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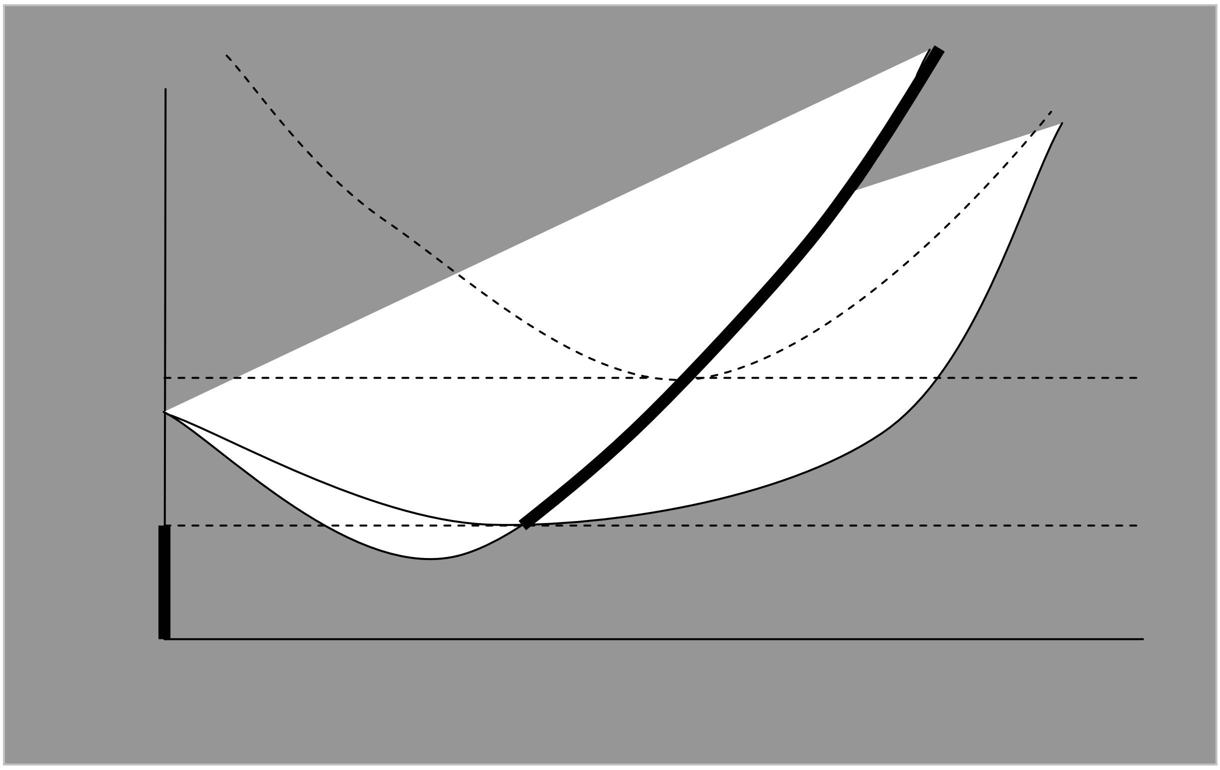
Production, Capital Stock and Price Dynamics in a Simple Model of Closed Economy



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Production, Capital Stock and Price Dynamics in a Simple Model of Closed Economy

JAN KODERA#, MIROSLAV VOŠVRDA *

Abstract

The purpose of this paper is to study a price level dynamics in a simple four-equation model. A basis of this model is developed from dynamical Kaldorian model which could be noticed very frequently in works of non-linear economic dynamics. Our approach is traditional. The difference is observed in a choice of an investment function. The investment function depending on the difference of logarithm of production and logarithm of capital (logarithm of the productivity of capital) is in a form of the logistic function. These two equations create relatively closed sub-model generating both production and capital stock trajectories. Two other equations describe the price level dynamics as a consequence of money market disequilibrium and continuously adaptive expectation of inflation. Our investigation is firstly aimed to core model dynamics, i.e., a dynamics of the production and capital stock. Secondly is to analyze dynamics of the model as a whole, i.e., to the first part is superadded the price dynamics and expected inflation dynamics depending on both an adaptation parameter of the commodity market and a parameter of the expectation. Thirdly we compute Lyapunov exponents for a simple model of closed economy showing it's a chaotic behaviour. Simulation studies are performed.

JEL Classification: E44.

Keywords: investment ratio, propensity to save, expected inflation, nonlinear system, and price dynamics

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1. Production Sector and Capital Formation Model – A Statement

The Kaldor model has became a kernel of nonlinear models of closed economy. There are descriptions of the Kaldor model in many textbooks for the economic dynamics. For example we can take it in Lorenz, H.-W. (1994). The similar form of the Kaldor model is analysed by Flaschel, P., Franke, R., Semmler, W. (1997). A traditional form of this model has the following form

$$\dot{Y} = \alpha\left[I(Y,K) - S(Y)\right], \tag{1}$$

where *Y*, *K* depend on time and stand for a production and a capital stock respectively. The parameter $\alpha > 0$ is the adjustment parameter. Investments *I* are increasing in the *Y* and are decreasing in the *K*. The savings *S* are an increasing function of *Y*. The equation (1) describes a production dynamics which is expressed as a consequence of disequilibrium between investments and savings.

The capital increase $\dot{K}$ is equal to the difference of investment and capital consumption. The capital consumption is assumed to be an increasing function of capital stocks *D*(*K*). The equation expressing capital dynamics is in the form as follows

$$\dot{K} = I(Y,K) - D(K)\,. \tag{2}$$

The investment function is supposed to be the product of propensity to invest *j* depending on an expected productivity of capital χ and a production *Y*. As we assume that the individuals expect the actual productivity of capital we have

$$\chi = \frac{Y}{K}\,. \tag{3}$$

From the equation (3) we can obtain $\varepsilon = \ln \chi = y - k$, where *y*, *k* stand for $y = \ln Y$, $k = \ln K$ respectively. For the investment function we assume

$$I(Y,K) = j(\chi)\cdot Y = j(Y/K)\cdot Y. \tag{4}$$

Using this notation we get

$$j(Y/K) = j(e^{\varepsilon}) = j(e^{y-k}) = i(y-k)\,. \tag{5}$$

A propensity to invest *j* is an increasing function of *ε* and it is assumed that it approaches to zero for decreasing *ε* to minus infinity and approaches to the maximum level for increasing *ε*. We assume that a product of a constant *μ* and a logistic function *λ*, depending on *ε*, is the fairly good approximation of the propensity to invest. The logistic function *λ* is a solution of the following differential equation

$$\frac{\mathrm{d}\lambda(\varepsilon)}{\mathrm{d}\varepsilon} = \lambda(\varepsilon)\cdot(a - b\cdot\lambda(\varepsilon)). \tag{6}$$

Let us consider an initial condition $\lambda(0) = \lambda_0$. Then the logistic function *λ* takes on the following form

$$\lambda(\varepsilon) = \frac{a\cdot\lambda_0}{b\cdot\lambda_0 + (a - b\cdot\lambda_0))\cdot e^{-a\cdot\varepsilon}}\,. \tag{7}$$

We receive the propensity to invest *i* in the following form

$$i(\varepsilon) = \mu\cdot\lambda(\varepsilon) = \frac{a\cdot\mu\cdot\lambda_0}{b\cdot\lambda_0 + (a - b\cdot\lambda_0)\cdot e^{-a\cdot\varepsilon}}\,. \tag{8}$$

or

$$i(y-k) = \mu\cdot\lambda(y-k) = \frac{a\cdot\mu\cdot\lambda_0}{b\cdot\lambda_0 + (a - b\cdot\lambda_0)\cdot e^{-a\cdot(y-k)}}\,. \tag{9}$$

For the saving function we have used the following expression

$S(Y) = (s_0 + s_1 \cdot y - s_2 \cdot \pi) \cdot Y.$	(10)

The above equation describes the dependence of savings on investments as the product of a production Y and propensity to save $s_0 + s_1 \cdot y - s_2 \cdot \pi$ which is not a constant. We assume that it depends on a production y and on an expected inflation π. The dependence on the y is positive; the dependence on the expected inflation π is a negative. The higher expected inflation π the higher reduction of savings. Let us rearrange the equation (1) using the expressions for investments and savings. We get

$\dot{Y} = \alpha \cdot [i(y-k) \cdot Y - (s_0 + s_1 \cdot y - s_2 \cdot \pi) \cdot Y].$	(11)

Dividing the equation (11) by Y, we get

$\dot{y} = \alpha \cdot [i(y-k) - (s_0 + s_1 \cdot y - s_2 \cdot \pi)].$	(12)

Let $D = \beta \cdot K^{\gamma}$, $\beta, \gamma \in (0,1)$ denotes a capital consumption expressing the depreciated portion of capital. A capital formation in the closed economy is described by the following differential equation

$\dot{K} = I(Y, K) - \beta \cdot K^{\gamma}.$	(13)

or by the following one

$\dot{K} = i(y-k) \cdot Y - \beta \cdot K^{\gamma}.$	(14)

Dividing the equation (14) by K we get

$\frac{\dot{K}}{K} = i(y-k) \cdot \frac{Y}{K} - \beta \cdot K^{\gamma-1}.$	(15)

Using logarithms instead of original values of Y and K we get

$\dot{k} = i(y-k) \cdot e^{y-k} - \beta \cdot e^{(\gamma-1) \cdot k}.$	(16)

The equations (12) and (16) describe the production dynamics and the capital formation, i.e. the dynamics of Kaldor model. The final forms of these equations are as follows

$\dot{y} = \alpha \left[\frac{a \cdot \mu \cdot \lambda_0}{b \cdot \lambda_0 + (a - b \cdot \lambda_0) e^{-a(y-k)}.} - (s_0 + s_1 y - s_2 \cdot \pi) \right].$	(17)

$\dot{k} = \frac{a \cdot \mu \cdot \lambda_0}{b \cdot \lambda_0 + (a - b \cdot \lambda_0) \cdot e^{-a(y-k)}.} \cdot e^{y-k} - \beta \cdot e^{(\gamma-1)k}$	(18)

2. Price Level and Expected Inflation Dynamics

Let us add to the considered model the equations for a price level and an expected inflation dynamics. Price level dynamics outflows from the disequilibrium in money market. Demand for money in the money market is assumed to be given by Fisherian demand for money equation

$M^d = \frac{1}{V(\pi)} P \cdot Y.$	(19)

where M^d - demand for money, P - price level, V - the velocity of money, π - expected inflation. A velocity of money V is assumed to increase with an expected inflation. Making the logarithm of the above equation we get

$m^d = p + y - v(\pi).$	(20)

where m^d - logarithm of demand for money, p - logarithm of price level, v - logarithm of the velocity of money. Logarithm of the velocity of money is assumed to be given by the following equation

$$v(\pi) = v_0 + \kappa \cdot \theta(\pi)\,. \tag{21}$$

where a constant v_0 is determined by a technological level of the banking sector. A parameter κ is a constant and θ is a logistic function solving the logistic equation

$$\frac{\mathrm{d}\theta(\pi)}{\mathrm{d}\pi} = \theta(\pi)\cdot\left(g - h\cdot\theta(\pi)\right). \tag{22}$$

Supplying an initial condition $\theta(0) = \theta_0$ we get particular solution of the above differential equation.

$$\theta(\pi) = \frac{g\cdot\theta_0}{h\cdot\theta_0 + \left(g - h\cdot\theta_0\right)\cdot e^{-g\cdot\pi}}\,. \tag{23}$$

Now we are ready to introduce an equation for the price level dynamics in the extended model. The price level dynamics is a consequence of the disequilibrium in money market. An equilibrium is expressed by the difference between supply of money m^s and demand for money m^d, so we get

$$\dot{p} = \sigma\cdot(m^s - m^d)\,. \tag{24}$$

where σ is an adjustment parameter. Replacing m^d from (20) and using (21), (24) yields

$$\dot{p} = \sigma\cdot[m^s - p - y + v_0 + \kappa\cdot\theta(\pi)]\,. \tag{25}$$

An adaptive expectation of inflation is expressed by

$$\dot{\pi} = \omega\cdot(\dot{p} - \pi). \tag{26}$$

Substituting from (25) to (26) we get

$$\dot{\pi} = \omega\cdot\left\{\sigma\cdot\left[m^s - p - y + v_0 + \kappa\cdot\theta(\pi)\right] - \pi\right\} \tag{27}$$

Using the relation (21) we get the final form of the equations describing the price level dynamics and the adaptive expectation of inflation.

$$\dot{p} = \sigma\cdot\left(m^s - y - p + v_0 + \kappa\frac{g\cdot\theta_0}{h\cdot\theta_0 + \left(g - h\theta_0\right)\cdot e^{-g\cdot\pi}}\right) \tag{28}$$

$$\dot{\pi} = \omega\cdot\left[\sigma\cdot\left(m^s - y - p + v_0 + \kappa\frac{g\cdot\theta_0}{h\cdot\theta_0 + \left(g - h\cdot\theta_0\right)\cdot e^{-g\cdot\pi}}\right) - \pi\right] \tag{29}$$

This system is, in the final form, composed by equations (17), (18), (28), and (29). The Jacobian of this system has the following form

$$\mathbf{A} = \begin{Vmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} & \alpha s_2 & 0 \\ \mathbf{A}_{21} & \mathbf{A}_{22} & 0 & 0 \\ -\omega\sigma & 0 & \mathbf{A}_{33} & -\omega\sigma \\ -\sigma & 0 & \mathbf{A}_{43} & -\sigma \end{Vmatrix}$$

$\mathbf{A_{11}} = \dfrac{\alpha a^2 \mu \lambda_0 \left(a\text{-}b\lambda_0\right) exp\left(\text{-}a\left(y\text{-}k\right)\right)}{\left[b\lambda_0+\left(a\text{-}b\lambda_0\right) exp\left(\text{-}a\left(y\text{-}k\right)\right)\right]^2}\text{-}s1$	$\mathbf{A_{12}} = \dfrac{-\alpha a^2 \mu \lambda_0 \left(a\text{-}b\lambda_0\right) exp\left(\text{-}a\left(y\text{-}k\right)\right)}{\left[b\lambda_0+\left(a\text{-}b\lambda_0\right) exp\left(\text{-}a\left(y\text{-}k\right)\right)\right]^2}$

$$\mathbf{A_{21}} = \frac{a\mu\lambda_0 exp(y\text{-}k)}{b\lambda_0+(a\text{-}b\lambda_0)exp(\text{-}a(y\text{-}k))} + \frac{a^2\mu\lambda_0 exp(y\text{-}k)(a\text{-}b\lambda_0)exp(\text{-}a(y\text{-}k))}{\left(b\lambda_0+(a\text{-}b\lambda_0)exp(\text{-}a(y\text{-}k))\right)^2}$$

$$\mathbf{A_{22}} = -\frac{a\mu\lambda_0 exp(y\text{-}k)}{b\lambda_0+(a\text{-}b\lambda_0)exp(\text{-}a(y\text{-}k))} - \frac{a^2\mu\lambda_0 exp(y\text{-}k)(a\text{-}b\lambda_0)exp(\text{-}a(y\text{-}k))}{\left(b\lambda_0+(a\text{-}b\lambda_0)exp(\text{-}a(y\text{-}k))\right)^2}$$

$\mathbf{A_{33}} = \dfrac{\omega\sigma\kappa g^2\theta_0\left(g-h\theta_0\right)exp\left(-g\pi\right)}{\left(h\theta_0+\left(g-h\theta_0\right)exp\left(-g\pi\right)\right)^2}-1$	$\mathbf{A_{43}} = \dfrac{\sigma\kappa g^2\theta_0\left(g-h\theta_0\, exp\left(-g\pi\right)\right)}{\left(h\theta_0+\left(g-h\theta_0\right)exp\left(-g\pi\right)\right)^2}$

In the matrix notations, we have expanded system $\mathbf{f}(\mathbf{x}(t))$, composed by equations (17), (18), (28), and (29), around equilibrium point $\mathbf{x}^* = \left(x_1^{\mathrm{i}}, x_2^{\mathrm{i}}, x_3^{\mathrm{i}}, x_4^{\mathrm{i}}\right) = \left(y^*, k^*, p^*, \pi^*\right)$ and $\mathbf{J}(\mathbf{x}(t))$=A is the 4x4 Jacobian matrix of $\mathbf{f}(\mathbf{x}(t))$ at $\mathbf{x}^*$. Considering the dynamical system as a map, the time evolution of distance is as follows

$$\mathbf{y}(t_{n+1}) - \mathbf{x}(t_{n+1}) = \mathbf{f}(\mathbf{y}(t_n)) - \mathbf{f}(\mathbf{x}(t_n)) \text{ for } n = 1,2,\ldots$$

and by the linearization we have

$$\mathbf{y}(t_{n+1}) - \mathbf{x}(t_{n+1}) = \mathbf{J}_n(\mathbf{y}(t_n) - \mathbf{x}(t_n)) + O\left(\left\|\mathbf{y}(t_n) - \mathbf{x}(t_n)\right\|^2\right).$$

The equilibrium point $\left(x_1^{\mathrm{i}}, x_2^{\mathrm{i}}, x_3^{\mathrm{i}}, x_4^{\mathrm{i}}\right)$ is stable if and only if the system

$$\begin{bmatrix} \dfrac{\mathrm{d}(x_1(t)-x_1^{\mathrm{i}})}{\mathrm{d}t} \\ \dfrac{\mathrm{d}(x_2(t)-x_2^{\mathrm{i}})}{\mathrm{d}t} \\ \dfrac{\mathrm{d}(x_3(t)-x_3^{\mathrm{i}})}{\mathrm{d}t} \\ \dfrac{\mathrm{d}(x_4(t)-x_4^{\mathrm{i}})}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial f_1(\mathbf{x})}{\partial x_1} & \dfrac{\partial f_1(\mathbf{x})}{\partial x_2} & \dfrac{\partial f_1(\mathbf{x})}{\partial x_3} & \dfrac{\partial f_1(\mathbf{x})}{\partial x_4} \\ \dfrac{\partial f_2(\mathbf{x})}{\partial x_1} & \dfrac{\partial f_2(\mathbf{x})}{\partial x_2} & \dfrac{\partial f_2(\mathbf{x})}{\partial x_3} & \dfrac{\partial f_2(\mathbf{x})}{\partial x_4} \\ \dfrac{\partial f_3(\mathbf{x})}{\partial x_1} & \dfrac{\partial f_3(\mathbf{x})}{\partial x_2} & \dfrac{\partial f_3(\mathbf{x})}{\partial x_3} & \dfrac{\partial f_3(\mathbf{x})}{\partial x_4} \\ \dfrac{\partial f_4(\mathbf{x})}{\partial x_1} & \dfrac{\partial f_4(\mathbf{x})}{\partial x_2} & \dfrac{\partial f_4(\mathbf{x})}{\partial x_3} & \dfrac{\partial f_4(\mathbf{x})}{\partial x_4} \end{bmatrix} \cdot \begin{bmatrix} (x_1(t)-x_1^{\mathrm{i}}) \\ (x_2(t)-x_2^{\mathrm{i}}) \\ (x_3(t)-x_3^{\mathrm{i}}) \\ (x_4(t)-x_4^{\mathrm{i}}) \end{bmatrix}$$

is stable, i.e. if all eigenvalues of the matrix of the system $\mathbf{f}(\cdot)$ have negative real parts. We denote Λ_i for i=1,…,4 eigenvalues of the matrix $\mathbf{J}_n(\cdot)$. The Lyapunov exponent λ_i is defined as follows

$$\lambda_i = \lim_{N\to\infty} \frac{1}{N} \ln\left|\Lambda_i^N\right| \text{ for } i=1,\ldots,4.$$

If $\max\limits_{i=1,\ldots,4} \lambda_i < 0$, the nearby trajectories have a stable fixed point. If $\max\limits_{i=1,\ldots,4} \lambda_i = 0$, the nearby trajectories have a stable limit cycle. If the dynamical system has very sensitive dependence on in initial conditions then it has a Lyapunov exponent greater than unity. Lyapunov exponents provide extremely useful tools for characterizing the behaviour of nonlinear dynamic systems. It is very important that they are invariant to topological setting. For asymptotically stable fixed points of a 4-dimensional system, we will have 4 negative

Lyapunov exponents. For asymptotically stable limit cycles or quasiperiodic attractors, we will have 4-k negative Lyapunov exponents for k<4 and k=1 for a limit cycle, or k=s for quasiperiodic dynamics on a T^s torus. Chaotic attractors are associated with presence of a least one positive Lyapunov exponent, which signals that nearby trajectories diverge exponentially in the corresponding direction. The presence of one or more positive Lyapunov exponents is related to the lack of predictability of these systems. This property is an essential feature of chaotic behaviour. What is a dimension such attractor. Consider the typical orbit on chaotic attractor and the associated set of Lyapunov exponents ordered from the largest λ_1 to the smallest λ_4. Suppose that the j-th is the largest integer for which $\sum_{i=1}^{j}\lambda_i > 0$. It implies that $\lambda_{j+1} < 0$. Then the dimension of the attractor is calculated as follows

$$D_L = j + \frac{\sum_{i=1}^{j}\lambda_i}{\left|\lambda_{j+1}\right|}$$

and called Lyapunov dimension.

3. Numerical Example of the Extended Model

Let us calibrate the model by numbers in accordance with the following table

Table 1

a	B	λ_0	s_0	s_1	s_2	A	β
1	1	0.5	0.2	0.05	0	35	0.1

γ	Σ	ω	μ	G	H	θ_0	K	v_0	m^s
1	0.6	0.8	0.25	1	1	0.5	15	1	2

The propensity to invest and the propensity to save expressed by the equations (9) and (10) respectively have after the calibration the following form

$$i(y-k) = \frac{0.25}{1+e^{-y+k}}, \qquad s = 0.2 + 0.05y. \tag{30}$$

Using them in the equations (12) and (16) we get numerical form equations for a simulation of the simple model of the closed economy

Production Dynamics Equation

$$\dot{y} = 35\cdot\left[\frac{0.25}{1+e^{-y+k}} - (0.2+0.05y)\right]. \tag{31}$$

Capital Formation Equation

$$\dot{k} = \frac{0.25}{1+e^{-y+k}}e^{y-k} - 0.1. \tag{32}$$

Price Dynamics Equation

$$\dot{p} = 0.6\left(2 - y - p + 1 + \frac{0.75}{1+e^{-\pi}}\right). \tag{33}$$

Adaptive Expectation of Inflation

$$\dot{\pi} = 0.8\left[0.6\left(2 - y - p + 1 + \frac{7.5}{1 + e^{-\pi}}\right) - \pi\right]. \qquad (34)$$

The initial conditions were chosen as $y(0)=3$, $k(0)=10$, $p(0)=1$, and $\pi(0)=0$. The trajectories and phase portrait of the numerical example are shown in Figures 1-4.

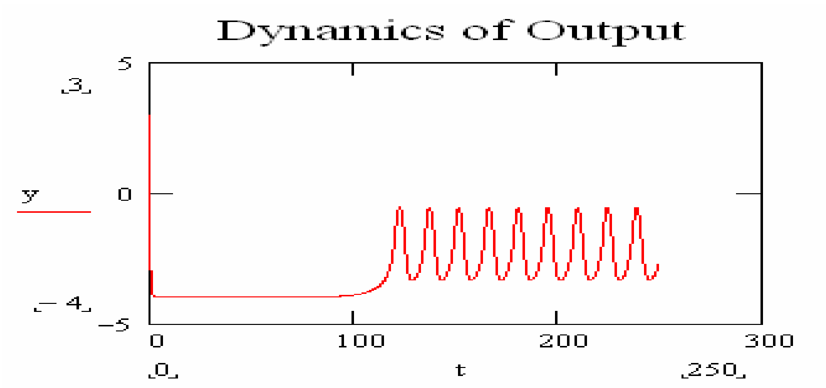

Figure 1

m^d

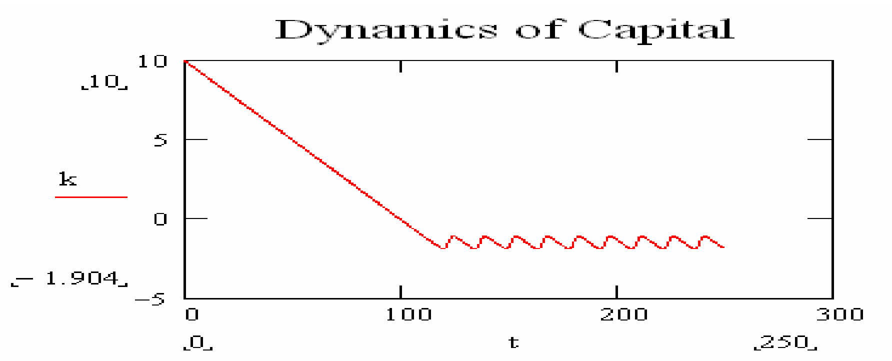

Figure 2

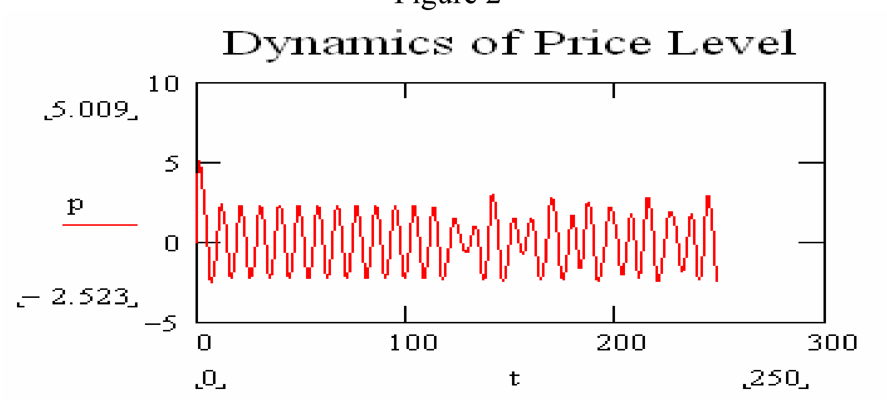

Figure 3

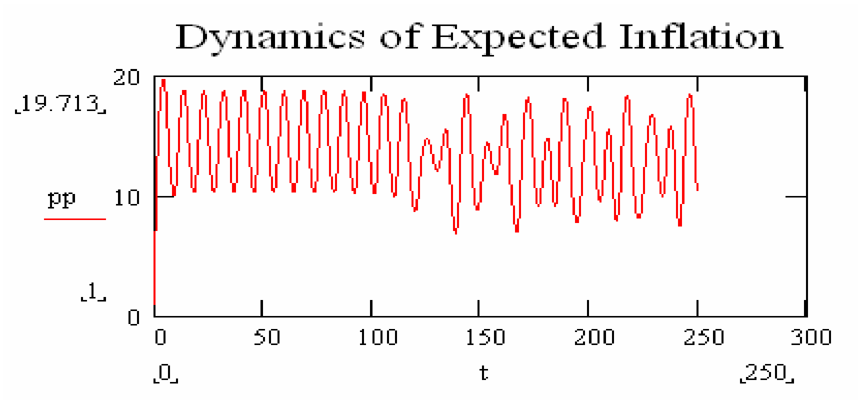

Figure 4

The phase portrait is demonstrated in Fig. 5

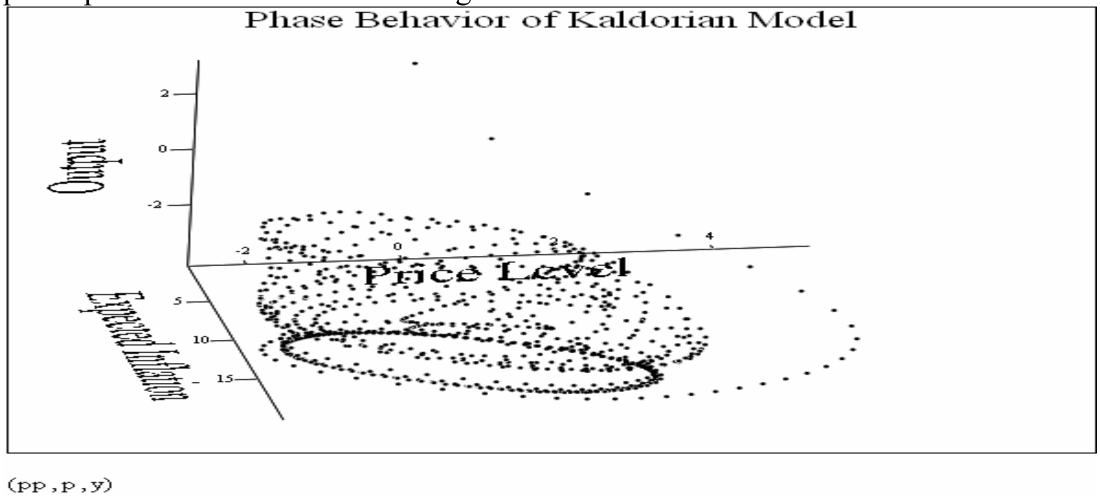

Figure 5

Eigenvalues of this system equations are as follows

$$\mathrm{eigenvals}(A) = \begin{pmatrix} 0.02 + 0.373i \\ 0.02 - 0.373i \\ -0.6 \\ -0.999 \end{pmatrix}$$

Lyapunov exponents have the following values 0.0635, 0.0, -0.0005, -1.7475. The Lyapunov dimension has the following value 3.03. A behaviour of Lyapunov coefficients, and the Lyapunov dimension for the simple model of the closed economy are demonstrated in Fig. 6.

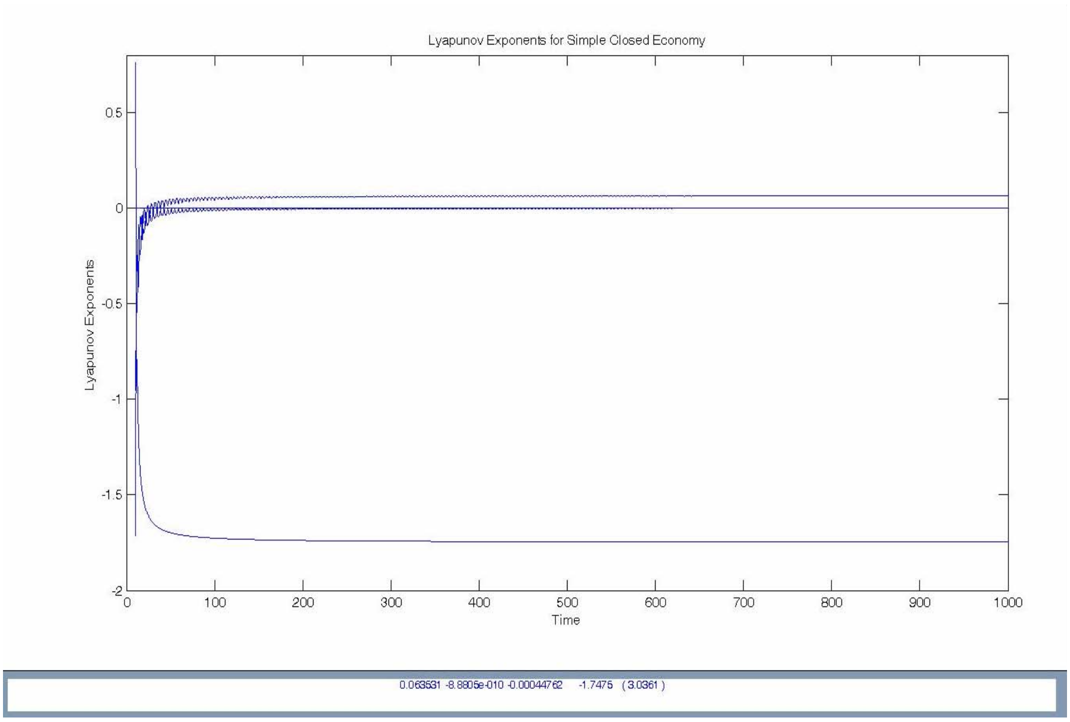

Figure 6

Conclusions

The four-equation model was formulated in this paper. This model is actually augmented Kaldor model which is not only very well known but is intensively studied in economic dynamics. The original Kaldor model had been created by the equations (17) and (18). We have used a non-linear investment function, which is the product of the production and the propensity to invest. The logistic function was chosen for the approximation of the propensity to invest. Another type of non-linearity in our model is the non-linearity used in a velocity of money. The velocity of money is defined in our approach by the non-linear function of expected inflation. The logistic function as a realistic approximation of the velocity of money was chosen as well. By simulations of numerical examples this augmented Kaldor model ((17), (18), (28), and (29)) has demonstrated more complex behaviour of the simple closed economic system. Values of Lyapunov coefficients demonstrate a chaotic behaviour and an existence of the stable limit cycle (Fig. 5).

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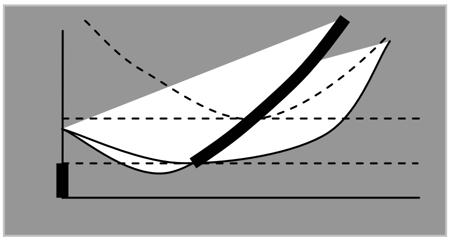

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