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SENSITIVITY ANALYSIS AND OPTIMIZATION ON SOME MODELS OF ARCHETYPES USING VENSIM – THEORETICAL ISSUE

Introduction

The main purpose of System Dynamics is to try discover the "structure" that conditions the observed behaviour of the system over time. System Dynamics try to pose "dynamic" hypotheses that endogenously describe the observed behaviour of system. One of such way is building so called "systems archetypes", popularized by Senge [Se90], Wolstenholme [Wo03; Wo04], many others. The proposal of mathematical structure for systems archetypes was first presented by Bourguet-Diaz and Perez-Salazar [BoPe03] and Kasperska [Ka06; Ka09]. In our paper, we choose such archetypes like: eroding goal, fixes that fail, success to the successful, accidental adversaries. It is know that growth, decline, goal seeking and oscillation are consequences of feedback loop dynamics [Fo61; Fo69; Fo71; Fo72; Fo75; Co91; Co94; Co96; Co98; St00; St02]. Such tool like sensitivity analysis by Vensim allow to investigate systems archetypes in aspect of "goodness" of structure and parameters to create desired behaviour, which is the introduction to optimization process as well. Optimization of SD models has a long history from first trials by Winch [Wi76; Ke77; Ke80; Ke83], then by Coyle [Co96; Co98].

Authors of this paper have undertaken the problem of optimization SD models in many papers [Ka02; Ka05; KaMa05; KaMa06; KaSło03; KaSło05]. First we use COSMIC and COSMOS (1994) and then Vensim (2002). The Vensim has many interesting possibilities concerning the realization of sensitivity and optimization experiments. Monte Carlo multivariate sensitivity works by sampling a set of numbers from within bounded domains. To perform one multivariate test the distribution for each parameters specified is sampled, and the resulting values used in a simulation. When the number of simulation is set, for example, at 200, this process will be repeated 200 times. In order to do sensitivity simulation you need to define what kind of probability distribution value for each parameter will be drawn from. The simplest distribution is the Random Uniform Distribution, in which any number between the minimum and maximum values is equally likely to occur.

The sensitivity testing of parameters is very interesting from methodological point of view, because such testing can be the entrance for optimization, because allows to detect: sensitivity parameters, bounds of their variations and of course can help to choose the objective function.

The aim of this paper is the presentation of some new results of authors investigation in the area of simulation and optimization with use of source models of archetypes in System Dynamics convention and with use of simulation language Vensim and Monte Carlo method.

Some models of systems archetypes. Structures, mathematical equations, simulation of behaviour

In literature of SD there are many examples of systems archetypes [Se90; Wo03; Wo04; BoPe03; BeKa12].

The structures are well known, but the mathematical equations are not so popular, and because of this there are lack of simulation experiments specially the optimization experiments, on models of archetypes. First authors present some chosen models of archetypes, on the base of proposals of Bourguet-Diaz, Perez-Salazar and on the base of own works on the field [KaMa06]. And then in article we will undertake the trial of sensitivity analysis and optimization on these models.

Like the object of experiments the following archetypes were choosing:

- Eroding Goal,
- Fixes that Fail,
- Success to the Successful,
- Accidental adversaries.

Let's present these structures. First structure is illustrated on Figure 1. This structure is consisted of two balancing loops: B1, B2. To express the changes in such system the following differential equations are created:

$$\dot{x}_1(t) = \frac{-1}{T_1} x_1(t) + \frac{1}{T_2} x_2(t)$$
$$\dot{x}_2(t) = \frac{1}{T_1} x_1(t) - \frac{1}{T_2} x_2(t)$$

with conditions:

$$x_1(0) = x_{10}$$
$$x_2(0) = x_{20}$$

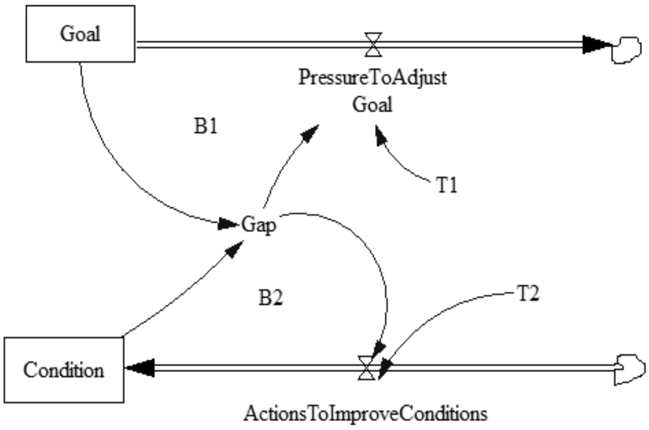

Fig. 1. Block diagram for Eroding Goal archetype
Source: Own results.

On the base of Bourguet-Diaz, Perez-Salazar the example is presented with the values: $T_1 = 5$, $T_2 = 10$, $x_{10} = 100$, $x_{20} = 40$. The results of simulation are presented on Figure 2.

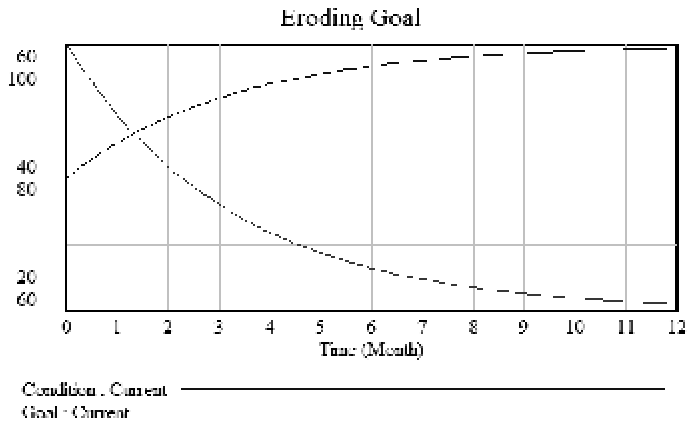

Fig. 2. The dynamics of behaviour of Eroding Goal archetype
Source: Own results.

In our paper „Sensitivity analysis and optimization on some models of archetypes using Vensim – experimental issue" we will present the results of sensitivity analysis on this model of archetype. Now, let concentrate on second archetype called "Fixes that Fail". That structure is presented on Figure 3.

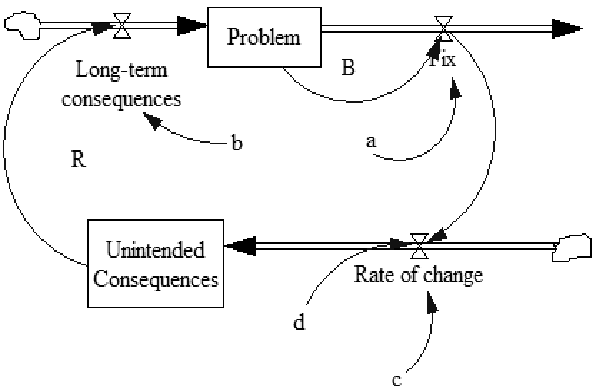

Fig. 3. Block diagram for "Fixes that Fail" archetype
Source: Own results.

This structure is consisted of two loops: B, R (balancing and reinforcing). To express the changes in such system the following differential equations are created:

$$\dot{x}_1(t) = -ax_1(t) + bx_2(t)$$
$$\dot{x}_2(t) = cx_1(t-d)$$

with conditions:

$$x_1(0) = x_{10}$$
$$x_2(0) = x_{20}$$

Where *d* is the delay in time units and *a, b, c* are proportionally parameters. On the base of Bourguet-Diaz, Perez-Salazar the example is presented with the values:

$$a = 0.5, \quad b = 0.5, \quad c = 0.4, \quad d = 5, \quad x_{10} = 50, \quad x_{20} = 0.$$

The results of simulation are presented on Figure 4.

Fig. 4. The dynamics of behaviour of "Fixes that Fail" archetype
Source: Own results.

In paper „Sensitivity analysis and optimization on some models of archetypes using Vensim – experimental issue" we will present the results of sensitivity analysis on this model of archetype. Now, let concentrate on third archetype called „Success to the Successful". Figure 5 presents the structure of this archetype.

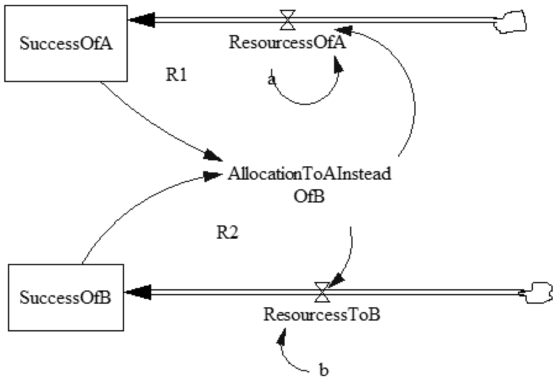

Fig. 5. Block diagram for "Success to the Successful" archetype
Source: Own results.

The structure is consisted of two reinforcing loops: R1, R2. To express the changes in such system the following differential equations are created:

$$\dot{x}_1(t) = ax_1(t) - ax_2(t)$$
$$\dot{x}_2(t) = -bx_1(t) + bx_2(t)$$

with conditions:

$$x_1(0) = x_{10}$$
$$x_2(0) = x_{20}.$$

On the base of Bourguet-Diaz, Perez-Salazar the example is presented with the values: $a = 0.1$, $b = 0.1$, $x_{10} = 5.5$, $x_{20} = 4.5$. The results of simulation are presented on Figure 6.

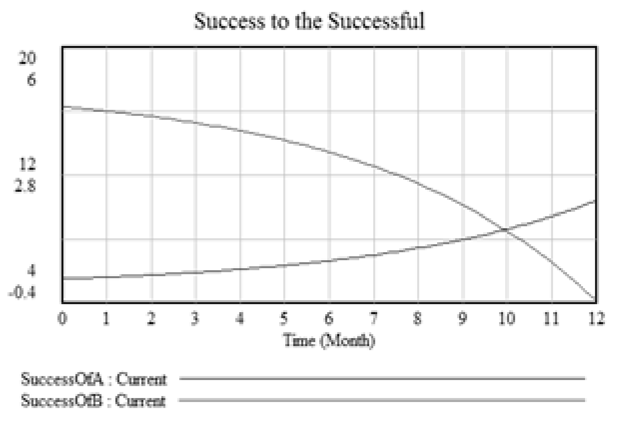

Fig. 6. The dynamic of behaviour of "Success to the Successful" archetype
Source: Own results.

The fourth archetype is archetype named "Accidental adversaries". Figure 7 presents the structure of this archetype.

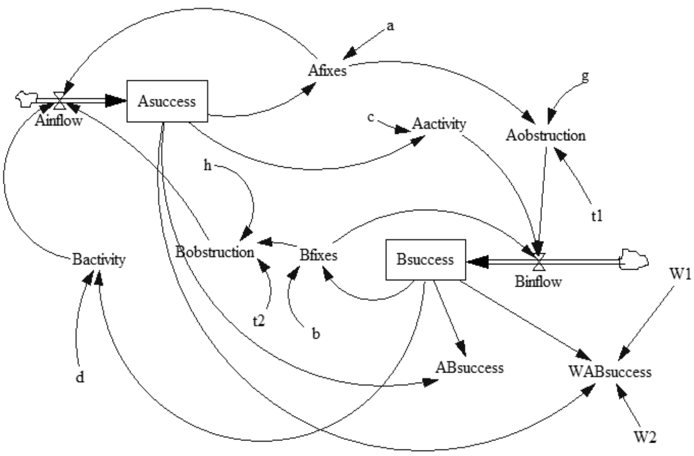

Fig. 7. Block diagram for "Accidental adversaries" archetype
Source: Own results.

In literature of the field there was lack of the mathematical model of this archetype. First author take this trial in paper [KaMa06]. It seems simple. Let x_1 will be the success of A, and x_2 – the success of B. So the equation are as follow:

$$\dot{x}_1(t) = -ax_1(t) + dx_2(t) - bgx_2(t - t_2)$$
$$\dot{x}_2(t) = -bx_2(t) + cx_1(t) - ahx_1(t - t_1).$$

The parameters: *a, b, c, d, g, h* express the balancing and reinforcing factors of loops (see: Figure 7). The parameters: t_1, t_2 are the time delays. We simulated the dynamics of this archetype, taking the values of parameters:

$$a = 0.4, b = 0.4, c = 0.2, d = 0.2, g = 0.6, h = 0.6, t_1 = 5, t_2 = 10 \ ,$$

and the initial values of levels:

$$x_1(0) = 250$$
$$x_2(0) = 150.$$

The results of simulation are presented on Figure 8.

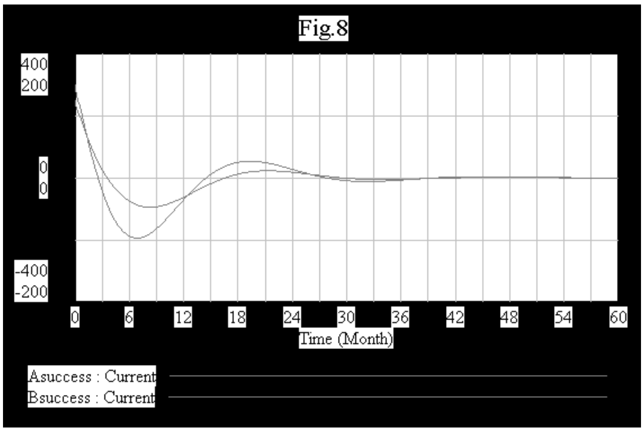

Fig. 8. The dynamics of behaviour of "Accidental Adversaries" archetype
Source: Own results.

The next archetype is archetype "Limit to Growth". This is one of the version of such archetype, Figure 9 presents its structure.

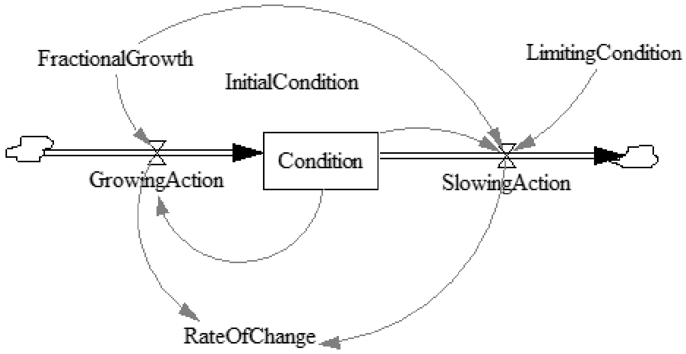

Fig. 9. Block diagram for “Limit of Growth” archetype
Source: Own results.

The structure is consisted of two loops: R (reinforcing) and B (balancing). To express the changes in such system the following differential equation is created:

$$\dot{x}(t) = ax(t) - ax(t)\left[1 - \frac{L - x(t)}{L}\right]$$

reordering:

$$\dot{x}(t) = ax(t) - \frac{a}{L}x^2(t)$$

thus:

$$\dot{x}(t) = a\left(1 - \frac{x(t)}{L}\right)x(t)$$

with condition:

$$x(0) = x_0 .$$

On the base of Bourguet-Diaz, Perez-Salazar the example is presented with the values:

L (limit of growth) = 100

a (fractional growth) = 0.1

$x_0 = 1$.

The results of simulation are presented on Figure 10.

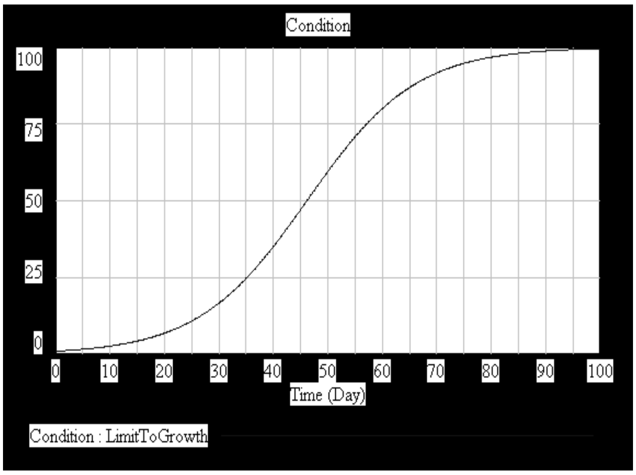

Fig. 10. The dynamics of behaviour of "Limit of Growth" archetype
Source: Own results.

Now, let present in theoretical part of our research, the precise mathematically formulation of solutions of chosen archetypes.

Precise mathematical formulation of solution of chosen archetypes – models of systems archetypes

This is very important because in literature of the field there are sometimes mistakes in such formulation.

The „Eroding Goal" archetype, saying precisely mathematically, is a first – order linear homogeneous differential equation.

$$\dot{x} = Ax, \qquad x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \qquad A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}.$$

In our case:

$$A = \begin{bmatrix} \frac{-1}{T_1} & \frac{1}{T_1} \\ \frac{1}{T_2} & \frac{-1}{T_2} \end{bmatrix}.$$

It is necessary to find two linearly independent solutions: x^1 *(t)*, x^2 *(t)*.

The way of doing this is as follow. We find eigenvalues of matrix A, from characteristic equation:

$$\det(A - \lambda E) = 0$$

(det is determinant of matrix). There are:

$$\lambda_1 = 0,$$
$$\lambda_2 = \frac{-T_1 - T_2}{T_1 \cdot T_2}.$$

The eigenvectors from them:

for $\lambda_1, v^1 = c\begin{bmatrix}1\\1\end{bmatrix},$

for $\lambda_2, v^2 = c\begin{bmatrix}\frac{-T_2}{T_1}\\1\end{bmatrix}.$

So, we get the fundamental matrix:

$$x(t) = \lambda_2 = \begin{bmatrix}1 & \frac{-T_2}{T_1}\\1 & 1\end{bmatrix}$$

and the solutions:

$$x^1(t) = e^{\lambda_1 \cdot t} \cdot v^1,$$
$$x^2(t) = e^{\lambda_2 \cdot t} \cdot v^2.$$

And there are the solution of system $\dot{x} = Ax$:

$$x_1(t) = c_1 + c_2 e^{\frac{-t}{T_2} - \frac{t}{T_1}} \cdot \left(\frac{-T_2}{T_1}\right),$$

$$x_2(t) = c_1 + c_2 e^{\frac{-t}{T_2} - \frac{t}{T_1}}.$$

Putting the values of parameters and condition like in example for "Eroding Goal" archetype $(T_1 = 5, \quad T_2 = 10, \quad x_1(0) = 100, \quad x_2(0) = 40)$. We get:

$$x_1(t) = 60 + 40e^{\frac{-3t}{10}},$$
$$x_2(t) = 60 - 20e^{\frac{-3t}{10}}.$$

Doing the similar calculations we obtain for "Success to the Successful" archetype, the exact solution (for example $a = 0.1$, $b = 0.1$, $x_1(0) = 5.5$, $x_2(0) = 4.5$):

$$x_1(t) = 5 + (0.5)e^{(0.2)\cdot t},$$
$$x_2(t) = 5 - (0.5)e^{(0.2)\cdot t}.$$

Finding the exact mathematical solution for archetype "Fixes that Fail" is not so easily, because of delaying argument.

Let's remind:

$$\begin{cases} \dot{x}_1(t) = -ax_1(t) + bx_2(t) & (1) \\ \dot{x}_2(t) == cx_1(t-\tau) & (2) \end{cases}$$

where:

a, b, c – parameters,

τ – delay time.

We receive:

$$x_1(t) = x_{10} \quad \text{for} \quad t \in [-\tau, 0]$$
$$x_2(t) = x_{20}.$$

For $t \leq \tau$ from the equation (2) we obtain:

$$\dot{x}_2(t) = cx_{10}$$

and in consequences:

$$x_2(t) = cx_{10} \cdot t + x_{20}$$

so:

$$\dot{x}_1(t) = -ax_1(t) + b(cx_{10} \cdot t + x_{20})$$
$$\dot{x}_1(t) + ax_1(t) = b(cx_{10} \cdot t + x_{20}).$$

The solution for equation:

$$\dot{x}_1(t) + ax_1 = 0$$

is:

$$x_1(t) = c_1 e^{-\lambda \cdot t}.$$

And the particular solution from method of forecasting, for the equation:

$$\dot{x}_1(t) + ax_1(t) = bcx_{10} \cdot t + bx_{20}$$

has the form:

$$x_{1\,perticular} = \alpha t + \beta.$$

So from comparison we find:

$$x_{1\,perticular} = \frac{bc}{a} x_{10} \cdot t - \frac{bc}{a^2} x_{10} + \frac{b}{a} x_{20}.$$

The general solution of equation:

$$\dot{x}_1(t) + ax_1(t) = b\left(cx_{10} \cdot t + x_{20}\right)$$
$$x_{1\,particular}(t) = c_1 e^{-\lambda \cdot t} + \frac{bc}{a} x_{10} \cdot t - \frac{bc}{a^2} x_{10} + \frac{b}{a} x_{20}.$$

To evaluate c_1 we use the initial condition $x_1(t) = x_1(0) = x_{10}$. So we obtain:

$$c_1 = x_{10} + \frac{bc}{a^2} x_{10} - \frac{b}{a} x_{20}$$

and:

$$x_1(t)_{general} = \left(x_{10} + \frac{bc}{a^2} x_{10} - \frac{b}{a} x_{20} \right) e^{-\lambda \cdot t} + \frac{bc}{a} x_{10} \cdot t - \frac{bc}{a^2} x_{10} + \frac{b}{a} x_{20}.$$

Remind that this was only for $t \le \tau$.

If we want find solution $x_1(t)$ for next steps, for example $t = \tau + dt$, we should come back for system:

$$\begin{cases} \dot{x}_1(t) = -ax_1(t) + bx_2(t) & (1) \\ \dot{x}_2(t) == cx_1(t-\tau) & (2) \end{cases}$$

From (2) we obtain:

$$\dot{x}_2(t) = cx_1(\tau + dt - \tau) = cx_1(dt).$$

Because $dt \le \tau$, we can use the general solution $x_{1general}(t)$, so:

$$\dot{x}_2(t) = c\left(x_{10} + \frac{bc}{a^2}x_{10} + \frac{b}{a}x_{20}\right)e^{-\lambda \cdot dt} + \frac{bc}{a}x_{10} \cdot dt - \frac{bc}{a^2}x_{10} + \frac{b}{a}x_{20}.$$

The process will be repeated until we get the solutions for whole horizon for t. We see that finding the exact solutions for x_1, x_2 is not so easy at all (comparing with numeric possibilities of Vensim). Finding the exact mathematical solution for archetype "Limit of Growth" is very easy. Let's remind the equation:

$$\dot{x}(t) = a\left(1 - \frac{x(t)}{L}\right)x(t),$$

where:

L – limit of growth,

a – maximum fractional growth,

and condition: $x(0) = x_0$. $\dot{x}(t)$ means derivative of $x(t)$, so we have:

$$\frac{dx}{dt} = a\left(1 - \frac{x}{L}\right)x$$

and:

$$\frac{dx}{a\left(1 - \frac{x}{L}\right)x} = dt.$$

Putting integrals for both sides we obtain:

$$\frac{1}{a}\int \frac{L}{(L-x)x}dx = t + c,$$

$$\frac{1}{a}\int \frac{x-x+L}{(L-x)x}dx = t + c,$$

$$\frac{1}{a}\left[\int \frac{dx}{L-x} + \int \frac{dx}{x}\right] = t + c,$$

$$-\frac{1}{a}\ln|L-x| + \frac{1}{a}\ln|x| = t + c,$$

$$-\ln|L-x| + \ln|x| = a \cdot t + \tilde{c},$$

$$\frac{x}{L-x} = \tilde{\tilde{c}} e^{a \cdot t},$$

$$x = L\tilde{\tilde{c}} e^{a \cdot t} - x\tilde{\tilde{c}} e^{a \cdot t},$$

$$x = \frac{L\tilde{\tilde{c}} e^{a \cdot t}}{1 + \tilde{\tilde{c}} e^{a \cdot t}} = \frac{L\tilde{\tilde{c}}}{e^{-a \cdot t} + \tilde{\tilde{c}}} = \frac{L}{\frac{e^{-a \cdot t}}{\tilde{\tilde{c}}} + 1} = \frac{L}{\tilde{\tilde{c}} e^{-a \cdot t} + 1}.$$

We obtain logistic curve. How to evaluate the constant $\tilde{\tilde{c}}$? Remember the initial condition $x(0) = x_0$:

$$x_0 = \frac{L}{\tilde{\tilde{c}} + 1} \quad \text{and} \quad \tilde{\tilde{\mathrm{c}}} = \frac{\mathrm{L - x_0}}{\mathrm{x_0}}.,$$

so:

$$x(t) = \frac{L}{\left(\frac{L - x_0}{x_0}\right) e^{-a \cdot t} + 1}.$$

This is precise solution of archetype “Limit to Growth”.

The results of simulation type sensitivity analysis and optimization will be presented in paper: „Sensitivity analysis and optimization on some models of archetypes using Vensim – experimental issue”, the same authors.

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ANALIZA WRAŻLIWOŚCI I OPTYMALIZACJA NA PEWNYCH MODELACH ARCHETYPÓW Z UŻYCIEM VENSIMA – UJĘCIE TEORETYCZNE

Streszczenie

Analiza, modelowanie i symulacja złożonych nieliniowych, dynamicznych i wielopoziomowych systemów ma długą historię, szczególnie w obszarze słynnej metody Dynamiki Systemowej. Współczesne języki symulacyjne, takie jak Vensim, pozwalają na łączenie symulacji z optymalizacją, co umożliwia ocenę wrażliwości parametrów w modelowanych obiektach i wybór optymalnych decyzji.

Zakres modelowanych obiektów jest bardzo szeroki: od modeli przemysłowych, po ekologiczne i ekonomiczne. Problem badawczy artykułu odnosi się do takich dyscyplin, jak: Teoria Decyzji, Teoria Organizacji, Badania Operacyjne.