution of the value of the good. The problem is solved for the basic structures: maximal profit and corresponding prices are found for each firm.

## KEY WORDS

open microeconomic systems, optimal prices, series and parallel structures

## CLASSIFICATION

ACM: Categories and subject descriptors: J.4 [Computer Applications]; Social and behavioral sciences – Sociology,

JEL: D4

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## INTRODUCTION

Research of behaviour of the economic agents buying and selling the goods in the market is one of primary goals of microeconomics. Analogies between exchange processes in economic systems and heat- and mass exchange processes in thermodynamic systems are promising methods of such research [1]. Irreversible microeconomics [2 - 4], using analogies to finite-time thermodynamics [5], allows one to solve problems of optimal control of the prices in irreversible processes of resources exchange. Some open microeconomic systems either without a firm or containing the only firm are examined in [3, 6]. A firm means a subsystem managing the prices and taking money - a basic resource - from a system. The analysis of firm of complex structure is given in [7].

Further the open microeconomic systems consisting of several firms are considered. Such systems take place in the competitive markets, at presence of intermediaries (dealers), at economic independence of divisions of the enterprise and in other cases.

## STATEMENT OF A PROBLEM

Let us consider the open microeconomic system consisting of $n$ firms-intermediaries, buying and selling a scalar resource. If the system represents the firm buying and selling a resource to the environment then the system is a homogeneous system. In the opposite case, when the system consists of several firms which sell a resource each other and to the environment then the system is a complex system. Each of firms in complex system may operate the prices of sale of a resource and aspires to receive the maximal profit. Let us consider a stationary mode at which streams in system do not change in time. For this mode we shall determine intensity of resources flows, the prices of sale of the goods for each of firms and compare the total profit taken from the system, with the profit of a homogeneous firm.

The solution of this problem will be carried out for the linear functions of a supply and demand describing the resources exchange between the system and its environment (markets).

## HOMOGENEOUS FIRM

First we describe a problem on maximal profit determination for a homogeneous firm exchanging a scalar resource with an environment, representing the distributed market with known density of distribution of value $v$ (marginal rate of substitution between the goods and money) $f(v)$ (Fig. 1). As the firm in a stationary mode can not accumulate a stock of the goods, intensities of input and output flows of the goods should be equal. Let us denote this flow intensity as $g$. Then the profit of firm is

$$\varpi = (p_1 - p_2)\cdot g. \tag{1}$$

Control variable is the price of sale $p_1$. The price $p_2(p_1)$ is determined from equality of input and output flows of the goods. The flow $g$ depends on the chosen price $p_1$ too.

### FORMAL STATEMENT OF A PROBLEM

The problem at issue *to determine such price of sale of the goods that the profit of firm should be maximal*:

$$\varpi = [p_1 - p_2(p_1)]\cdot g(p_1) \to \max_{p_1}. \tag{2}$$

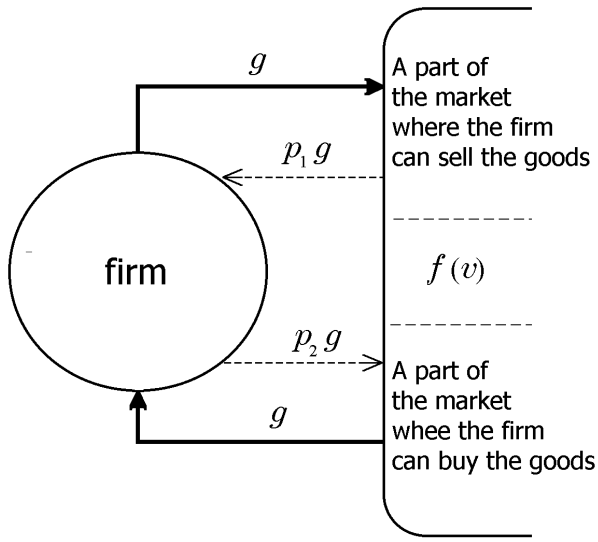


**Figure 1.** A homogeneous firm working in the distributed market.

## ALGORITHM OF THE SOLUTION OF THE PROBLEM

1. To determine dependencies $p_2(p_1)$, $g(p_1)$ from the condition of equality of input and output flows intensities.
2. To substitute these dependences in (1) and to solve the obtained problem. As a result of the solution we find values $p^*$, $p_2^* = p_2(p_1)$, $g^* = g(p_1)$ and value of the maximal profit $\varpi^*$.

Let intensity of purchases of the goods be determined by firm as following

$$g = \beta \int_{-\infty}^{p_2} (p_2 - v) f(v)\mathrm{d}v = \beta \left[ p_1 \int_{-\infty}^{p_2} f(v)\mathrm{d}v - \int_{-\infty}^{p_2} v f(v)\mathrm{d}v \right], \tag{3}$$

where $\beta$ is a constant factor. Value $\int_{\infty}^{p_2} f(v)\mathrm{d}v$ represents a part of the market $x(p_2)$ carrying out sale of the goods, and

$$m_v(p_2) = \int_{-\infty}^{p_2} v f(v)\mathrm{d}v \Big/ \int_{-\infty}^{p_2} f(v)\mathrm{d}v$$

is the expectation of the goods value at this part of the market. Therefore (3) can be rewritten as

$$g = \beta \breve{x}(p_2)[p_2 - \breve{m}_v(p_1)]. \tag{4}$$

Similarly,

$$g = \alpha \hat{x}(p_1)[\hat{m}_v(p_1) - p_1], \tag{5}$$

where $\alpha$ is a constant factor, $\hat{x}(p_1)$ is a part of the market carrying out purchase of the goods, $\hat{m}(p_1)$ is the expectation of the goods value at the part $\hat{x}$ of the market. Equating the right parts (4) and (5) and expressing $p_2$ we find dependence $p_2(p_1)$.

## EXAMPLE 1

Let value $v$ has the uniform distribution in segment $[0, p_0]$. Then

$$\hat{x}(p_2) = \frac{p_2}{p_0}, \qquad \hat{m}_v(p_2) = \frac{p_2}{2},$$
$$\hat{x}(p_1) = \frac{p_0 - p_1}{p_0}, \quad \hat{m}_v(p_1) = \frac{p_0 + p_1}{2}.$$

Intensity of the goods flow is equal to

$$g = \beta \frac{p_2}{p_0}\left( p_2 - \frac{p_2}{2} \right) = \beta \frac{p_2^2}{2p_0}. \tag{6}$$

or

$$g = \alpha \frac{p_0 - p_1}{p_0}\left( \frac{p_0 + p_1}{2} - p_1 \right) = \alpha \frac{(p_0 - p_1)^2}{2p_0}. \tag{7}$$

whence we express $p_2$:

$$p_2(p_1) = \sqrt{\frac{\alpha}{\beta}} \cdot (p_0 - p_1). \tag{8}$$

With the account of (7) and (8) we rewrite the problem (2) as following

$$\varpi(p_1) = \left[ p_1\left( 1 + \sqrt{\frac{\alpha}{\beta}} \right) - p_0\sqrt{\frac{\alpha}{\beta}} \right] \alpha \frac{(p_0 - p_1)^2}{2p_0} \to \max_{p_1}. \tag{9}$$

The solution of this problem is the control price

$$p_1^* = \frac{p_0(3 + 3\sqrt{\alpha/\beta}) - p_0\xi(\alpha,\beta)}{3\left(1 + \sqrt{\alpha/\beta}\right)}. \tag{10}$$

and corresponding to this price values

$$p_2^* = \sqrt{\frac{\alpha}{\beta}} \frac{p_0[1 + \xi(\alpha,\beta)]}{3\left(1 + \sqrt{\alpha/\beta}\right)}, \quad g^* = \frac{\alpha}{18} \frac{p_0[1 + \xi(\alpha,\beta)]}{\left(1 + \sqrt{\alpha/\beta}\right)^2},$$
$$\varpi^* = \frac{\alpha\beta}{54} \frac{p_0^2}{\left(\sqrt{\alpha} + \sqrt{\beta}\right)^2} [2 - \xi(\alpha,\beta)] \cdot [1 + \xi(\alpha,\beta)]^2, \tag{11}$$

where

$$\xi(\alpha,\beta) = \sqrt{1 + 6\sqrt{\alpha/\beta} - 6(\alpha/\beta)\sqrt{\alpha/\beta}}.$$

So, at $\alpha = \beta[\xi(\alpha, \beta) = 1]$ optimal prices are $p_1^* = 2p_0/3$, $p_2^* = p_0/3$, the flow intensity corresponding to these prices is $g^* = \alpha p_0/18$, and maximal profit of the firm is $\varpi^* = \alpha p_0^2/54$.

## EXAMPLE 2

Let the spectrum of distribution of the value $v$ be set $\{\breve{v}, \hat{v}\}$, and supply and demand functions at $p_1, p_2 \in$ \in $\{\breve{v}, \hat{v}\}$ are given in a linear form

$$g = \beta(p_2 - \breve{v}), \tag{12}$$

$$g = \alpha(\hat{v} - p_1). \tag{13}$$

Equating (12) and (13), we receive dependence $p_2(p_1)$:

$$p_2 = \frac{\alpha}{\beta}(\hat{v} - p_1) + \breve{v}. \tag{14}$$

Accounting (13) and (14) we write down problem (2) as

$$\varpi(p_1) = \left[ p_1 - \frac{\alpha}{\beta}(\hat{v} - p_1) + \breve{v} \right] \alpha(\hat{v} - p_1) \to \max_{p_1}$$

which solution looks like

$$p_1^* = \frac{(1 + 2\alpha/\beta)\hat{v} + \breve{v}}{2(1 + \alpha/\beta)}. \tag{15}$$

Values $p_2^*$, $g^*$ and $\varpi^*$ corresponding to the optimal solution are:

$$p_2^* = \frac{(1 + 2\beta/\alpha)\breve{v} + \hat{v}}{2(1 + \beta/\alpha)}, \quad g^* = \frac{\alpha(\hat{v} - \breve{v})}{2(1 + \alpha/\beta)}, \quad \varpi^* = \frac{\alpha\beta}{4(\alpha + \beta)}(\hat{v} - \breve{v})^2. \tag{16}$$

At $\alpha = \beta$

$$p_1^* = \frac{3}{4}\hat{v} + \frac{1}{4}\breve{v}, \quad p_2^* = \frac{1}{4}\hat{v} + \frac{3}{4}\breve{v}, \quad g^* = \frac{\alpha}{4}(\hat{v} - \breve{v}), \quad \varpi^* = \frac{\alpha}{8}(\hat{v} - \breve{v})^2,$$

that coincides with the solution received in [8].

If the spectrum of distribution of values of the goods can be divided into two subsets $V_1$, $V_2$, such that $p_1 < \min V_1$, $p_2 > \max V_2$, the solution of problem (2) for a system like (15), (16) at

$$\breve{v} = M[v \mid v \in V_2], \quad \hat{v} = M[v \mid v \in V_1].$$

## SERIES STRUCTURE

Let us consider the problem on determination of limiting possibilities of resource exchange process in a complex (non-homogeneous) economic system. The solution of the problem depends on the structure of the system. We consider two simple structures, which are the basic structures for any complex system. These are series and parallel structures.

First, let us consider series structure. The elementary case of series structure is shown in Fig. 2.

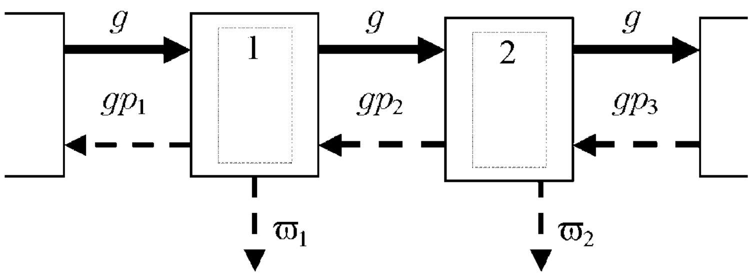


**Figure 2.** Consecutive structure of complex microeconomic system.

### FORMAL STATEMENT OF THE PROBLEM

Each of firms solves a problem on determination of the sales price to maximize its profit:

$$\varpi_1 = g(p_3 - p_1) \to \max_{p_2}, \tag{17}$$

$$\varpi_2 = g(p_3 - p_2) \to \max_{p_3, g}. \tag{18}$$

Restrictions imposed on the solution set are supply and demand functions

$$g = f_1(p_3), \tag{19}$$

$$g = f_2(p_1). \tag{20}$$

## ALGORITHM OF THE SOLUTION OF THE PROBLEM

1. To fix value $p_2$. Solving problem (18) and (19) we receive dependences $p_3(p_2)$, $g(p_2)$, $\varpi_2(p_2)$.
2. To solve problem (17) and (20) accounting the found dependence $g(p_2)$. As a result of the solution we find the optimum values $p_2^*$, $g^*$, $\varpi_1^*$.
3. To substitute values $p_2^*$, $g^*$ in the dependences received on a first step of algorithm. Doing so we find $p_3^*$ and $\varpi_2^*$.

## EXAMPLE 3

As in previous example we set supply and demand functions in a linear form (12), (13):

$$g = \alpha(\hat{v} - p_3), \tag{21}$$

$$g = \alpha(p_1 - \breve{v}). \tag{22}$$

Then problem (18) has the form:

$$\varpi_2 = \alpha(\hat{v} - p_3)(p_3 - p_2) \to \max_{p_3}.$$

Its solution $p_3^* = (\hat{v} + p_2)/2$, and the goods flow corresponding for this solution is $g(p_2) = (\alpha/2)(\hat{v} - p_2)$. Expression of price $p_1$ through the received dependence $g(p_2)$ and substitution $g(p_2)$ and $p_1(p_2)$ leads to the following form of problem (17):

$$\varpi_1 = \frac{\alpha}{2}(\hat{v} - p_2)\left[p_2 - \frac{\alpha}{2\beta}(\hat{v} - p_2) - \breve{v}\right] \to \max_{p_2}.$$

Solving this problem we find $p_2^*$:

$$p_2^* = \frac{(1 + \alpha/\beta)\hat{v} + \breve{v}}{2 + \alpha/\beta}, \tag{23}$$

whence

$$g^* = \frac{\alpha\beta}{2(2\beta + \alpha)}(\hat{v} - \breve{v}), \quad p_1^* = \frac{\left(4 + \frac{\alpha}{\beta}\right)\hat{v} + \frac{\alpha}{\beta}\breve{v}}{2\left(2 + \frac{\alpha}{\beta}\right)}, \quad \varpi_1^* = \frac{\alpha\beta}{4(2\beta + \alpha)}(\hat{v} - \breve{v})^2. \tag{24}$$

Having substituted (24) in the received dependence $p_3^*(p_2)$, we find

$$p_3^* = \frac{\left(3 + 2\frac{\alpha}{\beta}\right)\hat{v} + \breve{v}}{2\left(2 + \frac{\alpha}{\beta}\right)}, \quad \varpi_2^* = \frac{\alpha\beta^2}{4(2\beta + \alpha)^2}(\hat{v} - \breve{v})^2,$$

and the total profit of the firms

$$\varpi = \varpi_1^* + \varpi_2^* = \frac{3\alpha\beta^2 + \alpha^2\beta}{4(2\beta + \alpha)^2}(\hat{v} - \breve{v})^2. \tag{25}$$

Value $\varpi^*$ is less than profit of one firm working in the same markets calculated according to (16). Dependences of the profit extracted from the system with respect of number of the firms and ratio $\alpha/\beta$ are shown in Fig. 3.

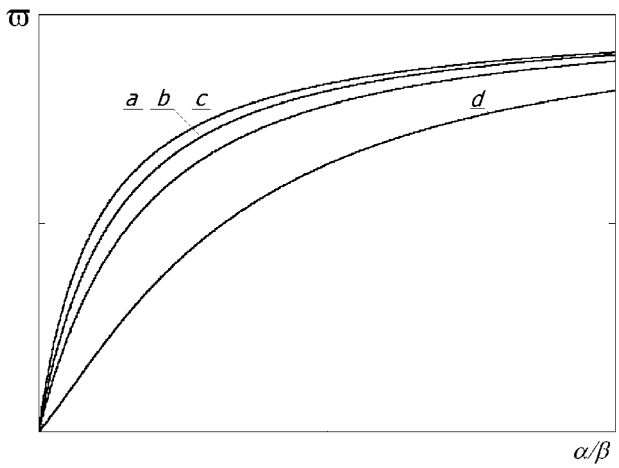


**Figure 3.** Dependence of the total profit of firms in system with series structure: a) homogeneous system, b) complex system with two, c) three, d) seven firms.

Note that there exists asymmetry of series structure: the first firm can choose the prices of sale of the resource, and receives more money than the second firm determining intensity of the resource exchange.

## PARALLEL STRUCTURE

Let us consider the system of parallel structure consisting of two firms, exchanging a scalar resource with the markets (Fig. 4). Each of firms aspires to maximize the profit by controlling of the prices of output resources flows.

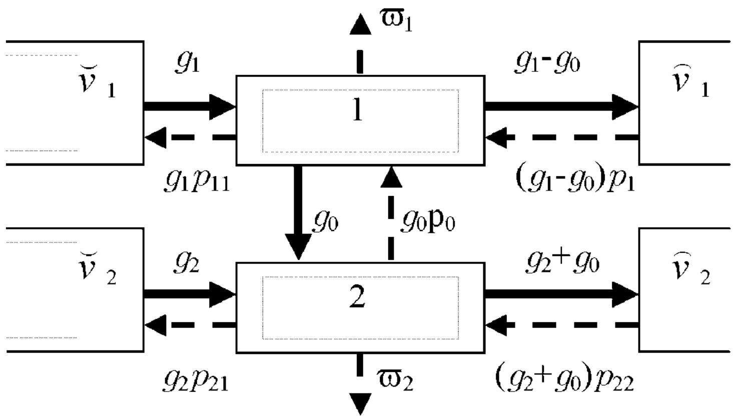


**Figure 4.** Complex microeconomic system with parallel structure.

### FORMAL STATEMENT OF A PROBLEM

The problem at issue is *to determine the prices of the goods sale providing the maximal profit of each of the firms working in the market*:

$$\varpi_1 = (g_1 - g_0)p_{12} + g_0 p_0 - g_1 p_{11} \to \max_{p_0, p_{12}}, \tag{26}$$

$$\varpi_2 = (g_2 + g_0)p_{22} - g_0 p_0 - g_2 p_{21} \to \max_{g_0, p_{22}}, \tag{27}$$

subject to supply

$$g_1 = g_1(\hat{v}_1, p_{11}), \tag{28}$$

$$g_2 = g_2(\breve{v}_1, p_{21}), \tag{29}$$

and demand for resources

$$g_1 - g_0 = f_1(\hat{v}_1, p_{12}), \tag{30}$$

$$g_2 + g_0 = f_2(\hat{v}_2, p_{22}), \tag{31}$$

where $\breve{v}_i$, $\hat{v}_i$ ($i \in \{1, 2\}$) are values of resources in the markets.

## ALGORITHM OF THE SOLUTION

1. Assuming the price $p_0$ to be fixed to solve problem (27), (29) and (31). As a result of the solution we receive dependences $p_{21}^*(p_0)$, $p_{22}^*(p_0)$, $g_0(p_0)$.
2. Using the received dependence $g_0(p_0)$ to solve problem (26), (28) and (30). We find optimum price strategy of the first firm $p_{01}^*$, $p_{11}^*$, $p_{12}^*$, and its maximal profit.
3. To substitute value $p_0^*$ in dependences found on the first step of the algorithm. We find price strategy of the second firm and its maximal profit.

The received solution can be compared to limiting opportunities of one firm working in the distributed markets of raw material and finished commodity with sets of possible values $\{\breve{v}_1, \breve{v}_2\}$ and $\{\hat{v}_1, \hat{v}_2\}$ accordingly.

## EXAMPLE 4

Let curves of a supply and demand be given in a linear form:

$$g_1 = \beta(p_{11} - \breve{v}_1); \quad g_1 - g_0 = \alpha(\hat{v}_1 - p_{12});$$
$$g_2 = \beta(p_{21} - \breve{v}_2); \quad g_2 + g_0 = \alpha(\hat{v}_2 - p_{22}).$$

At the fixed value $p_0$ we solve a problem

$$\varpi_2 = (g_2 + g_0)p_{22} - g_0 p_0 - g_2 p_{21} \to \max_{\substack{g_0, g_2, \\ p_{21}, p_{22}}} \left| \begin{array}{l} g_2 - \beta(p_{21} - \breve{v}_2) = 0; \\ g_2 + g_0 - \alpha(\hat{v}_2 - p_{22}) = 0. \end{array} \right. \tag{32}$$

We receive:

$$\begin{array}{ll} p_{21}(p_0) = \dfrac{\breve{v}_2 + p_0}{2}; & p_{22}(p_0) = \dfrac{\hat{v}_2 + p_0}{2}; \\ g_2 = \beta \dfrac{p_0 - \breve{v}_2}{2}; & g_0 = \dfrac{\beta\breve{v}_2 + \alpha\hat{v}_2}{2} - \dfrac{p_0(\alpha + \beta)}{2}. \end{array} \tag{33}$$

It is convenient to note the weighed average values of a resource in the markets as

$$v_{01} = \frac{\alpha\hat{v}_1 + b\breve{v}_1}{\alpha + \beta}, \quad v_{02} = \frac{\alpha\hat{v}_2 + b\breve{v}_2}{\alpha + \beta}.$$

In this notation the problem has the form

$$\varpi_1 = (g_1 - g_0)p_{12} + g_0 p_0 - g_1 p_{11} \to \max_{\substack{g_0, g_2, \\ p_0, p_{11}, p_{12}}} \left| \begin{array}{l} g_0 - \dfrac{\alpha + \beta}{2}(v_{02} - p_0) = 0; \\ g_1 - \beta(p_{11} - \breve{v}_1) = 0; \\ g_1 - g_0 - \alpha(\hat{v}_{12} - p_{12}) = 0, \end{array} \right. \tag{34}$$

and its solution is

$$p_0^* = \frac{1}{3} v_{01} + \frac{2}{3} v_{02}, \tag{35}$$

$$p_{11}^{*} = \frac{1}{3}v_{01} + \frac{1}{6}v_{02} + \frac{1}{2}\breve{v}_1; \quad p_{12}^{*} = \frac{1}{3}v_{01} + \frac{1}{6}v_{02} + \frac{1}{2}\hat{v}_1;$$

$$g_0^{*} = \frac{\alpha+\beta}{6}(v_{02} - v_{01}); \qquad g_1^{*} = \beta\left(\frac{v_{01}}{6} + \frac{v_{02}}{3} - \frac{\breve{v}_1}{2}\right).$$

Substituting the found value $p_0^*$ (35) in (33) we find the optimal prices and flows intensities for the second firm:

$$p_{21}^{*} = \frac{v_{01}}{6} + \frac{v_{02}}{3} + \frac{\breve{v}_2}{2}, \quad p_{22}^{*} = \frac{v_{01}}{6} + \frac{v_{02}}{3} + \frac{\hat{v}_2}{2}, \qquad g_2^{*} = \beta\left(\frac{v_{01}}{6} + \frac{v_{02}}{3} - \frac{\breve{v}_1}{2}\right).$$

Finally, substituting these optimum values in expressions for the profit (32) and (34), we find total value of the profit extracted from the system:

$$\begin{aligned}\varpi^{*} &= g_2^{*}(p_{22}^{*} - p_{21}^{*}) + g_0^{*}(p_{22}^{*} - p_{12}^{*}) + g_1^{*}(p_{12}^{*} - p_{11}^{*}) = \\ &\beta\left(\frac{v_{01}}{6} + \frac{v_{02}}{3} - \frac{\breve{v}_1}{2}\right)\frac{\hat{v}_2 - \breve{v}_2}{2} + \beta\left(\frac{v_{01}}{3} + \frac{v_{02}}{6} - \frac{\breve{v}_1}{2}\right)\frac{\hat{v}_1 - \breve{v}_1}{2} + \\ &+ \frac{\alpha+\beta}{6}(v_{02} - v_{01})\left(\frac{v_{02} - v_{01}}{6} + \frac{\hat{v}_2 - \hat{v}_1}{2}\right)\end{aligned} \tag{36}$$

Comparison of values of the profit calculated by (36) and the profit of the appropriate homogeneous system at $\alpha = \beta$ for various values of differences $\Delta v_1 = \hat{v}_1 - \breve{v}_1$ and $\Delta v_2 = \hat{v}_2 - \breve{v}_2$ is shown in Fig. 5.

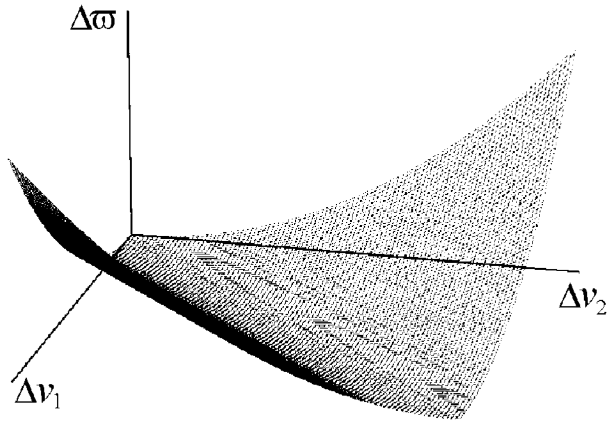


**Figure 5.** Increment of the profit $\Delta\varpi$ in system of parallel structure due to the prices diversification as a dependency on differences of the goods values in the markets.

## CONCLUSIONS

The elementary structures of complex systems can be used for modelling the complex microeconomic systems consisting of series and parallel structures.

It is necessary to note, that series connections between firms result in reduction of the profit although parallel structure may result in increase of the total profit due to the prices diversification.

## ACKNOWLEDGMENTS

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# KRAJNJE MOGUĆNOSTI IZMJENE RESURSA U SLOŽENOM, OTVORENOM, MIKROEKONOMSKOM SUSTAVU

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## SAŽETAK

Razmatran je problem krajnjih mogućnosti mikroekonomskog sustava s nekoliko tvrtki. Svaka tvrtka teži povećanju dobiti. Tokovi dobara između tvrtki određuju strukturu sustava. Stoga sekvencijalna struktura odgovara posrednicima (engl. *dealers*) koji djeluju na tržištu, a paralelna struktura tržišnom natjecanju. Sustav u problemu je otvoreni, ekonomski sustav zbog eksternih tokova iz izvora opisanih raspodjelom vrijednosti dobra. Problem je riješen za osnovne strukture i za svaku tvrtku određene su najveća dobit i odgovarajuće cijene.

## KLJUČNE RIJEČI

otvoreni mikroekonomski sustavi, optimalne cijene, serijske i paralelne strukture

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# SOCIAL EQUIVALENT OF FREE ENERGY

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## SUMMARY

Characterisation of unbounded resources of a social system within the sociological interpretation has resulted in a large number of different notions, which are relevant in different situations. From the view point of statistical mechanics, these notions resemble free energy. In this paper the concept of social free energy is introduced and first steps toward its development presented. The social free energy is a function equal to physical free energy appropriately determined for the social system, with intrinsically sociological interpretation as a measure of social action obtainable in a given social system without changes in its structure. Its construction is a consequence of response of a social system to recognised parts of environment dynamics. It is argued that development of a social system response resembles exciting the normal modes of a general, physical system.

## KEY WORDS

social systems, social free energy, adaptation, organisation, dispersion relation

## CLASSIFICATION

ACM: Categories and subject descriptors: J.4 [Computer Applications]; Social and behavioral sciences – Sociology

JEL: A13, O30

PACS: 89.65.-s, 89.75.Fb

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## INTRODUCTION

Social systems are complex systems. Prevalently, they have been verbally described. Deeper understanding of their dynamics benefits from their quantitatively based description. Recently, in a number of independently conducted researches, the role of the isostructural social action was emphasised, its interpretation tested and evolution simulated [1 – 8]. Social action is collection of all resources of a social system which are not bound to regular dynamics. It measures parts of material and immaterial, individual and collective collections of elements the corresponding types of which are observed in social dynamics. Resources falling within social action, therefore, are included in dynamics irregularly, for neutralisation of unwanted environment influence, i.e. for improving adaptation of a system in a stochastic environment. Environment is stochastic, otherwise unspecified, thus includes, e.g. other social systems. Ideally, neutralisation is performed without significant changes in social system structure, thus corresponding social action is termed isostructural social action. Following recently argued claim, it will be referred to as a social free energy because of its resemblance of physical free energy [7, 8].

The importance of social free energy is that it is the quantity which individuals and groups unwittingly evaluate in order to use it as a basis for interpretation of past, present, or predicted future social system states.

Formulated parts of concept of social free energy are given elsewhere. They include working out of some aspects of social free energy, its meaning in different situations and formulation of indicator about the reached level of social system adaptation. Up to now, analysis implied on the one hand given social system structure and on the other hand fixed understanding of environment dynamics. The explicit taking into account of their time dependency adds to understanding of the intrinsic dynamics of social free energy, e.g., its formation and redistribution. The corresponding inclusion is by no means straightforward, as the full time dynamics of these, mutually highly related processes extremely complex and presently intractable.

In this paper the interplay between the change in understanding of environment dynamics and in social system structure is analysed. A general environment influence is assumed, and is followed with the discussion of its consequences bringing about better adaptation of a corresponding social system. Generically, consequences include redistribution of resources from social free energy into bounded part of resources. That preliminary analysis of redistribution process reveals several characteristics of bounded resources: (i) they are structured, (ii) the possibility of their structuring depends primary on characteristics of the social system, while (iii) their quantity depends primary on interpretation of environment. In particular, and connected with point (i), the structuring of bounded resources is analysed here.

The outline of the paper is as follows. In the second section social free energy and related quantities are described in more detail. In the third section the observable, yet infinitesimal change in environment influence is assumed and its average consequences described. It is followed in the fourth section with more abstracted description of bounding of part of social free energy. Discussion of other, presently unrelated yet manifestly similar collective forms exploiting social free energy is contained in the fifth section, while conclusions and lines of future development are given in the sixth section.

## SOCIALLY INTERPRETED PHYSICAL QUANTITIES

Among physical quantities, the thermodynamic ones are particularly appealing for use in social system dynamics description aiming to reach quantitative level. The thermodynamics is about aggregated description of systems, originally physical. Considered in a broader sense, it effectively optimises simplicity of description (as the usual number of quantities introduced is relatively small) and extent to which it describes states of systems close to equilibrium. Thus thermodynamics collects system indicators, representations of an intense reduction of information existing within the system. These properties have been recognised by several authors, as seen in their applications of thermodynamic quantities onto human and other biological systems description.

In particular, social free energy was recognised as profit [1], common benefit [2], availability [3], free value of canonical portfolio [4], balanced average cost [5], or general quantity utilized in description of economic processes [6], or as a general quantity describing overall system-environment interaction [7, 8]. While seemingly different, it was argued that these notions refer to the same, referent quantity on which the interpretation of different system states is based. Other thermodynamic quantities, e.g. entropy, temperature [9] and extropy [10] were also applied in human systems. Temperature is prevalently interpreted as a measure of manifest dynamics. Extropy is found useful in describing complex systems as it measures deviation from arbitrarily chosen referent state. By that, one overcomes the problem of linking the current state with the equilibrium state, which itself is rather problematic for characterisation.

## ENVIRONMENTALLY INDUCED PROCESSES

Further in the text the following scheme of system-environment interaction is assumed: (i) some element of environment dynamics occurs constantly, but not necessarily regularly, (ii) that element influences social system dynamics, (iii) both the element and its influence are recognised by the social system, (iv) intra-system processes are started aiming at better adapting the system to environment. The listed sequence occurs constantly, simultaneously for different elements of environment dynamics. The short-term and long-term processes are qualitatively different.

Let us use two examples to illustrate the sequence listed: firemen service and agriculture. Firemen service does not exist in less structured societies. It is a specific structure realised as a consequence of environment influence (fire). For organisations above some level of development, firemen service becomes prerequisite of further persistence and development of the system. Firemen service is not tended to contradict the otherwise determined dynamics of the system, but to enable its further dynamics. The level of development of fully developed firemen service is aligned with the level of development of other services, as they all share same technological, legislative and other bases. It is a fact that fire as an environmental influence is possible constantly, what is prolonged onto the duration of the firemen service as a collective form.

In case of agriculture, the same two elements are seen; environment influence and system response. Influence is realised as existence of a finite quantity of bread grains, fruits and vegetables the humans could use for living. The response is realised as food-production which follows characteristic dynamics of purposefully prepared plants. Improvement in agriculture includes structuring of legislative, educational, scientific and other types of collectives contributing in turn to stability of reached level of understanding along with its further development.

Several processes are covered within the notion of response to environment influence. As a rule they include transfer of resources which were bounded within the system, and which becomes linked to a particular structure, itself developed as part of the response. Newly formed structure in general does not influence intensity of dynamics of the rest of dynamics, but changes the set of roles in the system value set.

A recognition of an element of environment dynamics means that the value set of corresponding social system is broadened with interpretation of that element. It figures as elementary environment excitation, the term described in detail elsewhere.

The response of the system on environment influence is alignment with the fact that a part of environment complexity is recognised, and with the tendency to optimise consequences thereby caused. Response is individual and collective. Further in the text the emphasis is put on the collective response. There are several attributes of collective response: duration, extent and role. Duration is expressed through characteristic time unit equal to value of time interval between properly defined start and end of the response. Extent is characteristic distance of space region in which the response is significant. Finally, role is expressed in value set underlying total dynamics of social system, thus its response included. Value is a settled measure of response to both the environment dynamics and the human dynamics.

The environment dynamics then enables one to understand better the intrinsic character of social systems – the structuring during response means realisation of previously potential mode of dynamics; structuring is connected with transfer of resources. Such a transfer was possible before it actually occurred within the response. However, without external influence there was no need for corresponding resource transfer and generally there was no spontaneous structuring.

Once formed, each structure is involved in complex dynamics, e.g., in structure-structure dynamics. Overall, that dynamics determines in turn the previously stated characteristics of the structure, which generally significantly differs and varies. However, it is argued further in the text that the structures share universal framework, combining their duration, extent and role.

## DYNAMICS OF SOCIAL FREE ENERGY

Structuring which accompanies the system response generally includes, as illustrated in the previous section, resource transfer from social free energy into regular dynamics, as covered by social temperature. The transfer is naturally accompanied with the human actions. The diversity of these actions and overall resource transfers is divided into four categories depending on whether the human response is collective or individual, and whether it is short-term or long-term response. The long-term response usually in interpreted as restructuring of the system, while the short-term response is isostructural. Out of the four combinations of responses in this article the short-term collective response is analysed in more detail.

Application of the social free energy along with the social entropy onto description of social systems brings about intuitive macro-level results. In particular, the analysis of two hypothetical systems which are extremal regarding their adaptivity and level of living illustrates that point. Let in the system A the social free energy attains its minimal value and that all resource augmentation is transformed into enlargening of the social entropy. The corresponding development is characterised with the maximal number of different behaviours. However, at the same time the stability is minimal. The other system, system B, is characterised with the lowest possible value of social entropy and that all the resources transferred from the environment become part of the social free energy. That system is maximally adapted to its environment. However, its internal tension is maximal, as there exist for relativelly long time significant discrepancy between possible and understandable level of living on the one hand, and the realised level of living on the other hand. These illustrations point to the fact that generally the longest duration achieve systems which simultaneously optimise their social free energy and social entropy, i.e. which optimise the adaptivity and goal attainment.

If one would like to express changes in thermodynamically based quantities, then meta-theoretically the appropriate starting point is the Gibbs differential

$$dF = -S\mathrm{d}T, \tag{1}$$

strictly valid for equilibrium processes without changes of boundaries. Qualitatively, it expresses the fact that resources belonging to the social free energy influences level of living, in particular intensity of actions in known ways of living. The equilibrium character here points to relativelly durable processes. In order to overcome that restriction and obtain the form for changes of social free energy valid for short-term collective processes, the explicit taking into account of human collectives is needed.

## COLLECTIVE EXCITATIONS IN SOCIAL SYSTEMS

Overall, the longer the duration, the more precisely the role is determined. The relation between the role and extent is not so straightforward, as the role is presumably set within the verbal context of value set. The conjecture posed is that the extent and role are linked. The underlying relation is designated *dispersion relation*. In order to reveal the link the role should be suitably quantified, from the point of view of the corresponding value set, ideally independently of the extent. Quantification is performed firstly by linking the role with observable time characteristics of dynamics, and subsequently by linking the later with the extent.

Let us consider several examples in order to illustrate the use of dispersion relation in characterising collective excitations: spectators at a stadium [11] and firms.

### SPECTATORS AT A STADIUM

Spectators usually come with rather large devotion to the match, or sport event watched, so that their equivalent social temperature is rather high. Therefore, the external stimulus to behaviour of spectators – the dynamics of sport watched, triggers rather easily different collective modes. A sideways consequence is that many of the modes are mixed or damped. Several differentiated modes are:

1. intense fan support triggered by impressive action on the ground,
2. constant support of group of fans and
3. Mexican wave.

It is assumed presently that these three modes are ordered in the sequence of larger wave vector (thus smaller extent), and in the sequence of larger value, i.e., the intensity of the spectators needed. The sketch of the dispersion relation thereby implied is in Fig. 1. The duration of all these modes require several considerations. It is estimated that in the same order the modes are listed their duration raises. This seems paradoxical in comparison with the constancy (i.e., throughout the match or the event) of the fan support. However, the fan support is considered a highly damped mode which is constantly excited by the large energy content of the fans involved.

To the same group of collective excitations as spectators at a stadium the participants at a concert, intelligent mobs and similar groups of people belong.

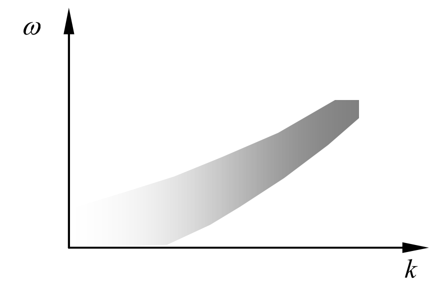


**Fig. 1.** Sketch of the dispersion relation of spectators at a stadium. The brighter grey level points to the larger dissipation, i.e., shorter duration of an elementary mode.

## FIRMS

Firms are collectives which are rather durable in comparison with the groups of spectators, concert participants etc. Their extent and value vary considerably. Generally, the distribution of the extent of firms points to a large number of localised firms and relatively small number of delocalised firms. However, some trend in duration is not extractable from the well-known, intuitive facts.

The basic evolution of processes in terms of their dispersion relation at the present level is the following one: initially, the collective excitations are non-realised, known prevalently as ideas, with similar probability of realisation throughout the region containing social systems with similar techno-cultural level reached. That gives a finite initial average repetition rate, value and practically infinite extent. In time, people develop ideas, apply them and develop their realisations, all in constantly interfering way. Because of the work conducted, on the one hand the average value of the excitation raises. On the other hand, it becomes more aligned to humans, hence in its extent the differences on the scales smaller than the characteristic scale of the system(s) appear. Because of the enhancing interest the people find in the excitation, its dissipation enlarges. The sketch of the described evolution of excitations, i.e. the accompanied dispersion relation, is shown in Fig. 2.

Such a shape implies one measurable consequence – the existence of a well-defined initial energy $\omega_0$, representing the energy each human needs to adopt the idea of the excitation.

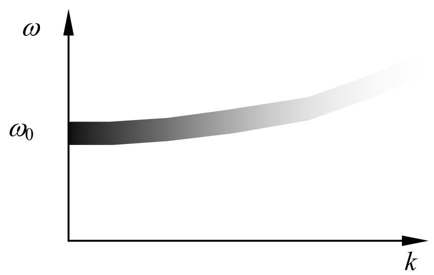


**Fig. 2.** Sketched dispersion relation of the excitation the evolution of which is described in the text. Presently the only general characteristic is $\mathrm{d}\omega/\mathrm{d}k > 0$. The change in line intensity points to the assumed change in excitation intensity, i.e., the level it influences people.

## CONCLUSIONS AND LINES OF FUTURE DEVELOPMENT

The conjecture argued about in this article is that the existing structure of social systems is a consequence of the tendency for better adaptation to environment dynamics. On the one hand, therefore, a lot of structures could serve as collective excitations the analysis of which reveals some underlying regularity of collectives, e.g., their dispersion relations. On the one hand, however, not all collectives are suitable for initial analysis, because their dynamics could bring about the ceasing of the initial impetus attributed to them in the form of the relativelly strong localisation or dissipation, overall their ubiquitouty and indistinguishability. Overall, as the optimal collectives for further development of the concept the relativelly new structures are extracted and in subsequent work the quantitatively based analysis will be performed.

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# SOCIJALNI EKVIVALENT SLOBODNE ENERGIJE

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## SAŽETAK

Karakterizacija nevezanih resursa socijalnog sustava u okviru sociološke interpretacije rezultirala je različitim interpretacijama, značajnim u različitim situacijama. Sa stajališta statističke mehanike te interpretacije odgovaraju slobodnoj energiji. U ovom radu je koncept socijalne slobodne energije uveden i upotpunjen s prvim koracima u njegovoj razradi. Socijalna slobodna energija je funkcija iznosa jednakog slobodnoj energiji određenoj za socijalni sustav, intrinsično sociološke interpretacije u obliku mjere socijalnog djelovanja ostvarivog u određenom socijalnom sustavu bez promjene njegove strukture. Njeno oblikovanje posljedica je odziva socijalnog sustava na raspoznate dijelove dinamike okoline. Raspravljano je o tome da razvoj odziva socijalnog sustava odgovara pobuđivanju svojstvenih modova općeg, fizikalnog sustava.

## KLJUČNE RIJEČI

socijalni sustavi, socijalna slobodna energija, adaptacija, organizacija, disperzijska relacija

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# HUMAN COMMUNICATION AS MEDIATING THE UNITS OF PARAMETERISED ENVIRONMENT

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## SUMMARY

Human communication is prevalently a mediated process. Mediators are units of environment, which are attributed functions within the local value set. They are utilised in such a way as to optimise the change of human states.

In this article, a mediator–centred interpretation of the human communication is given. The interpretation follows closely the concept of mediated interaction developed within physics. It is conjectured that collection of mediators, which the humans use, has a well–defined average. The averaged collection permits reliable interpretation as a human communication spectrum. Relation of the intensity of a spectral component with regard to different senses, and with regard to intensity of interaction is discussed.

## KEY WORDS

human interaction, environment excitations, mediators, communication spectrum

## CLASSIFICATIONS

APA: 2700

JEL: C0, D80

PACS: 89.70.+c

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## INTRODUCTION

Humans interpret their actions and processes observed in environment using a value set. The value set is a complex convolution of socio-biological elements. The social part means interaction among humans, the significant part of which is communication. For the purpose of this article the communication is defined as a part of human interaction which primarily affects human interpretation of them and of environment. Frequent consequences of communication are other human actions. Human communication is a representative type of human interactions in the sense that it is rather structured, well-known, widely-adopted, constantly performed, dynamic and important for individual and collective well-being. Because of these facts, communication has been studied constantly. Generally, communication combines individual biological and psychological characteristics, social characteristics in the form of informal and formal rules as well as the characteristics of human environment in the form of available means of communication [1]. A sideway consequence is that it is rather interdisciplinary in origin. Recently, development of electronically founded means of communication (wireless communication and Internet based communication) enabled humans to carry out one step further – hence intensify – most of the processes the communication has contributed to. These processes include on the one hand human integration [2], information dissemination, transparent and traceable processing of actions and on the other hand human alienation and manipulation.

The communication is not clearly understood, as is seen from the fact that it has more than twenty different definitions [3]. The definition stated here is a human-centred definition, in the sense that the main causes and consequences of communication are seen on humans. In that sense, the essence of communication is projecting of human, internal dynamics. Other elements are solely means, utilisable parts of environment which contribute to efficient projecting. Because of that, the means – e.g., modes, duration, underlying norms and other characteristics of communication – are unimportant for the essence of communication. That accounts for the fact that in virtually every spontaneously formed human system communication has been possible. Therefore, realised communication modes are subset of all possible communication modes, the subset formed from the local techno-cultural basis as represented in the value set. However, the further fact is that a minute subset of possible communication modes is exploited. The existence of rules, which among other have restricting meaning in construction of speech, written text etc., point to that fact. The spontaneity in forming the communication modes reveals the existence of additional criteria applied, the criteria being the consequence of human characteristics. Because of that, analysis of the realised communication modes, In contrast with possible, yet non-realised modes, has a potential in making known human characteristics. To summarise, by focusing the research at the communication modes with human influence suppressed, one enhances probability to extract criteria which led to observed communication modes, which in turn enables better understanding of humans.

In particular, the quantitative interpretation of human communication enables us to better understand interplay among the different individual and collective human characteristics, as well as the possibility of their further purposeful modifications and design.

In this article human communication is interpreted as a mediated process. Details of mediators are given, and the combination of tied human and environment characteristics elaborated. The article belongs to recent series of the articles in which the emphasis is put on mediator details.

The crucial starting point, that humans are substantial origin and source of communication is, because of the operability, developed further in the two premises:

(i) for each assumed flow of human dynamics there is the optimal set of means of communication,

(ii) the set of means of communication utilized by a human has a well-defined average

The set is optimal if it enables humans to realise dynamics which is the least different to the assumed one, the difference being appropriately introduced within the local value set. The main result of the article is the conjecture that ordering of the averaged set of means of communication using a scalar parameter is correct and reliable. By means of it the spectrum of human communication is formed.

The spectrum makes possible predicting the impact of a new communication mode onto the human communication in the following way: the averaged communication of a human with a given characteristics has some optimal form. All means of communication contributing to approaching of real communication to the optimal one are suitable and adoptable. On the contrary, all means which enlarge deviations are unsuitable.

The outline of the article is as follows. In the second section, because of a self-contaidness, the notion of mediator is elaborated. In the third section the human senses and mind are analysed as the formal and the central element guiding communication, respectively. The concept of a human communication spectrum is elaborated in the fourth section, with the preliminary theoretical and experimental results presented. In the fifth section the summary of the results with the perspective for follow-up work are given.

## MEDIATORS

Each and any human value set provides one with a local interpretation of environment as a collection of units of a particular type. Within the value set, each of these units is (i) differentiated from the rest of surrounding, i.e. other units, (ii) attributed a function. Units exist naturally, or are prepared artificially. In both cases, their formation is traced to some other units, which were combined using an energy amount distributed in a specific way. Thus, the units are part of the environment – the environment excitations. Units are elementary in the sense that each unit has a specific function, and serves as the least part of environment making possible the function's realisation [4]. The units are therefore *elementary environment excitations* (EEEs). Because of the difference in their characteristic dynamics and characteristic human dynamics, some EEEs are considered as monolithic and opaque environment structures (e.g., house, road, river) implying static quality and some as easily manipulatable structures (e.g. paper, money [5], e-mail [6], sound) implying dynamism.

Let us illustrate with some detail the notion of EEE on the examples of a mobile phone and of a textual message from Short Message Service (SMS). The former is example of an EEE which is not a mediator (to be described later in the text), while the later is the example of the EEE which is a mediator. The mobile phone is made from raw materials existing in environment, after inclusion of energy and human knowledge and skills, hence is an environment excitation. Its recognised function is enabling distant people to communicate with marginal or irrelevant interference with their momentary activities. Mobile phones couple humans and communication units in their environment. The mobile phones are considered as the least part of environment required for the corresponding function fulfilment. The mobile phone stated function is neither overpowered with their complex structure the users have knowledge of, nor with the fact that average user extracts occasionally, mentally or physically some of the mobile phone parts, e.g., battery, antenna, display, buttons or memory card. The mobile phones have sideways characteristics of contributing to the owner status presentation. Existing mobile phones differ in dimensions, capabilities and design. Their number changes, and their average contribution to communication is intensifying the possibility to connect and separate people. As a rule their form clearly differentiates them from the rest of EEEs, the exceptions being the toys and terrorist weapons. Overall, mobile phones are owned and represent EEEs bounded to individuals. They are not communication units, on the contrary to SMS. The SMS is a discrete communication unit, existing in a rather structured, artificial environment. Firstly that environment was the mobile phone network, which was subsequently broadened to fixed telephone network and Internet. SMS are excitations of that environment as they require some skills and efforts for their writing, some amount of energy for their transfer and some amount of money for the overall stabilisation of that structure. SMS function is indication of the auxiliary communication, prevalently as a precursor of other, more thorough communication types. SMS use spans rather broad time and space intervals (from duration of several seconds and range between humans of several meters to durations of several days and ranges of several thousands kilometre). SMS differ in their content.

The duration, extent and value are attributes of EEEs. The duration of an EEE is the average time the particular type of realised EEEs is considered as performing its function, i.e. as being in the excited state of the environment they were predicted. That has various components, like are physical, technological and social. Let us illustrate that on the example of mobile phone. Physical life-time is prevalently determined by the battery life-time. After battery empties, the mobile phone changes its predicted excited state with some other (which again is attributable the life-time). The battery refilling means re-establishing the mobile phone in the initial state. Some contribution to the life-time of the predicted state originates in the possibility of breaking and stealing the mobile phones. Technological life-time combines the duration of the technology used in transferring the signal between the mobile phone and the net operator (e.g., duration of a particular protocol). Social life-time is rather heterogeneous as it includes duration of the net card validity, fashion influences etc. E.g., some mobile phone may be in working order, but not used as being considered old-fashioned or technically insufficient by a majority of people. Substantially, duration of the EEEs shortens with intensifying interaction with other EEEs and humans. E.g., mobile phones are kept out of other people reach, protected from devastating atmospheric influence, etc.; SMS are coded in order not to interfere with other SMS during their transfer as electrical signals, and in order to suppress errors in the transfer.

Humans have two types of interactions with EEEs: (i) screening and (ii) mediated interaction. The first group includes all the EEEs which are linked to an individual and which contribute to his or her status, role, appearance, capabilities and diverse impressions by others (e.g., mobile phone). The second group includes all the EEEs which are transferred from one human to at least another human (e.g., SMS). Generally, the transfer is causal and a direct consequence of individual interpretation of his or her own state and state of environment. The EEEs which are regularly utilised in the mediated interaction are referred to as the *mediators*.

EEEs, hence mediators also, are attributed the *social mass*. It is the relative measure of resistance of a human system to a change of the EEE state. Let us concentrate on the case of mediators, as their predicted function includes transfer. The change in question is mediator transfer, and sources of resistance are e.g., legislative or economic sources. Mediator transfer starts with its emission from a sender and absorption by a receiver. E.g., consider a finite amount of money transferred between two humans. Initially money contributed to the initial state of a sender, hence money screens the sender, because of what is not separately treated. In that way, for the social environment that amount of money does not exist before it is introduced by the sender, i.e., separated from the sender, i.e., emitted into the social space. Similar interpretation goes with the receiver, who is screened with the money after its receiving, i.e., the absorption. Along with the money, the SMS, e-mails, voices, packages and other exchangeable EEEs may be emitted and absorbed.

Mediators which are transferable in a relatively short time interval bring about the synchronous communication. Conversely, if duration of a transfer is relatively long the corresponding communication is asynchronous. Relatively short (long) time intervals are those which are on average much shorter (longer) than the average duration of receiver and sender individual dynamics.

The causality of processes in which humans emit mediators and the regularity inferred from the observations, reveal the connection between the change of individual states and mediator characteristics. Mediators serve as part of the environment transcending some individuals, thus enabling them to perform the state change. The precise amount of change is determined within the local value set, with *local* prevalently meaning *within* the social system. The relatively long duration of a human system and invariance of the interpretation within the space region belonging to the system, bring about denoting the indicators using their value and extent (the dispersion relation which links value and extent is for collective EEEs analysed in the other paper by the same author in this issue. It can similarly be introduced for mediators).

The presented picture, in which there are separated humans, interacting with well-defined and mutually separated mediators is a simplification. Realistic situations include mutual multi-level interactions between all listed elements, e.g., separation of SMS and e-mails exists, but is not total as there is possibility to send SMS which will be received as an e-mail and vice versa.

## HUMAN-MEDIATOR INTERACTION

Human internal dynamics is the cause of emission of mediators. Their absorption is constant impetus for further change of states. While mediators are processed mentally, their absorption and emission are connected with human senses: gustative, tactile, olfactory, auditory and visual sense.

By influencing the senses the absorption of EEEs takes place. In communication the tactile, auditory and visual influences are prevalently utilized. The average range of communication is of the order of 1/2 m for tactile, 10 m for auditory and 100 meter for visual. Communication is direct or mediated. In particular, auditory and visual communications are strictly mediated: in auditory communication is realised through the disturbances called voices or sounds which propagate through physical atmosphere or a combination of atmosphere and electric circuits, while in visual communication the sender reflects the light beams which the receiver uses for inference about the sender state (appearance, movements, gestures, etc.), again in atmosphere or a combination of atmosphere and electric circuits. In case of a noisy environment, darkness or opaque partition-walls these types of communication are not possible. Tactile communication can be direct (shaking hands, patting, etc.) or mediated [5]. The quiet atmosphere with naturally existing light and electric nets are two parts of environment making possible specific type of communication. The former is naturally existing, while the later is an artefact, thus they are again specific EEEs, which are slightly modified by senders. The subset of EEEs, which is modified during communication, is called a *medium*.

The fact that the medium is one EEE, within which other EEEs are transferred, should be addresses in more detail. It is connected with the introduction of EEEs as units attributed function within the local value set. In that sense, the medium is the least part of environment which makes possible a particular communication channel. However, it is a complex structure, consisting of subunits, which – within the very same value set, are however again units with a different function attributed, e.g., conveying of a particular information content.

Nowadays, a variety of different EEEs are utilised in communications: telephone, SMS, e-mails, VOIP, video-conferencing, … As an illustration, SMS and e-mails were introduced as a sideway consequence of technology, and their proliferation has come as a rather large surprise [6]. On the other hand, the unsuccessful attempts to introduce video-telephony were also surprises [7]. The constancy of the trends of use of different mediators reveals the underlying close connection of mediators and human internal dynamics.

Communication mode depends on communicating agent needs and capabilities for communication, communicating agent formal and informal set of rules, available communication equipment, and on characteristics of transferred information. Most of these characteristics are nowadays subjected to rapid change. While precise way of further communication development may be reliably predicted only in short-term, it seems opportune to analyse the limiting or saturated state, in which material prerequisites for communication reached the saturation states. In other words, it is assumed that then communication equipment is freely and widely available and that all communicating agents adopted a unique set of communication guiding rules. In the limiting state, therefore, communication characteristics are set by the intrinsic characteristics of transferred information and of individual agents. Operationally, characteristics of ideal communication state may serve as additional criteria for precise setting of future communication mode development.

All communications are collective in origin, e.g., interpretation of voices requires adopted language, a part of a collective structure, the value set. The existence of a particular medium requires underlying energy content with a particular history of formation. That is clearly seen in the media for electronically transmitted communication, which consists of a firm infrastructure.

## HUMAN COMMUNICATION SPECTRUM

The underlying assumption in this article is that humans are origin of communication, which is conveyed in accordance with their needs. Humans, who adopted the value sets which are mutually similar enough, share the level of change in interpretation of environment the particular EEE during communication causes.

Different EEEs after interpretation provides one with some quantity of information. The each piece of information content of an EEE is attributed a specific number denoting its quantitative measure. The scale thereby spanned is called its dimension.

As crucial characteristics of EEEs in this article the set of their dimensions is used. For face to face communication the estimated number of dimensions spanned is considerably larger than for other communication modes, hence is considered as effectively infinite. The face to face communication is considered as at least visual and auditory communication with negligible level of obstructing influences (noise, inadequate lighting, non- or weakly-transparent compartments, etc.). It includes speech semantic dimensions, sound dimensions, movements, gaze, etc.). For auditory communication without accompanied visual communication, the number of dimensions is reduced, yet relatively large – it consists of the number of different dimensions in speech as information flow and sound flow. For the communication through text (which includes visual elements) the number of dimensions is further reduced and lowers as lowers the possibility to form the text. Text is particularly structured and prepared part of environment, which includes a medium (like a paper or a display), interpreting code (alphabet and grammar) and which reflects additional norms and customs (different expressions, slang, emoticons, … ). The development of SMS and e-mail mediated communication reveals the interplay between the human needs and environment capabilities for exciting particular EEEs.

The average set of EEEs, utilized in relatively long time interval thus in relatively large number of different situations and individual states, in relatively stationary human states is conjectured to have a regularity of determining moments, like are mean value and variance. Such a set is called a spectrum. It is further analysed using the scale of an average information content transferred between two humans. The average of their relative distance is known. That distance is a consequence of a number of different factors, e.g. habits, local environment, daily dynamics, etc. The distance serves as a representative of these factors. It is assumed that average distance and job intensity, number of mutual activities etc. on average are related.

The significant dynamics of communication innovations is observed as constant and rapid development of communication devices, protocols etc. It brought about the myriad of possibilities utilizable in communication. Because of that, in more and more occasions it is not the environment but the human characteristics which determine the realized communication means. Therefore, the utilized set of communication means is projection of human characteristics, as a socio-biological construct, onto the environment. The elements of the utilized set are exploited in accordance with their capability to transfer the characteristics of human states with certain rate. In principle, the average information transfer is calculable, making possible the ranking of means of communication. Let us illustrate these points continuing with the SMS; it is documented that the form of SMS is suitable in initiating communication. If stimulating, the SMS-based communication rapidly, i.e. after at most few messages, transforms into other types of communication that enable the persons involved to enhance the rate of information transfer, e.g. use of telephone or face to face communication [2]. Contrary to that, the SMS-based communication may cease sooner or later, depending on whether the quantity of information to be transferred is marginal or irrelevant.

The averages of utilized means of communication of a human are, overall, relatively stable, thus making possible correct and meaningful definition. The set of utilised communication units, which are represented in some average, when ranked according to the rate of information transfer is a *human communication spectrum*.

The hypothetical shape of a human communication spectrum, presently, is delineated in Fig. 1. In it, the assumed distance-dependent average intensity $I(r)$ of transferred quantity of information is shown. The transfer may bring about attractive or repulsive interaction.

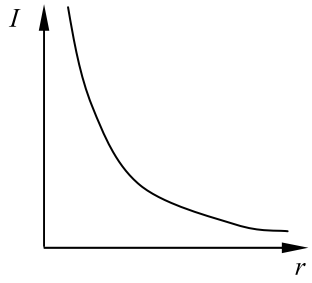


**Fig. 1.** Presently assumed form of average human communication spectrum.

In Fig. 1 the assumed, idealisation is sketched. It is formed from all existing communication means, each of which generally contributes like is shown in Fig. 2.

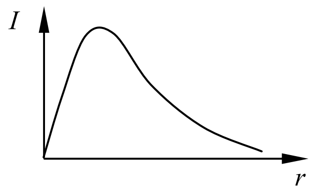


**Fig. 2.** General contribution of a communication mode to the human communication spectrum.

The distance for which the maximum of $I$ in Fig. 2 is achieved depends on the mode. E.g., it is the least for gustative, then tactile, olfactory, auditory and visual communication. This list is subject to gradual change as underlying technological basis (presumably electronic in origin) broadens the list of artificially formed media, which besides existing audio-visual, shows tendency to include the olfactory and tactile channels. Such a media have more pronounced collective character in comparison with the non-electronic ones.

## CONCLUSIONS AND PROJECTIONS

Relating the origin of communication with the individual human dynamics induces the need for different interpretation of environment, which becomes the collection of functionally determined units – elementary environment excitations (EEEs). In this article the EEEs related to the communication are analysed. They are related to the human characteristics and operationalised in the form of human communication spectrum. It is the ordered average of communication means. The ordering is performed by the average contribution to the overall information transfer between the communicating humans.

In order to deepen that interpretation in further work the data about the communicating habits need to be collected and analysed. Suitable part of the available communication means is the electronically based communication, as it is recorded and consists of discrete and well-separated units.

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# KOMUNIKACIJA IZMEĐU LJUDI KAO IZMJENA JEDINICA PARAMETRIZIRANE OKOLINE


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## SAŽETAK


Komunikacija između ljudi većinom je ostvarena putem medijatora. Medijatori su jedinice okoline kojima je u lokalnom skupu vrijednosti pridružena funkcija. Upotrebljava ih se tako da je odgovarajuća promjena stanja ljudi optimirana.

U ovom radu izložen je pristup ljudskoj komunikaciji s naglaskom na medijatorima. Interpretacija slijedi koncept međudjelovanja putem medijatora razvijen u okviru fizike. Razmatra se tvrdnja da je skup medijatora, koje ljudi upotrebljavaju, dobro definiranog prosjeka. Uprosječen skup omogućuje pouzdanu interpretaciju spektra komunikacije ljudi. Razmotrena je relacija između intenziteta spektralne komponente i osjetila te intenziteta međudjelovanja.



## KLJUČNE RIJEČI

ljudska komunikacija, pobuđenja okoline, medijatori, spektar komunikacije

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# NEUMANNIAN ECONOMY IN MULTI-AGENT APPROACH. INVESTIGATION OF STABILITY AND INSTABILITY IN ECONOMIC GROWTH

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## SUMMARY

Axiomatic foundation of non-equilibrium microeconomics is outlined. The economic activity is modelled as transformation and transport of commodities (materials) owned by the agents. Rate of transformations (production intensity), and the rate of transport (trade) are defined by the agents. Economic decision rules are derived from the observed economic behaviour. The non-linear equations are solved numerically for the Neumannian economy. The emergence of the equilibrium market structure appears as an order out of chaos process.

## KEY WORDS

economics, irreversibility, growth, chaos

## CLASSIFICATION

JEL: C62, O12

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# INTRODUCTION

Neumann, in his 1937 paper introduced a model economy to study the conditions for equilibrium growth [1]. In the present paper the Neumannian economy will be investigated in an irreversible (thermodynamic like) multi-agent approach.

There is a basic similarity between chemistry and economics, namely that they are concerned with transformation and transport of material. Formal description of the material flows in economics and in chemistry lead to equations of the same structures, with some important differences. In thermodynamics the laws of transport and transformations are formulated as the First and Second Law of Thermodynamics. The analogous formulation in economics for the First Law is trivial [2]. Economic activity can be described via the changes of the quantities of goods. Second Law states that the purpose of economic activity to be better off (later we give a more precise definition). The First Law, in its direct or indirect form, was already articulated by economists. The classical economists accepted it. Neoclassical approach considers it trivial and non-important. Second Law is applied in a stronger form. We always choose the best possibility.

Organization of the paper is as follows. In Section 2 the thermodynamic description of chemical systems will be outlined. First and Second Law will be given in such form, which can be applied also in economics. In Section 3 a thermodynamic (or irreversible) microeconomics is outlined. In Section 4 we give numerical solutions for the Neumannian economy [1]. The results show a chaos-order-chaos behaviour.

# THERMODYNAMICS

## A BRIEF SUMMARY OF THE HISTORY OF ECONOMICS AND THERMODYNAMICS

Analogous properties of chemical and economic processes are well known for a long time. Kalman Szily, a physicist, gave a lecture in 1871 with the title *Communistic state of the physical world*, where he used some economic examples to explain the First and Second Law of Thermodynamics. In 1903, Jankovich [3] published a paper on the mechanical foundation of value. Imre Fenyes, professor of thermodynamics, emphasized the similarity between the economic goods and the thermodynamic quantities. Here we can cite hints by von Neumann [4], Samuelson [5], Moffat [6] and Berry and Andresen [7], among others. In an excellent summary on the use of physical analogies by an early neoclassic [8], Mirowski writes: "The metaphor of energy/utility which neoclassical economics appropriated was derived from the physics of a specific historical period: the years of the mid nineteenth century just prior to the elaboration of the second law of thermodynamics." [9]. Yet, pre-entropic physics has been basically a theory based on mechanical considerations, without a "time-arrow", without irreversibility.

There were several attempts to exploit the analogous properties of the thermodynamic entropy and the utility concept of neoclassical economics [10]: Rozonoer [11, 12], Bródy et al. [13], or utility and internal energy [14], Stepanic et al [15], Mironova, Amelkin and Tsirlin [16]. These analogies are useful but different from the irreversible approach.

## LAWS OF THERMODYNAMICS

There are two basic approaches to understand the equilibration process: a macro (thermodynamics) and a micro (statistical mechanics) approach. Nowadays the statistical approach is more popular. Statistical mechanics, developed initially by Ludwig Boltzmann, defines entropy as the logarithm of the number of "microstates". Boltzmann's definition of entropy rather suggests the order/disorder metaphor. Boltzmann's statistical approach is a useful tool in a wide range of applications.

Classical (or phenomenological) thermodynamics starts from the observed properties of our material world.

### First Law

In thermodynamic investigations it is worthwhile to distinguish between the extensive variables (volume, energy) and intensive variables (e.g. temperature, pressure). An extensive variable must satisfy two conditions. First, its time dependence is described by the generic balance equation:

$$\mathrm{d}X/\mathrm{d}t = J + G, \tag{1}$$

where $J$ is the flux, and $G$ is a generalized source term. Second, it must be *additive*, in the sense that if $X^a$ and $X^b$ are values of the variables for two systems $a$ and $b$, the variable has the value $X^a + X^b$ for the combined system, consisting of the union of the two. A general rule of thermodynamics states that all the interactions of the thermodynamic system with its environment take place through the flows of extensive variables. Mass, energy, the number of molecules and total volume are examples of extensive properties. That property is summarized in the First Law.

<u>First Law:</u> Any simple system has particular states that are characterized completely by extensive quantities.

The postulate reflects an important feature of thermodynamic systems. The evolution of the system is governed by the balance equations of extensive quantities, in the form:

$$\mathrm{d}X_{\mathrm{ki}}/\mathrm{d}t = \sum_{\mathrm{kl,i}} J_{\mathrm{kl,i}} + G_{\mathrm{ki}}, \tag{2}$$

where index $i$ and $l$ identify the subsystem, $X_{ik}$ is the quantity of the extensive parameter $k$, $J_{\mathrm{il,k}}$ denotes the flow from the system l to the system i.

The independent set of extensive variables necessary to describe a given system is determined essentially by trial and error. The choice is not unique. It depends on one's purpose or (from another perspective) on the accuracy of one's measurements. For example, consider the air in a room. For certain purposes it is sufficient to treat it as an equilibrium gas. But for a more precise measurement one has to take all the different types of molecules present in the air into account. In still more precise calculations one might also consider the different isotopes. Going to extremely fine details it might be necessary to consider the internal structures of the atoms. In real calculations it is necessary that we take into account only those details what are important for the problem in question.

### Second Law

The Second Law of thermodynamics is essentially different from the First Law, since it deals with the direction in which a process takes place in nature. It expresses the preferences of Nature. Not every change which is consistent with the balance equations is a possible change. The conservation laws do not suffice for a unique determination of natural processes. As for instance, in the previous example, the water equation offers no information, whether hydrogen and oxygen actually combine to form water, or water decomposes into hydrogen and oxygen or whether such a process can go into both directions.

The essence of the Second law is that all the independent elementary (infinitesimal) processes that might take place may be divided into three types: natural processes, unnatural (forbidden) processes, and reversible processes:

- natural processes are all such that actually do occur (e.g., heavy body falls down),
- unnatural processes (the reverse of natural processes); such processes never occur spontaneously, only as the forced processes,
- as a limiting case between natural and unnatural processes are the reversible processes. They do not actually occur, but they are important for mathematical causes.

The Second Law implies a relation between the quantities connected with the initial and final states of any natural process. The final state of a natural process has to be discriminated from the initial state, while in a reversible process they have to be in some sense equivalent.

### Non-equilibrium thermodynamics – Dynamics

The balance equations describe the time evolution of the systems, the relation of flows and the distribution of stocks has to be defined empirically. These relations are empirical, material dependent, but not arbitrary. The flows must obey the Second Law. That condition has a great power. It allows us to introduce the concept of thermodynamic forces, and the force law which connects the flows with the state variables.

The uni-directionality of natural processes is formulated in the form of a dynamic law in non-equilibrium thermodynamics. The change (flow) is proportional to the force (difference in intensive parameters, $\delta Y_k$)

$$J_{\mathrm{i}} = \sum_{\mathrm{k}} L_{\mathrm{ik}} \delta Y_{\mathrm{k}}, \tag{3}$$

where $L$ is the so called conductivity matrix. It is positive definite. That property of matrix $L$ follows from the Second Law. That is the "time's arrow". Thermodynamic based microeconomics.

## IRREVERSIBLE ECONOMICS

For the mathematical structure of irreversible microeconomics see [17]. Here we summarize the most important definitions and concepts [18].

An economic agent (EA) is defined for our purposes as the smallest entity with an implicit or explicit decision-making rule. An EA would normally be either a firm or an individual. EA are characterized by their scope of activities, by their knowledge, experiences and by their stocks of goods and money. Our primary interest is the change of stocks and its economic effect. Every stock which can be affected by the economic activity of an agent can be listed, and those also, which affect the economic activity of the agent. The list of goods may contain the money, but it is not necessary.

An agent consumes, produces or exchanges the goods. In *consumption* the quantity change is always negative. *Production* is a transformation of stocks from the initial form to a final form. Here the change is positive for the products and byproducts, and negative for the input materials. Total quantity increases only when there is an input from the nature. Otherwise the obligatory losses decrease the total quantity of goods. T*rade* modifies only the owner of stocks. Economic actions are trade and production.

Trade and production are described as decisions. EA selects or rejects the offers provided by other EAs or (in case of production) by his/her internal state.

Decisions are tantamount to selections from a limited set of possibilities for immediate action. The set of possibilities is constrained by the external environment (for example, the legal framework) and by the assets of the agent, including financial assets, physical assets and intangibles such as knowledge, know-how, reputation, and so on.

**Proposition 1 (First Law):** Evolution of an economic system is described by the balance equation for stocks of goods and money.

**Proposition 2 (Second Law of Economics):** The purpose of economic action is to increase the expected economic welfare.

There is no economic action decreasing the expected economic welfare. It is the no loss rule. That rule implies that every agent has a measure to rank her/his belongings as a measure of economic welfare. The economic welfare of an economic agent is a function of the stocks of goods and money belonging to the economic agent: $Z = Z(X)$ The proof is given in [17]. Sign convention is selected so that $\mathrm{d}Z > 0$ for allowed (no-loss) processes, and $\mathrm{d}Z < 0$ for forbidden (loss-making) transactions.

Assuming the function $Z$ is continuous and differentiable, the partial derivatives in respect of the stocks can be interpreted as the marginal $Z$-value of the good $i$. It is measured in welfare/quantity units. Let $M$ is for the quantity of the money owned by the agent. The marginal $Z$-value of money is the marginal change of the welfare, that is: $w_M = \partial Z/\partial M$. The marginal value of the good i is:

$$v_i = \frac{\partial Z / \partial X_i}{\partial Z / \partial M}.$$

The expected change of economic welfare is:

$$\mathrm{d}Z = w_M \left(\sum_i v_i \mathrm{d}X_i + \mathrm{d}M\right), \tag{4}$$

The expected gain (profit) in trade of a unit of good i for price $p_i$ is $F = (v_i - p_i)$, the expected gain for production $F = vC$. $C_i$ is the change of the i$^{th}$ good in a unit production. It is positive for the products and by-products, and negative for the input materials**.**

The technology defines the production vector. The agent defines the production level. Technology (capital) gives an upper limit ($y_{max}$), but real systems work with less efficiency.

Assumption: Production level is proportional to expected profit, that is

$$y_n = L_n vC. \tag{5}$$

In trade the unit processes are given by the market institutions. Traded quantity when agent *k* trades with the agent *m* at price pi will be proportional to the expected gain, that is

$$y_{km,i} = L_{km,i}\,(v_i - p_i). \tag{6}$$

Trade is viable only if the agent m agrees the same quantity with opposite sign. Price, $p_i$ comes form the solution of equation

$$\sum_{nm} y_{nm,i} = \sum_{nm} L_{nm,i}\,(v^n{}_i - p_i) = 0, \tag{7}$$

where the summation is for the agents participating in the bargaining process.

The equation system is closed. (We omit the indices for the sake of clarity and brevity.)

Balance equations:

$$X(t+1) = X(t) + L(v-p) + L_n vCC, \tag{8}$$

$$M(t+1) = M(t) - pL(v-p), \tag{9}$$

$$L(v-p) = 0. \tag{10}$$

It is a non-linear coupled mapping. The properties can be investigated with numerical solutions. A numerical solution needs the following data:

- identification of the agents,
- the production vectors
- initial stocks,
- welfare function and the coupling parameters ($L$).

Technological innovations and monetary policy of the economic system may also have to be specified. Further, exogenous effects such as consumption not connected with production, taxation, depreciation, and natural constraints, if any, must be specified.

## NEUMANN ECONOMY

Our minimum model of an economy has 3 economic agents, corresponding to three sectors, namely: agriculture, industry, and households and we apply the simplifying assumptions of Neumann, namely:

- vector $C$ is constant,
- nature is infinite (there are free goods of nature in quantities without limit),
- consumption consists of two parts, a fixed part and a part which is proportional to the production,
- labour is considered as a normal stock (the households produce it),
- agents get interest payment for their money stock.

### SELECTION OF THE WELFARE FUNCTION

For the present investigations a logarithmic welfare function was selected:

$$Z_n = \sum_i X_{in} \cdot \log(C_n M_n / X_{in}), \tag{11}$$

where $X_{in}$ is the stock i of the agent n, $M_n$ is the money stock of the agent $n$, $C_n$ is constant.

Production vectors: Agriculture (2 | –0,13 | –0,08), Industry (–4 | 2 | –0,36) and Households (–1,83 | –1 | 2).

The coupling parameter $L$ for all trades is assumed to be unity, viz. $L = 1$. The production coupling parameters are: $L_1 = 0{,}352$, $L_2 = 0{,}288$ and $L_3 = 0{,}352$.

The interest rate is given for the money. After each cycle the money of the agents is multiplied with $\alpha$.

Initial stocks were selected as:

| | Money | Food | Tools | Labour |
|---|---|---|---|---|
| Agriculture | 1000 | 22,98 | 18,51 | 14,07 |
| Industry | 1000 | 22,05 | 19,34 | 14,16 |
| Households | 1000 | 21,97 | 18,86 | 14,73 |

## NUMERICAL SOLUTIONS

Figure 1 shows the intensity of production as a function of time. Time means here the number of completed cycles. The interest rate is $\alpha = 1{,}0005$.

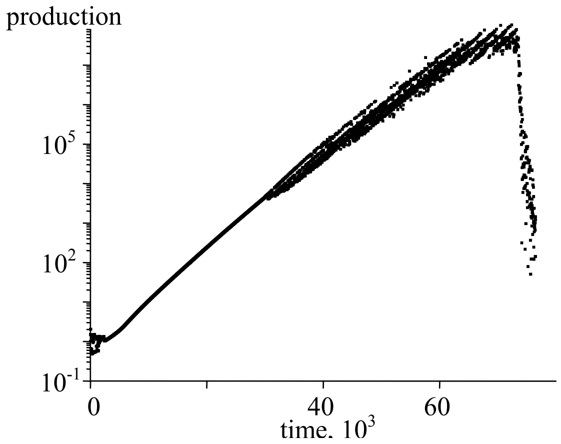


**Fig. 1.** Production as a function of time.

The system starts from chaos. The initial period (in a magnified form it is in Figure 2) is the non-equilibrium part. The initial stock distribution did not correspond to the equilibrium. Fig. 2 demonstrates the working of the invisible hand. Order develops from chaos. Fluctuations decrease, quasi-periodic oscillations emerge with decreasing amplitudes. The system finds the equilibrium path. There is a near-exponential growth of the production intensity. The equilibrium growth is stable only for $\alpha = 1{,}0000$. Nevertheless the agents' welfare increases unequally. This inequality leads to the loss of stability, a new chaos appears.

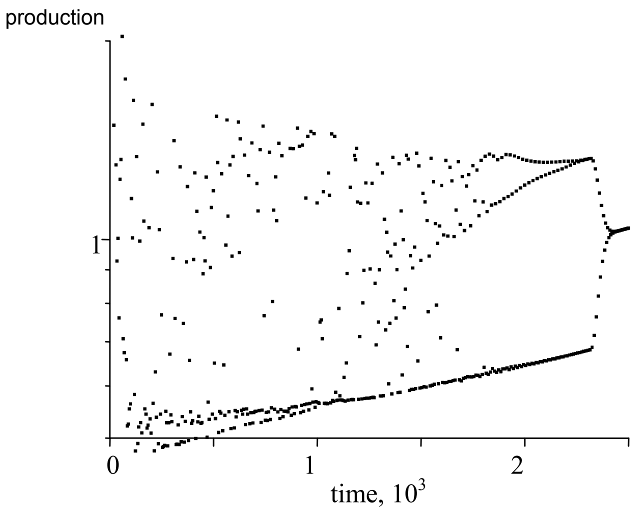


**Fig. 2.** Working of the invisible hand.

The time needed to reach the instability (or the collapse of economy) is called as the lifetime of the economy. Life time is defined by the technology (production vectors) and the interest rate. In Figure 3 the lifetime is plotted as a function of interest rate. The figures confirm Neumann's result, the golden result, for a given technology there is only one interest rate, which gives a stable growth. All the other interest rates give growth with limited stability, but in the nearly stable growth regimes the price ratio is nearly constant.

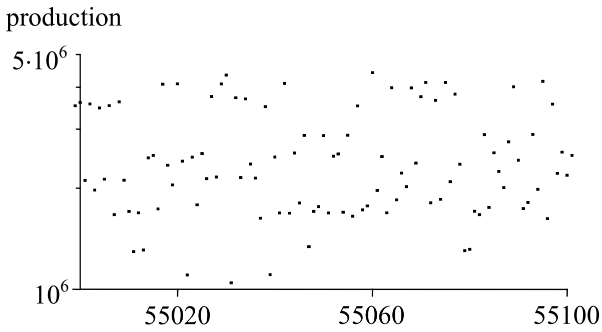


**Fig. 3.** Emergence of chaotic behaviour.

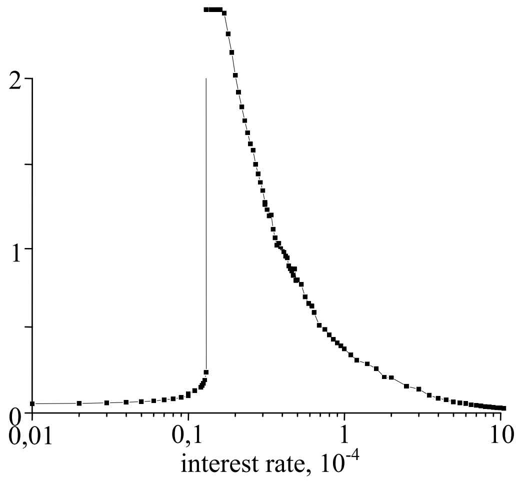


**Fig. 4.** Life time versus interest rate.

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Journal of Evolutionary Economics **6**, 347-360, 1996.

# von Neumannova ekonomija u pristupu modeliranja pomoću agenata. Istraživanje stabilnosti i nestabilnosti u ekonomskom rastu

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## SAŽETAK

Aksiomatski temelji neravnotežne mikroekonomije su skicirani. Ekonomska aktivnost modelirana je u obliku transformacije i transporta sredstava (materije) koje posjeduju agenti. Stopa transformacije (intenzitet proizvodnje) i stopa transporta (trgovina) definirani su agentima. Pravila ekonomskog odlučivanja izvedena su iz opaženog ekonomskog ponašanja. Nelinearne jednadžbe rješavane su numerički za von Neumannovu ekonomiju. Struktura ravnotežnog tržišta javlja se kao proces stvaranja reda unutar kaosa.

## KLJUČNE RIJEČI

ekonomija, ireverzibilnost, rast, kaos

*Interdisciplinary Description of Complex Systems* 2(1), 79-87, 2004

# FORESIGHT AS A SPECIAL CHARACTERISTIC OF COMPLEX SOCIAL SYSTEMS

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## SUMMARY

There is a great difference between ordinary and emergent complex systems [1]. One of main differences is the foresight ability of emergent systems. This paper shows some methodological approaches to forecast the possible future behaviours of complex social systems.

## KEY WORDS

futures studies, emergent, foresight, future orientation, evolutionary modelling

## CLASSIFICATION

ACM Categories and descriptors: J.4 [Computer Applications]; Social and behavioral sciences,

APA: 3040, 4010,

JEL: A0,

PACS: 87.23.Ge, 89.65.-s

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## STARTING POINTS

The 90's in Hungary gave an excellent basis to think about the future, futures studies and within of them the forecastability of complex social systems in a fresh way. The long lasting period of transition from the eastern type of socialism to the modern western style democracy put new questions concerning our relation to the future and the role of futures studies in forming our society. Under these circumstances we have met the forecasting problems of emergent complex social systems in reality. We have found that the main characteristics of emergent social systems are that *their existing forms are the orientation to the future and the alternativity*. Orientation to the future means that human component of the complex social system interprets, explains, values and scans its environment. Homo Sapiens thinks about how to adapt to its changing environment or to change the environment and itself continuously. During that process the human component makes the social system uncertain and gives to it alternative existential forms concerning both the present and the future of it as well. These characteristics of social system become very strong in its transitional period. The question to be answered by the futurists is: how to forecast the future of this strongly changing or evolving social system?

## ANSWERING NEW PRACTICAL NEEDS IN FUTURES STUDIES

### FUTURE ORIENTATION OF THE AVERAGE PEOPLE

Future orientation first appeared in futures studies as some pessimistic attitude [2]. Negative future orientation, future shock, in Toffler's assessment, is the result of the individual being overburdened by challenges of the future and excessive environmental stimuli, under which he breaks down. The message of Toffler's book, however, is not only that changes are harmful because they exhaust society's ability to adapt but also *the future orientation; a positive attitude to the changes* can help one to prepare for and live with the changes. The Hungarian experience showed the magnification and problematic nature of the negative attitude to the changes. It was a surprise, since before the transition the lack of change or invariability that had become depressing.

Future orientation is a unique feature and capacity of human beings. This way of thinking is influenced not only by the past and the present but the future too. Additionally, human mind reflects its ideas and expectation regarding to the future. Humankind has a historical view and also has an attitude to the future, which is expressed in the future orientation. Decisions and actions of the future-oriented person are guided more by his/her intentions, goals and desires for the future, than by his/her experience of the past. Future-related inspirations are the driving forces of human activities [3].

Future orientation can be analysed empirically by surveys. Examining future orientation provides specific knowledge concerning individuals' attitudes to the future. In some of our surveys we analysed for example the following questions:

- how deeply people are interested in future and how they activities reflect this future orientation?
- what is the role of "future orientation" in forming individuals' life strategies, and
- what is the role of "future orientation" in shaping future views and social programs?

Empirical analysis can discover the nature of the components of future orientation, for example, interest in and thinking about the future, dealing with the future, decreasing the uncertainty of the future, activities performed in the interest of the future and expectations of the future; on the harmonious or disharmonious relationship of opinions concerning the components; and particularities of the future orientation of certain social groups trained according to different point of view.

*Research into future orientation can constitute one part of all types of forecasts which embrace how individuals and citizens think of the future, what they expect from it, and what they intend to do towards.* Research into future orientation does not constitute forecast in itself, but it includes activities related to forecast which may prove to be useful amid circumstances of social transformation.

## FUTURE ORIENTATION BASED FORESIGHT OF THE HUNGARIAN VOCATIONAL TRAINING

In one research project we set as an objective to give an outline of the alternative development trends of the Hungarian vocational training with the tools of the futures studies [4]. Our starting point was that the extrapolation of the past tendencies of development in our forecasts for the future would not function as an incentive to new, innovative thinking and concepts. Therefore, the functional change, role and tasks of vocational training in Hungary amid changing socio-economic trends need to be reviewed by using a new approach to this problem.

To the outline the alternatives, alternative scenarios, for vocational training in Hungary, our attention was focused on:

- international comparison; how do the countries and regions, now on top of the development charts, define the socio-economic functions of vocational training and the corresponding tasks?
- what is the opinion of the decision-makers of Hungarian vocational training on the problem of Hungarian vocational education, the alternatives of solution and the prospects for future development?
- is there any clear alternative for our vision of the future in the way the prospects are viewed by the functional participants of the system of vocational training, including their expectations, which can be interpreted both as local manifestations of and the solutions to the global or regional problems of vocational training, that hold out the prospect catching up with others, expressing the problems characteristic only of Hungary and putting forward solutions alternatives adaptable by that country?

In our international outlook we have focused on products of futures studies that aim to describe the future models of society and concentrate on the long-term strategy of education and vocational training. We have interviewed the participants of the vocational training system on how they see the problems and the possible development of the Hungarian vocational training, the ways of solving these problems and the possible developments of the system. These actors are as follows:

- schools (teachers and trainers) involved in vocational training, i.e. the providers of vocational training services,
- children and their parents who participate in training, or are directly linked to vocational training services, and
- employers, the customers of vocational training.

Each actor is competent in different issues, therefore, on the basis of their opinions and expectations we can gain valuable information about the social and economic environment, functions and possible systems of vocational training.

In our forecast methodology we used elements and solutions in three primary aspects:

- an international outlook
- empirical studies of the future in Hungary and
- processing of basic forecast information.

Our international outlook was directed to the actual problems related to the development of education and vocational training in the world today and in different geographical regions and countries, the response to those problems, the objectives and tasks on hand to find a solution to the functional reform of vocational training rather than at the current state of affairs in terms of global, regional and national level vocational training are at the standard of development to be considered as guideline to be followed. We are of the view that this is the most practical framework of knowledge to be used in terms of international outlook, given the globalisation, the increased openness of our country and our future plans of accession.

The approach to empirical studies of our future by using the method known as an one-round interviewing of experts was different from that of traditional methods of futures studies in that *our interviews were not confined to experts, and that opinions other those considered typical were also taken into account*. By our view, involvement of non-experts was essential, because vocational training in a global environment will be a part of the service sector. *Involving views other than those considered typical was an important element our survey*, as in our society, which is currently undergoing a process of gradual pluralisation, opposing views and ideas are an inseparable part of the new system. Given the view that future is open (as it has not materialised yet), opposing views and alternative thinking should be brought out into the open rather than be suppressed.

In processing basic forecast-related information we have developed a schedule consisting of two work phases. *Phase one* was devoted to the collection of identical or similar, diverging or uncertain views in specific areas examined, which were then arranged into systems of logical uniformity, which produced future alternatives and variants in education and vocational training. In the *phase two* comparative analysis was performed, leading to a complexity of future alternatives and variants of vocational training in Hungary by logical linking of diverse scenarios for vocational training regarding the future, including social expectations voiced in those areas.

*Our improved methodology was a step forward in the direction of a forecasting method where the question to be answered was "what might be" rather that "what will be"*. By presenting the future as different alternatives and also by using a new methodology in our forecasting work, we set forth a perception of future along with the feasibility of ideas in which the future manifests and functions in the present time in the form of expectations, thinking, ideas, objectives and a will to act. *This perception of the future is referred to a special type of foresight.*

## EVOLUTIONARY MODELLING IN FUTURE STUDIES

The range of *possible futures of socio-economic processes can be researched by applying the evolutionary methodological bases* [5]. Evolutionary models of demographic and economic processes were built up and some possible futures states were generated by these models.

*The evolutionary demographic model for Hungary* concentrated only on the possible changes of fertility patterns, and their consequences to the change in population number. The starting point was that individuals follow several habits depending on their lifestyles, cultures and future orientations. The term of social gene was used to project the maternity habits in Hungarian society. It means that the different generations of women in which age and with how much probability want to bear a child during their life path. The analysis and forecasting of dynamic variability of fertility patterns make possible to show up a wide interval of changes on population number in the future. This model dynamics shows that *the forecast is more uncertain and this uncertainty cannot be only handled stochastically* [6].

*The evolutionary economic model interprets the economic reality not only as the system of connections of the facts in time but also as the time-and-space dimension of facts resulting from the foresight and activities of the economic actors who play a part in the creation of the facts.* It stresses that in the economy the changes do not simply happen but they are the results of the activities of economic actors. These actors do not know the future completely, they have but assumptions about and expectations for it, but they may strive to survive and to improve their situation. This is why they cannot make optimising decisions. Their activities may be guided by routine, traditions, learning, foresight and renewal alike [7 – 10]. *By the help of the laws of interconnectivity between the different systems it states a non-equilibrium description of the economy.*

It follows from this concept of the economy that *chance is a determining element of both the economy and of our theoretical model.* Chance can make economic changes probable but can also generate them. Chance can be brought about by the incomplete rationality of economic actors and the changes in interaction between the economic system and its environment. It is this chance that allows the theoretical creation through the evolutionary model of the possible range of economic change.

E*volutionary approach and modelling may enrich the storehouse of forecasting and, thus, that of futures studies and its methodology too*. Amid conditions of instability, the evolutionary theory and modelling can further develop the scientific bases of research and study focussing on forecasting the domains of the possible futures. The concept of evolution provides the attitudinal framework within which the different planes of time and space, the past, present and future can be conceived as they interact. *Evolution is not only a biological analogy but a statistically irreversible change that leads to the formation, iteration and transformation of an organised structure of time and space.* The space-and-time dimension, the connection of the different time and space planes, is, therefore, a characteristic constituent part of evolutionary theory and its models. The sequence, the passing of time generates the iteration of the steps. During one iteration the events and possibilities of the previous and the forthcoming time (the past and the future) together determine the characteristics of the current time (the present).

In evolutionary models *there is an organic link between the past, present and future*, which can be used for the reconstruction, understanding, explanation and forecasting alike of the social and economic reality. Using them for forecasting, however, is limited in the sense that it can provide only a short-range description of the probable future of a modelled sphere of realities. *The possible behaviour in time of the* *demographic and economic system and the changes in their dynamic characteristics may also help us conclude within what time range the well-known deterministic and stochastic methods allow us to forecast, and under what conditions and when we must make do with the limited nature of the possibility to foresee.*

*Evolutionary models can show the future only with uncertainty and in its potential.* This feature constitutes its strength, however, as it *helps to discover a rather wide range of future possibilities, which makes the separation of what is and what is not possible in the demographic process and economy far more reliable.* The possible domain of the socio-economic future is wider of course, as it may comprise different renewing and declining futures beside the consequence future. Our models are able to generate these future domains automatically.

Social and economic forecasts are not only about stating what is possible but also about *providing distinct alternatives* within our means. These models in themselves are not suitable for that, but combined with other forecasting methods they can theoretically provide a more reliable forecast than the hitherto used combinations of methods. These latter could also provide alternatives but without us actually proving their possibility. With the evolutionary approach and the use of our models we can turn around the logic of forecasting. *First we explore the future social and economic possibilities and then we look for and form - among the possibilities - the acceptable, tenable, desirable, etc. social and economic alternatives with the help of other forecasting methods.* The direction of further methodological research is, therefore, to explore what other or new combinations of methods can be used together with evolutionary models for making social and economic forecasts that provide alternatives, too.

## FUTURE PROSPECTS OF FUTURES STUDIES

There are two paradigms in progress in the contemporary futures studies: the evolutionary futures studies and the critical futures studies [11]. The traditional futures studies focuses on the different variants of probable futures which are the consequences of the past and the present. If the materialised future was not among the previous range of forecasts - which happens very frequently - then the problems or the limits of the traditional paradigm of normal science become visible at once. If futures studies turns towards the futures which are qualitatively different from the "consequence futures", then one must transcend the earlier paradigm and start to build an "interpretative scientific paradigm". The way of reconstruction of theoretical and methodological base of futures studies shows that two alternative paradigms - evolutionary and critical futures studies - are shaping.

### FORESIGHT IN THE EVOLUTIONARY FUTURES STUDIES

Theories and methodological trends dealing with the forecasting possibilities of emergent complexities are named evolutionary futures studies. Evolutionary futures studies supposes the future should be a kind that is open, defined and undefined at the same time, and is the scene of human activity. The uncertainty of the future is evolutionary, as the risk is the survival of human society.

According to this notion the subject of futures studies is *the evolution of so-called emergent complexities, which include everything, even human being her- and/or himself*. Thus futures studies as a social science focuses on complexities of which human being and his or her society are organic parts. Human being plays a part in these complexities not only as a biological but as a psycho-social being too. His or her biological participation and evolution are less significant for the purposes of futures studies because changes of this nature are very slow and their time span transcends the sphere of interest of futures studies. Human being's ability to feel, to think and to form different social organisations, however, is considerably more changeable than his or her biological entity, which is why the real subject of futures studies is the interaction between the former quality and its natural and artificial environment as well as its evolution.

The representatives of evolutionary futures studies *accept the hypotheses of the general evolutionary theory as regards its general features*. They stand for the notion that the evolutionary change of emergent complexities is generated by external environmental changes, but the development of complexities unfolds through inner counter-reactions. An evolutionary change takes place when the mechanisms that reduce fluctuations are no longer able to hinder errors, and the growing fluctuation sets complexity on a new course by generating bifurcating mechanisms. In this time a number of options, possible social futures emerge, and it is extremely uncertain which of the possible futures will transform complexity and saturate its subsystems [12]. Once the competition among the futures is settled, a period of dissipation ensues when the changes engulf and reshuffle complexity, thus giving rise to a new level of evolution.

Evolutionary shift is preceded by the accumulation of tensions and deviancies of differing character and crises. These can be recognised by means of society's information system. Evolutionary shift, however, is a great deal more difficult to forecast due to its uncertainty. For this end not only an evolutionary approach is needed but also *the ability to recognise the possible new value patterns unfolding in society*.

*Human being plays a defining role in this approach*. His or her position and role, however, depend on the cognitive interpretative notion of the future. In evolutionary futures studies *human being plays an important role as one of the components of progressive complexities*. The knowledge about progressive complexities and their evolutionary movement furnishes insight into the future expectation, values, goals and activities of human being and his or her social institutions as well as their changes. This knowledge forms part of the cognitive map of reality. Evolutionary futures studies, therefore, examines the dynamics of different social complexities in order to explore the map of possible prior knowledge and understanding of the future. Therefore in the practice futures studies has to study the future orientation, invention of people, their groups and institutions and their changes. *These kinds of human thoughts, options, wills, plans, and actions for the future can also be seen as special forms of human foresight*.

## FORESIGHT IN THE CRITICAL FUTURES STUDIES

According to the critical futures studies *the future can be interpreted not only as something that will be materialise as time passes but also as something that exists in the present too, in our thoughts and emotions*. This future affects the present and forms an integral part of life's rules. Besides being a peculiar form of cognitive interpretation, it is also an emotional (optimism, pessimism, hope and fear). This future which exists in the present is the most developed form of human foresight. The latter is a human ability to protect human beings from harm and to render their activity smooth and uninterrupted. It emerges in the course of learning and can be developed. At the human being's current level of development thinking of the future and having a consciousness of the future can no longer be regarded as two separate forms of thinking.

In this way the present is, on the one hand, the limited time category of "here and now", on the other hand, an "extended present" in our conscience, able to condense and update the past, the present and the future. *Human foresight functions in this extended present*. That is why critical futures studies targets this type of future envisaged as human foresight. Its task is discovering human foresight on the one hand and the further development of this activity, raising it to the social level on the other hand [13].

Futures studies that focus on human foresight break with the time-honoured and widespread concept of traditional futures studies. By forecasting the future the old method provides a prior knowledge of the future. Opposite to this, critical futures studies considers this impossible and undertakes nothing more than to discover the future contents existing in the present, to analyse them critically, to socialise them and to provide help in developing individuals' and social institutions' ability to foresee. Due to its links to human foresight and its critical attitudes to it, *this type of futures studies is also called foresight*.

## THE NEED OF FURTHER DISCUSSION ABOUT FORESIGHT AND ITS ROLE IN THE EMERGENCE OF COMPLEX SOCIAL SYSTEMS

Human foresight activity has a crucial importance in the further development of different futures activities. But there are a lot of questions to be answered for that *the foresight gets his right place in futures studies and forecasting practice*:

- there are different foresight meanings (from future orientation to hopes and fears of future events) arising from the practical needs and the theoretical-methodological research works,
- the application of quantitative evolutionary models shows that data may play an important role in signing the limits of our subjective desires and dangerous future zones,
- at present both the qualitative and quantitative approaches of the foresight run side by side, and
- the options of new information and communication technology have not been exploited yet in different foresight activities and futures studies.

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# PREDVIĐANJE KAO POSEBNO SVOJSTVO SLOŽENIH SUSTAVA

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## SAŽETAK

Velika je razlika između ordinarnih i izrastajućih složenih sustava [1]. Jedna od glavnih razlika je mogućnost predviđanja kod izrastajućih složenih sustava. Ovaj rad pokazuje metodološke pristupe predviđanju mogućih budućih ponašanja složenih društvenih sustava.

## KLJUČNE RIJEČI

proučavanje budućnosti, nastajanje, predviđanje, stav prema budućnosti, evolucijsko modeliranje

*Interdisciplinary Description of Complex Systems* 2(1), 88-94, 2004

# COMPLEXITY AND UNCERTAINTY IN THE FORECASTING OF COMPLEX SOCIAL SYSTEMS

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## SUMMARY

The better the model, the more features of the problem it explains. However, showing that the model has similarities to that of a phenomena is often less significant in applications due to lack of data. Forecasting, as special application of modelling, is neither an exception: besides statistical data one should use several types of subjective assumptions about the present and the future state of the model. In case of complex models, this fact is extremely important, because these models use often unobservable, hidden or – regarding its future evolution – uncertain variables. We developed a simple mathematical approach how these uncertainties can be managed in the model. We shall also show how these uncertainties can influence the behaviour of modelled variables, and how an approximate for time horizon of forecasts can be calculated.

## KEY WORDS

complex systems, futures studies, foresight, modelling, time horizon

## CLASSIFICATION

ACM Categories and descriptors: J.4 [Computer Applications]; Social and behavioral sciences,

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## INTRODUCTION

It must have been an early discovery that understanding social phenomena needs complex modeling approach. Modeling difficulties, especially in the case of formal modeling, however, seemed to be much harder to surmount as explaining the results of the partial, noncomplex models. E.g. in economics, utility functions are an easy and capable tool for explaining several types of economic behavior, but formal model builders using this tool had never even been aimed to explain why and how these utility functions were chosen. Of course, all of them know very well, that the tool they use is the contact point to many other social behavior and phenomena. But, believing in traditional scientific separation of disciplines, these contact points are regarded as curtains indicating the border, the things behind which they simply do not want to care. Complex model approach concentrates on the targeted phenomena, uses interdisciplinary components if necessary. But as complex model approach covers a wider range of processes, it also demands a wider range of data, which is often inaccessible. Sometimes inaccessible data is only because of the fact that statistical offices supply only traditional models with aggregate macro data that is not detailed in the demanded complex way. Further research and experiments may access this data. But these research and experiments can also be very expensive or probably unfeasible: the data remains inaccessible, fitting the model needs further assumptions.

## UNCERTAINTY

In the following, we shall show on a very simple example how uncertainty can be managed within a very simple model. Let us consider a certain social quantity $x$ that can be observed continuously. We are certain about the growth rate of this quantity $\alpha$, that should be considered to be constant even on the long run. The evolution of this quantity is given by

$$x(t) = x_0 e^{\alpha t}. \tag{1}$$

where $x_0$ denotes the initial value of the variable $x(t)$ at time 0. We are aware that most social processes are observed with more complex dynamics and structure, but here in this simple example we chose also a simple dynamics. In fact, here parameter $\alpha$ plays only a symbolic role, that shows the models self-deterministicity, as $1/\alpha$ denotes how strong the model depends on its own parameters: e.g. if $\alpha$ is negative, that large $\alpha$ values mean short-time memory of the process.

Regarding the small increments of $x$ we write the previous form of the evolution of the process as:

$$\frac{\mathrm{d}x(t)}{\mathrm{d}t} = \alpha x(t)\,. \tag{2}$$

We assume, that all type of uncertainties are due to an additive term to this expression:

$$\frac{\mathrm{d}x(t)}{\mathrm{d}t} = \alpha x(t) + f(t)\,. \tag{3}$$

where $f(t)$ denotes some type of "disturbing" processes, that are not managed by the model. Of course as $f(t)$ is an external variable, we do not know much about its behaviour, and we can have basically two types of assumptions. In the practice of data-analysis some probabilistic behavior is often assumed for uncertainty. The simplest example for this type is the white noise, which means in words that the uncertain variable $f(t)$ is independent from the process $x$, but also from its previous values (uncorrelated), and the "size" of the uncertainty (variance of $f(t)$) does not change in time. Note that, as above in case of parameter $\alpha$, the choice of white noise is also an illustration of the stochastic variables that may appear in the model. Another way to manage uncertainty in the model is to choose $f(t)$ from a set of functions without any probabilistic assumptions. In this case (3) must be solved for all element of this set, and the future value, in case this type of uncertainty is the only one present, is the set of future value of all possible evolution of the process. The simplest example for this type of uncertainty is to assume $f(t)$ to be small: $|f(t)| < \varepsilon$ for all $t$. Note that modeling using interval dynamics e.g. multifunctions is not unknown for economists (Debreu became a Nobel-prize for his research in this field [3]). Now, we solve for all "small" (measurable) functions (3). The uncertainty under these assumptions can be measured by the diameter of the interval of the future value of $x$:

$$E_{\text{Det.}}(x(t)) = \max_{|f|<\varepsilon} x_{f(t)} - \min_{|f|<\varepsilon} x_{f(t)}, \tag{4}$$

where $x_f$ denotes the solution of (3) for the measurable function $f$.

Fortunately, we have an analytical solution of (3) for all (measurable) functions:

$$x_{f(t)} = x(t) = \int_0^t \mathrm{e}^{\alpha(t-s)} f(s)\mathrm{d}s\,, \tag{5}$$

In particular, if $f$ contains stochastic and a deterministic part (a white noise and a "small" function), the solution can be written in the following form:

$$x(t) = \sigma\int \mathrm{d}W(s)\cdot \mathrm{e}^{\alpha(t-s)} + \int \mathrm{d}s\cdot f(s)\mathrm{e}^{\alpha(t-s)}\,, \tag{6}$$

where $\mathrm{d}W$ denotes the white noise, $\sigma$ is the measure of the stochastic uncertainty and $f$ is a "small" function. We see, that in our special simple case, the two types of uncertainties (the stochastic and the deterministic one, i.e. the first and the second part of the solution in (6) can be calculated independently. Note that this is now a very favorable case to consider, because in general even if analytical solutions are supplied, it is not ensured that the evolution of the system (e.g. in case of chaotic dynamics) will result contiguous sets for the deterministic disturbance.

The interpretation of equation (6) can be approached from either the stochastic or the deterministic side. On the one hand, let us fix the deterministic disturbance function $f$. Now we get a stochastic process, and the future values of variable $x$ are stochastic variables that can be managed by the usual probabilistic methods. If another possible disturbance function is chosen, we get another stochastic process. It is clear that one possible way to interpret the solution is a set of stochastic processes, and according to this the interpretation of the future variable $x$ is a set of random variables. On the other hand, let us realize the white noise, and calculate all the results of the deterministic disturbance function $f$. This yields a set function where for each $t$ the future value of $x$ is a contiguous set (interval). If another realization is taken, we get another set function and intervals for the future value. In this sense the future value of $x$ is a "random interval variable", which gives intervals as a result when realized.

Let us analyse the solution (6) by calculating for any given time $t$ the measures of uncertainty for the two terms. The measure of uncertainty of the first, stochastic term is the variance:

$$\mathrm{Var}\left[\int_0^t \mathrm{d}W(s)\mathrm{e}^{\alpha(t-s)}\right] = \int \mathrm{d}s\left[\mathrm{e}^{\alpha(t-s)}\right]^2 = \frac{\mathrm{e}^{2\alpha t}-1}{2\alpha}.$$

The measure of the "deterministic uncertainty" is the measure (i.e. length) of the interval, which can be calculated

$$\mu_L\left\{\int \mathrm{d}s f(s)\mathrm{e}^{\alpha(t-s)} : f \in F_\varepsilon\right\} = \varepsilon\frac{\mathrm{e}^{\alpha t}-1}{\alpha}.$$

where $\mu_L$ denotes the Lebesgue-measure and $F_\varepsilon$ the set of real functions that maps to $[-\varepsilon, \varepsilon]$.

Comparing the measures of the two different type of uncertainty we see, that for small time-scales ($t << 1/\alpha$), the stochastic one behaves as the square root function, while the deterministic one is linear. For large time-scales ($t >> 1/\alpha$) however both expressions behave as $\mathrm{e}^{\alpha t}$. This means that for small time-scales always the stochastic type of uncertainty is dominant. For large time scales the two type of uncertainty follows the same law, however, it depends on the parameters which is the larger, Figs 1 and 2.

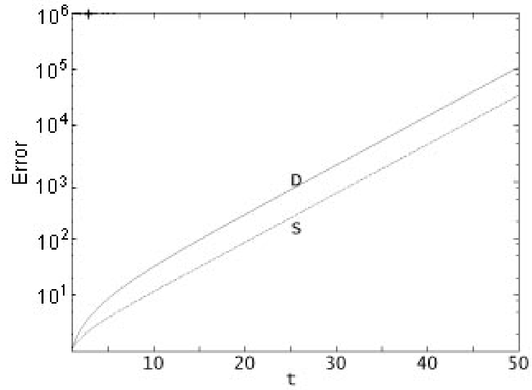


**Figure 1.** The two types of uncertainty follow the same rule on the long-run (illustration).

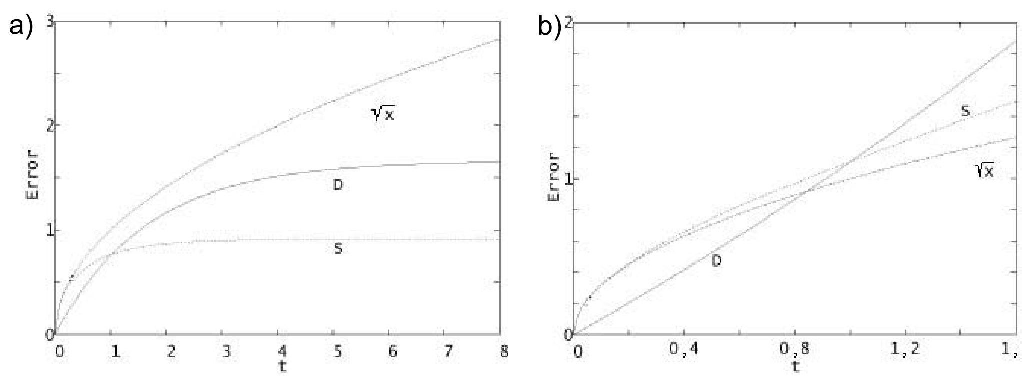


**Figure 2.** The two types of uncertainty on short-run. Parameter $\alpha$ is a) negative, b) positive.

Of course, the most important question is, what is the interpretation of a future variable with mixed types of uncertainty.

Nowadays it is usually accepted to have stochastic uncertainty in a model. It is also accepted, that different future scenarios are worked out to manage easier the future complex behavior of the system. It is however not clear how to interpret future scenarios with stochastic variables (see table 1). Now we are facing a similar problem in our model.

**Table 1.** The impact of different types of uncertainty.

| Type of uncertainty | None | Stochastic |
|---|---|---|
| none | deterministic value | Statistics |
| deterministic | scenario | ? |

If we have small stochastic uncertainty than we can use an interpretation similar to the scenarios. If we have small deterministic (external) impact, we can use stochastic models (even on long run, as proven above). The problem arises when the two type of uncertainty have about the same impact. Our opinion is, that it is impossible to put a question about the future variable in this case. The main problem with this kind of mixed uncertainty is that the stochastic noise is large enough to make the "deterministic noise" (intervals) overlap, but not large enough to disperse them disjunctly. Therefore both approaches to interpret the future value fail. In fact, this is not the case, in which we do not know anything about the system. But it is the case, in which the two types of uncertainty together results in a much higher level of uncertainty compared to the accepted level. As we see in our simple model, stochastic uncertainty is always dominant for short time-scales. It depends on the parameters of the model, whether or not the deterministic uncertainty takes over for long time-scales. If so, then there exists a point where the usual probabilistic methods fail due deterministic perturbance. We define this point as the point where the measures of the two types of uncertainty are the same. According to the above, we regard this point as a goodness of the forecast: the larger this value is, the more stability our model has, against not modeled (e.g. external) perturbance. We call this point time horizon of the forecast, which is not to be regarded as a cutting point of our forecast to throw anything away behind this point, but as a characteristic value for our model, where increasing the value the model improvement should keep an eye on. Time horizon approximations are recently developed on complex models of demographic processes [1, 2].

Now, we calculate the time horizon of our simple model. Firstly we determine the condition of the existence of the time horizon. As mentioned previously, the deterministic noise can be small enough to be smaller for the whole evolution of the model. In this case there is only one solution of the equation

$$\varepsilon \frac{e^{\alpha t}-1}{\alpha} = \sigma \sqrt{\frac{e^{2\alpha t}-1}{2\alpha}}\,, \tag{7}$$

namely $t = 0$. So, the condition is

$$\left|\frac{\varepsilon}{\sigma}\right| \le \sqrt{\frac{\alpha}{2}}\,.$$

If the deterministic noise (i.e. $\varepsilon$) is small, stochastic models are appropriate also for the long time-scales. If this condition does not hold, the time horizon should be considered, so the (only) positive solution of (7) should be calculated:

$$\left|\frac{\varepsilon}{\sigma}\right| = \sqrt{\frac{\alpha}{2}\cdot\frac{e^{\alpha t}+1}{e^{\alpha t}-1}}\,.$$

Thus, how far we can predict with our simple model depends on how strong the deterministic noise is present in the model (compared to the stochastic noise), $\varepsilon/\sigma$ and on how strong the model is determined through its inner dynamics, $\alpha$.

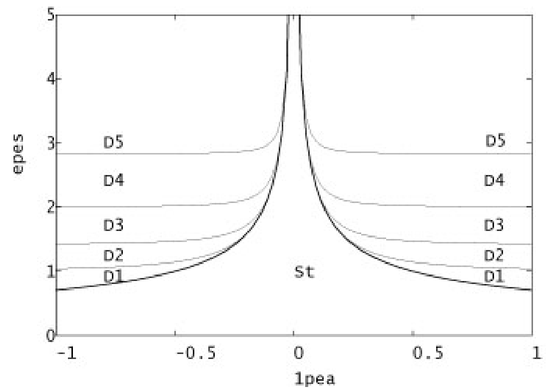


**Figure 3.** Regions for different time horizons ($D_1$, …,$D_5$), and the stochastic stable region (Stoch.).

In figure 3 we can see several regions of the model parameters defined by the different time horizons (not that in the figure not $\alpha$ but $1/\alpha$ is plotted for a better overview). It is clear that in case of strong internal dynamics of the model, the deterministic noise has little impact on the process, but for each finite $\alpha$ a certain threshold can be given above which the influence is significant and time horizon should be considered. The regions of $D_1$, …, $D_5$ are separated by the iso-time-horizon lines for time horizons of 0,125, 0,25, 0,5 and 1. It is interesting to see, that the real "model risk" for forecast is the parameter $\alpha$, the strength of internal determination of the model. Two similar models with little difference in internal determination can have larger difference in time horizons than two similar models with little difference in deterministic noise. If the parameter $1/\alpha$ is negative, it is also to be interpreted as the memory of the system. If the system has large memory stochastic stability can be disrupted by small deterministic noise. In case of large memory, the time horizon is mainly the function of the deterministic noise. The real model risk in this case is similar as above: at a certain memory, a little change in deterministic noise can have large impact on the time horizon. In words, we would express this property as above this threshold the model would be depend stronger on other non-modeled (e.g. external) processes rather that its own dynamics.

## CONCLUSIONS

The time horizon is defined for forecasting models of social phenomena as a test of the dependency of non-modeled or external processes. As almost all social phenomena is embedded strongly in a complex background, non-modeled processes should be quite often considered. Often these processes are not included in the model, because it is hard or impossible to obtain information about them. Stochastic models are used quite often especially in economics. These models proved to be unstable if other non-modeled processes (e.g. politics) can have large influence on the process. The question whether the impact of these processes from the complex background should be considered as large or small depends also on the internal dynamics of the system. Systems with small memory or characteristic internal dynamics are less sensitive to these effects.

## ACKNOWLEDGMENT

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# SLOŽENOST I NESIGURNOST U PREDVIĐANJU SLOŽENIH SUSTAVA

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## SAŽETAK

Što je bolji model, više svojstava objašnjava. Međutim, dokazivanje sličnosti modela i pojava obično je manje važnosti zbog nedostatka podataka. Predviđanje, kao posebna primjena modeliranja, pritom nije izuzetak: osim statističkih podataka potrebno je primijeniti nekoliko vrsta subjektivnih pretpostavki o sadašnjem i budućem stanju modela. U slučaju složenih sustava ova je činjenica posebno značajna, jer njihovi modeli upotrebljavaju obično nemjerljive, skrivene, ili – obzirom na njihovu buduću evoluciju – nesigurne varijable. Postavljen je jednostavni matematički pristup baratanju s nesigurnostima u modelu. Dodatno je pokazano kako nesigurnosti mogu utjecati na ponašanje modeliranih varijabli i kako se određuje približni iznos horizonta vremena predviđanja.

## KLJUČNE RIJEČI

složeni sustavi, proučavanje budućnosti, predviđanje, modeliranje, horizont vremena

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# FIRST GENERATION MULTI-AGENT MODELS AND THEIR UPGRADES

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## SUMMARY

Multi-agent systems consist of interactive and independent agents of different kinds in a "world" of the computers. The key issue of multi-agent modelling is its ability to produce emergent phenomena at macro level from "micro-behaviour". For now this approach became a widely used methodology in socio-economics and ecology. This paper presents three famous first generation models and then drafts some of their upgrades, especially the agent-based computational economics, the spatial planning approach and the ecological models. Finally some conceptual developments are presented and discussed.

## KEY WORDS

simulation, early multi-agent models

## CLASSIFICATION

ACM Categories and descriptors: I.2.11 [Computer Applications]; Distributed Artificial Intelligence, Multiagent systems

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## SOME FEATURES OF "FIRST GENERATION" MULTI AGENT MODELS

Multi-agent simulations of human or animal interactions show that simple agents and simple rules can generate aggregate effects, frequently identified as emergent phenomena. The first glorious period of this new methodology was a real breakthrough in the paralyzed social science methodology. Surprisingly the second wave was not as intensive as the first one, although the number of publications, Internet portals and conferences on top of multi-agent systems are steadily increasing.

Publications about multi-agent simulation of social phenomena have mainly dealt with conceptual or demonstrative issues and the usage of real data was rather seldom. In the last few years we could observe the increased popularity of multi-agent methodology for simulating real and complex problems. I present three famous "first generation" multi-agent models to illustrate the path which lead to the currently emerging questions. These models are Schelling's "Segregation" model, Epstein and Axtell's "Sugarscape" model, and the "Peppered Moths" model of Wilensky.

### SCHELLING'S SEGREGATION MODEL

Segregation into different regional neighbourhoods was often considered to be a result of direct discrimination or of the effects of economic conditions. Schelling pointed out that if families (i.e. black and white) prefer to live in neighbourhoods, in which their own ethnic group is a majority, and they are able to move to the nearest location which satisfies this desire, complete segregation will inevitably emerge. The simulation models the behaviour of two types of agents in a small world. The "red" agents and "green" agents get along with one another, but each agent wants to make sure that it lives near some of "its own". The simulation shows how these individual preferences lead to large-scale patterns [1, 2]. Explanation of "macro" phenomena with "micromotivations" is extremely useful and became popular. *Schelling's model had an important role to demonstrate this, since relatively small individual preferences lead to significant overall segregation.*

### EPSTEIN AND AXTELL'S "SUGARSCAPE" MODEL

This is an excellent illustration of a model which yields numerous interesting results about the emergence of evolution of social phenomena, although the agents are rather simple. In this artificial society the agents move within a grid, in which each cell has a changing quantity of 'sugar'[1]. Agents have to eat sugar to survive. The amount of sugar at each location varies spatially and according to the consumed quantity. If agents harvest more sugar than they need immediately, they can save it or trade it with other agents. Agents can see at a distance which varies randomly depending on their `genetic endowment', so that some of them can see many cells away while others can only see adjacent ones. Agents are goal-oriented and move by the rule: find an unoccupied cell, which has the highest available sugar level and move there. They also differ in their 'metabolic rate', that is the rate at which they use sugar. They die when their sugar level falls to zero and new agents replace the dead ones.

The model has demonstrated the 'survival of the fittest' mechanism successfully. Agents with poor vision, high metabolic rates and located in little sugar for harvesting area die quickly. The model also shows that even if agents start with an approximately symmetrical distribution of wealth, a strongly skewed wealth distribution soon develops. This is because a few, relatively well-endowed agents are able to accumulate more and more sugar, while the majority only barely survive or die [3].

### WILENSKY'S "PEPPERED MOTHS" MODEL

*That model simulates a classic example of natural selection through the example of the peppered moths of Manchester, England.* The peppered moths use their coloration as camouflage from the birds that would eat them. Historically, light-coloured moths predominated because they blended in well against the white bark of the trees they rested on. However, due to the intense pollution caused by the Industrial Revolution, Manchester's trees became discoloured with soot, and the light-coloured moths began to stick out, while the dark-coloured moths blended in. Consequently, the darker moths began to predominate. Now, in the past few decades, pollution controls have helped clean up the environment, and the trees are returning to their original colour. Hence, the lighter moths are once again thriving at expense of their darker cousins. This model simulates these environmental changes, and how a population of moths, initially of all different colours, changes under the pressures of natural selection. *The most important thing is how the entire set of moths changes the colour over time.*

During the first few initial time-steps, the moth population booms, then the moth population fluctuates between different levels, some of which are quite large. The moths give birth to many offspring, but the world in which they live is finite - it has finite space and resources. If the population exceeds the available resources (carrying capacity), the moths tend to die a lot faster than they would otherwise. Under normal circumstances, the average population will tend to stay constant, at a level dependent on the speed and selection rates. In case of drastic change in the environment all of the moths are killed in a few time-steps [4].

Otherwise the too fast environmental change is frequently a subject of ecological simulations. *Most of these models analyse the adaptability of ecosystems to the accelerated changes, i.e. caused by the climate change or by some human activities.*

## UPGRADES OF THE FIRST GENERATION MODELS

Needless to say that besides the above three simulations, many other first generation models were published. *I selected these to show, because the mainstream of agent-based modelling of socio-economic phenomena has integrated the approaches and concepts of the above models.* The “Sugarscape” model was a pioneer in simulating economic behaviour, while Schelling’s “Segregation” model and the “Peppered Moth” model can be evaluated as a reference for the later spatial simulations and ecological models.

### AGENT-BASED COMPUTATIONAL ECONOMICS

*Sugarscape was upgraded by Epstein and Axtell.* They pointed out, that agents’ behavior becomes more complex when the model is extended to simulate inter-agent trade, thus `spice' is introduced as additional commodity. Similarly to sugar, spice is distributed over the landscape and is also necessary for the agents’ survival, while sugar and spice are independent from each other. Additionally, agents can barter sugar for spice, if they are short of one. *This upgrade of the model evolved interesting new rules.* For example agents need to have an algorithm to compare their needs for the two commodities to choose the possible cells they could move. Agents also need functions of comparing the commodities when making or receiving offers to barter, negotiating a price and determining the quantities of exchange. *In this way*

*Sugarscape can be used for testing a number of scenarios of economic behavior, market descriptions, pricing, etc.* Epstein and Axtell draw several conclusions from observing the trading in this extended model. All barters occur in a local context, negotiated between pairs of agents without any central authority or 'auctioneer'. Nevertheless, prices do converge to an equilibrium level as predicted by neo-classical economic theory, although this equilibrium is statistical rather than deterministic one, and some individual trades always occur at prices that deviate from the equilibrium price. Furthermore, the aggregate quantities traded are less than the market- clearing quantities predicted by economic theory. Another interesting consequence of introducing trade into the model is that the distribution of wealth among the agents becomes even more skewed and unequal [3, 5].

Fruitful and widely used extensions of Sugarscape are the so-called “Agent-based Computational Economics” (ACE) models. Of course ACE has other origins too, like computer science, cognitive science and evolutionary economics. (A symbolic triangle of the approach is presented in Figure 1.) As Tesfatsion argues: “agent-based computational economics is the computational study of economies modelled as evolving systems of autonomous interacting agents with learning capabilities. One principal concern of ACE researchers is to understand why certain global regularities have been observed to evolve and persist in decentralized market economies despite the absence of top-down planning and control. …The challenge is to demonstrate constructively how these global regularities might arise from the bottom up, through the repeated local interactions of autonomous agents. A second principal concern of ACE researchers is to use ACE frameworks normatively, as computational laboratories within which alternative institutions, market designs, and organizational structures in general can be studied and tested with regard to their effects on individual behaviour and social welfare“ [6].

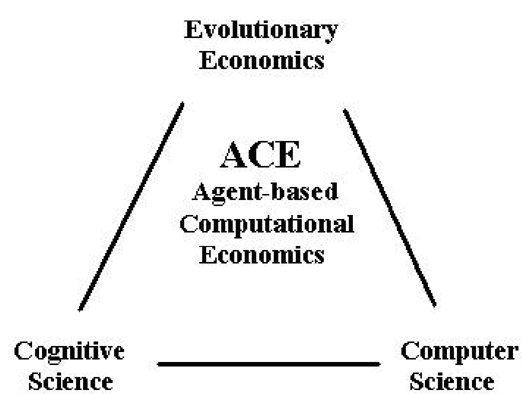


**Figure 1.** The ACE triangle [4].

This interaction between micro- and macrostructure has been recognized by economists for a long time from A. Smith to Hayek and Schelling. Tesfatsion distinguishes eight research areas to illustrate the usefulness of ACE methodology. These are the followings: (1) “Learning and the Embodied Mind” refers to the usage of learning algorithms in social sciences and economics; (2) “Evolution of Behavioral Norm” which can be best explained with the words of Axelrod “a norm exists in a given social setting to the extent that individuals usually act in a certain way and are often punished when seen not to be acting in this way." [7]. This approach examines the growth and decay of norms as an evolutionary process using agent-based computational experiments. Mutual cooperation among self-interested agents through reciprocity is analysed; (3) "Bottom-up Modeling of Market Process" is one of the most active areas of ACE. It deals with specific markets, like electricity, labor, financial, entertainment, Internet, etc.; (4) "Formation of Economic Networks" deals with transaction networks, partner selection and competitive markets; (5) "Modelling of Organizations" is the research area of constitution and functionality of organizations; (6) "Design of Computational Agents for Automated Markets" is a relatively new area of researches; (7) "Parallel Experiments with Real and Computational Agents" focuses on human-subject experimentation; and (8) "Building ACE Computational Laboratories" [8].

## SPATIAL PLANNING AND ECOLOGICAL MODELS

Many papers were published to upgrade Schelling's popular segregation model, either to test the concept on real data or to extend it with additional variables [9]. *But wider extensions and applications of the above presented original segregation and evolutionary models are "spatial planning" and "ecological models".* Both represent a significant research area. In the present paper I can only draft these approaches.

*Spatial planning* is a complex method, regarding either its object (socio-economics, ecosystems, landscapes, etc.), or its process, (many actors, with different world's representation and different interests, individually attached to specific territories). Geographical Information Systems (GIS) is in the focus of spatial agent modelers from the second half of the nineteenths. As Ferrand says, "issues like exchange and coevolution of spatial representations between many distant actors, negotiation support and simulation, multi-actor multi-criteria decision support for continuous spatial planning, are usually not addressed by current GIS" [10]. He proposed to use Multi-Agents Systems (MAS) to enhance or develop such functionalities and presented two approaches: in the first he used Multi-REACTIVE-Agents Systems to solve the complex spatial optimization problems encountered in the search for least environmental impact area for infrastructures, where environmental sensitivities, structural constraints and different localized actors decision systems are used. In the second approach, he used Multi-COGNITIVE-Agents Systems to support and simulate the exchange and dynamics of spatial representations and policies, considering the general political values, the specific spatial constraints, and the socio-relational characteristics of embedded actors [10].

*Ecological models* simulate different layers of natural (and human) dynamics as complex and adaptive systems. In ecology MAS are known as individual-based models (IBM), which were first developed at the end of the 1980s. There were two reasons for introducing this approach: first, the need to take into account the individual behaviour, primary because of its genetic uniqueness and, secondly, the fact that each individual is situated and their interactions are local [11].

The problem of different layers triggers both theoretical and practical questions. In the context of the ecology "… it reflects the importance of the levels chosen for observing a given system. In ecology, there is no natural scale for observing all types of phenomena. Conventionally, the hierarchy of scales … refers to levels of organization: cell, organism, population, community, ecosystem, landscape, biome and biosphere". One of the major challenges facing ecology is being able to take into account a multiplicity of scales of study in order to integrate - during a phase called "transfer of scale" - each of the phenomenon studied at their specific level [12].

## A SPECIFIC NATURAL ENVIRONMENT – SOCIETY SIMULATION

One of the new generation MAS socio-ecological models is “Simulation of environment degradation caused social conflicts and cooperation” which is a model to demonstrate some interactions between society and environment and within society. The model focuses on “environment $\Rightarrow$ society” and “society $\Leftrightarrow$ society” impacts. “Society $\Rightarrow$ environment” interactions are modelled as embedded elements of the employed framework.

The key question of this research is: how environment degradation caused societal reactions, basically conflicts and cooperation can be modelled at general level. The model contains many important embedded functions, i.e. “technology development”. The curve of this function is adopted from different sources. Other functions are only partially set-in and some parameters of them can be calibrated on the graphical user interface of the program, i.e. “technology development caused pollution”. The rest of the model’s functions can be directly adjusted, i.e. “spreading of local pollution” and “vulnerabilities”. Thus, other important research question is: how to calibrate the functions and parameters of the model.

Besides the calibration-type research questions the model provides some contribution to others issues, like “when environmental changes become irreversible?”, “how and what kind of conflicts and cooperation are generated by environmental degradation?”, “how fast is the reaction of the humanity?” (what is its inertia?), “how fast is the environment degradation?”, “which one will happen first, irreversible environmental processes or fast-enough social reactions?”, “is adaptability enough?”, etc. This kind of research questions are frequently posed worldwide [13].

“The simulator program of “Simulation of environment degradation caused social conflicts and cooperation” was NetLogo, which is a programmable modelling environment for simulating natural and social phenomena. It is particularly well suited for modelling complex systems developing over time. Modellers can give instructions to hundreds or thousands of independent “agents” all operating in parallel. This makes possible “to explore the connection between the micro-level behaviour of individuals and the macro-level patterns that emerge from the interaction of many individuals.” [14].

Conclusion can be drawn from the simulation process both at general and specific levels. The simulation demonstrated that the general level outcomes are sensible to the initial parameters and to the shapes of the “built-in” function curves. Some runs resulted fluctuations or slow rise of the output curves, some others indicated dramatic changes for the near future. Consequently calibration and model verification seems equally important. The analysis of specific effects – for example when other variables were held constant – indicated the perfect functionality of the model and the necessity of further in-depth analysis of the problems.

Some of these models are built for demonstration purposes, while others are based on real-world data [15].

## RECENT DEVELOPMENTS IN MODEL-BUILDING PRACTICE

The famous first generation multi-agent models demonstrate certain forms of evolution, 'survival of the fittest' mechanisms, segregation and market-like behaviour. Besides the development of new, advanced multi-agent based simulator programs, we can count on the wider usage the MAS models to solve multidisciplinary problems of real life. With some delay to the extension of research subjects, the researchers interest turned towards model-building strategies and knowledge base (i.e. ontologies) improvement. As Flores-Mendez argued “it is important that agents not only have ontologies to conceptualize a domain, but also that they have ontologies with similar constructions” [16].

Another interesting issue worth to mention is the problem of layers within the models. To deal with this practical problem, Sallach introduces a “hermeneutic” which intends to convey a multilevel interactive dialogue, capable of realizing controlled models of social complexity. He has developed a so called “Situated Social Ecology” (SSE) design framework for this purpose [17]. Sallach refers to Devlin and Rosenberg who have formalized their analyses have developed a technique called 'layered formalism and zooming' (LFZ analysis). LFZ analysis starts by making an initial non-mathematical analysis of the data, but which makes use of mathematical formalisms. This formalism, namely the “situation theory” is a branch of mathematics developed in the early 1980s, and discussed later by Devlin [18]. Then, that initial analysis is the subject to a process of stepwise refinement and increased formalism. Whenever a problem is encountered, the mathematical precision should be increased, as it applies to the problem area. That is to 'zoom in' and examine the problem in detail. When the problem has been resolved, one can 'zoom out' again. At each step of the refinement process, the minimal possible level of formalism and the minimal possible level of precision should be used, thereby minimizing the likelihood of any inadvertent alteration to the data under consideration. The analysis is checked against the data after each stage in the analysis refinement cycle. As a result the balance between the mathematical and the sociological aspects of the analysis is determined not by the analysts but by the data. In short, the process of formalization is used as an analytic technique. The aim is not to produce a formal theory. Indeed, there can be so many symbols floating around that denote decidedly 'soft' entities (such as contexts), that it would take a lifetime to come close to anything that might resemble a 'formal system' in the mathematician's usual sense [19].

## SUMMARY AND CONCLUSIONS

This article have picked up some relevant, frequently quoted papers from the coloured palette of multi-agent applications bibliographies to illustrate the milestones from the first generation models to some of today’s new approaches. No doubt that this methodological challenge will further help researchers in studying socio-economic and ecological complexities of the real world.

## REMARKS

[1]‘sugar’ is the symbol of the wealth.

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# Prva generacija modela agenata i njihove nadgradnje

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## SAŽETAK

Modeli agenata sastoje se od interagirajućih i neovisnih agenata različite vrste u "svijetu" računala. Ključni element modeliranja pomoću agenata je njihova mogućnost reproduciranja izrastajućih pojava na makro-razini iz "mikro-ponašanja". Do sad je ovaj pristup prerastao u široko primijenjivanu metodologiju u socio-ekonomiji i ekologiji. Ovaj ra predstavlja tri poznata modela iz prve generacije i skicira njihove nadgradnje, posebno računalnu ekonomiju temeljenu na modeliranju pomoću agenata, pristup prostornog planiranja i ekološke modele. Naposljetku, koncepti daljnjeg razvoja su prikazani i diskutirani.

## KLJUČNE RIJEČI

simulacija, rani modeli agenata

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