Sensitivity Analysis and Optimization for Selected Supply Chain Management Issues in the Company – Using System Dynamics and Vensim

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Abstract

The aim of our paper is to present the new results of research work on optimization and simulation for some logistic problems in the company. The System Dynamics (SD) method and the Vensim simulation language are applied in order to solve specific managerial problems described by Forrester in the model of supply chain. The historical model of Customer-Producer-Employment System by Forrester (Forrester, 1961) has not been examined with the sensitivity analysis, from the “automatic” testing perspective. Optimization experiments have not been conducted, either. It is surprising, since the model is old and widely known. The opportunities offered by the Vensim language allow us to perform such analysis. The visualization called “confidence bounds” is used, to show the behaviour of chosen variables over a period of time. The Monte-Carlo method is applied for sampling a set of numbers from within bounded domains (distribution for each searching parameters is specified). The authors of this paper conducted numerous experiments in this scope. This paper presents their results and offers some conclusions formulated at the end.

Keywords: System Dynamics, sensitivity analysis, optimization, Vensim.

Introduction and literature review


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of Management by Jay W. Forrester. The approach can be applied to dynamics
problems arising in complex social, managerial, economic or ecological
systems. The main purpose of System Dynamics is to try to discover the
“structure” that conditions the observed behaviour of the system over time.
System Dynamics tries to pose “dynamic” hypotheses that endogenously
describe the observed behaviour of system.

In the area of System Dynamics method, there have not been much theory
or practice related to combining simulation and optimization. Although the
first trials were sufficiently long ago (Keloharju, 1977, 1980, 1983; Winch,
1976), the fact is that incorporation or embedding simulation to optimization
(and vice versa) has not been as popular as it should be in our view. Probably
one of the main reasons was the lack of effective tools. Popular software
packages originally used in SD modelling and simulation, did not offer
possibilities of automatic optimization (for example: languages DYNAMO,
DYSMAP (Kasperska and Mateja-Losa, Slota, 2006). Only such packages
as COSMIC and COSMOS and Vensim (Ventana, 2007) make it possible to
connect simulation and optimization. Hence some papers published in the
field of SD (e.g. Coyle, 1996, 1998), though the work on this subject is still
scarce. The authors of this paper have some experience with the so-called
embedding simulation in optimization and vice versa, having conducted
numerous experiments on DYNBALANCE family of models (Kasperska, 2005,
2009; Kasperska and Mateja-Losa, 2005, 2006; Kasperska, Mateja-Losa and

The SD models usually contain several parameters. It is interesting to
examine the effect of their variation on simulation output. We select some
parameters and assign maximum and minimum values along with a random
distribution over which to vary them to see their impact on the model
behaviour.

Vensim has a method of setting up such sensitivity simulation. Monte
Carlo multivariate sensitivity works by sampling a set of numbers from within
bounded domains. To perform one multivariate test, the distribution for
each specified parameter is sampled, and the resulting values are used in
a simulation. When the number of simulations is set, for example, at 200, this
process will be repeated 200 times.

In order to perform sensitivity simulation, the user needs to define what
kind of probability distribution values for each parameter will be drawn.
The simplest distribution is the Random Uniform Distribution, in which any
number between the minimum and maximum values is equally likely to occur.
The Random Uniform Distribution is suitable for most sensitivity testing and
is selected by default. Another commonly-used distribution is the Normal
Distribution (or Bell Curve) in which the value near the mean is more likely
to occur than the values far away from the mean. The results of sensitivity testing can be displayed in different formats. Time graphs display behaviour of a variable over a period of time. The variables spread values which combine to form individual simulation traces.

Research method
The object of the experiments is the model named “Customer – Production – Employment”, described in the literature by Forrester (1961) and Łukaszewicz (1975). The authors of this article used the description of the model, abbreviations for parameters and variables after Łukaszewicz. Our intention is not to present the model, which is well-known, but to draw the reader’s attention to the sensitivity and optimization experiments. In our paper we suggest the process of “automatic” sensitivity analysis and optimization by Vensim.

Analysis and study

Presentation of the object of the experiments and the assumptions of the simulation
Figure 1 presents the structure of the model “Customer – Production – Employment” in Vensim convention.
Figure 1. Model “customer-production-employment system”

Source: Authors’ research, on the basis of Łukaszewicz (1975).
Table 1 presents the assumptions of the simulation of the above model.

**Table 1. Assumptions of the simulation**

<table>
<thead>
<tr>
<th>Name of levels</th>
<th>Initial value of level</th>
<th>Name of parameters</th>
<th>Initial value of parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Order Filling, Inventory Reordering</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PZ</td>
<td>1000</td>
<td>K</td>
<td>4</td>
</tr>
<tr>
<td>ZW</td>
<td>700</td>
<td>CUS</td>
<td>15</td>
</tr>
<tr>
<td>MW</td>
<td>4000</td>
<td>CSW</td>
<td>2</td>
</tr>
<tr>
<td>US</td>
<td>1000</td>
<td>CWG</td>
<td>1</td>
</tr>
<tr>
<td>SW</td>
<td>700</td>
<td>CZPM</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPM</td>
<td>6</td>
</tr>
<tr>
<td><strong>Manufacturing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZM</td>
<td>2800</td>
<td>PRD</td>
<td>2.66</td>
</tr>
<tr>
<td>ZK</td>
<td>1200</td>
<td>CPKM</td>
<td>6</td>
</tr>
<tr>
<td>PM</td>
<td>4200</td>
<td>MOP</td>
<td>1</td>
</tr>
<tr>
<td>PK</td>
<td>1800</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Material Ordering</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>MM</td>
<td>6000</td>
<td>WDM</td>
<td>6</td>
</tr>
<tr>
<td>DM</td>
<td>3000</td>
<td>CDM</td>
<td>3</td>
</tr>
<tr>
<td><strong>Labor</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>KD</td>
<td>375</td>
<td>CPO</td>
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</tr>
<tr>
<td>PP</td>
<td>0</td>
<td>CKK</td>
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<tr>
<td>PO</td>
<td>0</td>
<td>CPW</td>
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<tr>
<td>CZ</td>
<td>0</td>
<td>WPK</td>
<td>0</td>
</tr>
<tr>
<td>CNPZ</td>
<td>4</td>
<td>CLO</td>
<td>20</td>
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<td><strong>Customer Ordering</strong></td>
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<td></td>
</tr>
<tr>
<td>BK</td>
<td>30000</td>
<td>CKN</td>
<td>3</td>
</tr>
<tr>
<td>ZP</td>
<td>3000</td>
<td>CUD</td>
<td>4</td>
</tr>
<tr>
<td>CK</td>
<td>30</td>
<td>CZPM</td>
<td>1</td>
</tr>
<tr>
<td>CD</td>
<td>4.7</td>
<td>CPKM</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CWG</td>
<td>1</td>
</tr>
<tr>
<td><strong>Cash, Profit and Dividends</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KS</td>
<td>10000</td>
<td>WSP</td>
<td>80</td>
</tr>
<tr>
<td>PR</td>
<td>50000</td>
<td>CWG1</td>
<td>100</td>
</tr>
<tr>
<td>RM</td>
<td>6000</td>
<td>WCM</td>
<td>20</td>
</tr>
<tr>
<td>PD</td>
<td>20000</td>
<td>CRM</td>
<td>3</td>
</tr>
<tr>
<td>PF</td>
<td>0</td>
<td>SKW</td>
<td>50</td>
</tr>
</tbody>
</table>

*Source:* based on Forrester (1961) and Łukaszewicz (1975).
Results of the experiments on sensitivity analysis and optimization for some logistics problems in the company

There are numerous logistics problems in the “Customer – Production – Employment” model. We would like to draw the reader’s attention to some of them.

Problem number 1 – Too long time of delivery from Producer to Customer. To conduct this experiment we selected the parameters: “CUD” (Time to Adjust Quoted Delivery at Factory), “CZPM” (Delay in Clerical Processing at Factory), “CWG” (Delay in Shipping at Factory), and observed the confidence bounds for variable “CD” (Delay in Quoted Delivery at Factory). The results are presented in Figure 2.

![Figure 2](image)

Figure 2. Confidence bounds for variable “CD” for variation of parameters: “CUD” ∈ (3,5), “CZPM” ∈ (0.5,1), “CWG” ∈ (0.5,1)

Our aim was to shorten the “CD” time”. So we planned the optimization experiment consisting in minimization and used the optimization setup by Vensim, which is shown on windows on Figures 3 and 4.
The results of the experiment are presented in Table 2.

The second problem is: Too large fluctuations of labour level in the company. To conduct this experiment we selected the parameter “CLO” (Time for Backlog Adjustment at Factory), and observed the confidence bounds for variables: “KD” (Production Workers at Factory), “CZ” (Total Labour Change at Factory). The results are shown in Figures 5 and 6.
The results of the experiment are presented in Table 2.
The second problem is: Too large fluctuations of labour level in the company.

To conduct this experiment we selected the parameter “CLO” (Time for Backlog Adjustment at Factory), and observed the confidence bounds for variables: “KD” (Production Workers at Factory), “CZ” (Total Labour Change at Factory). The results are shown in Figures 5 and 6.

**Figure 5.** Confidence bounds for variable “KD”, for variation of parameter “CLO” € (10,30)

**Figure 6.** Confidence bounds for variable “CZ”, for variation of parameter “CLO” € (10,30)
Our aim was to shorten the “CZ”. As above we planned the optimization experiment, consisting in minimizing the value of that variable. The results of the experiment are presented in Table 2.

The third problem is: Too large fluctuation of “KS” level (Cash Balance at Factory).

To conduct this experiment we selected the parameter “CWG1” (Finished-Goods Price at Factory), “SKW” (Standard Inventory Cost per Item at Factory), “WSP” (Wage Rate at Factory), “PRD” (Productivity of Labour at Factory). The observed confidence bounds for net profit are demonstrated in Figure 7.

Our aim was to maximize “PF” (Net Profit Rate at Factory). We conducted the optimization by Vensim (see: windows in figures 8 and 9). The results are presented in Table 2.
Sensitivity Analysis and Optimization for Selected Supply Chain Management Issues in the Company – Using System Dynamics and Vensim

Our aim was to maximize "PF" (Net Profit Rate at Factory). We conducted the optimization by Vensim (see: windows in figures 8 and 9). The results are presented in Table 2.

**Table 2. Results of optimization experiments for logistic problem**

<table>
<thead>
<tr>
<th>Problem (no.)</th>
<th>Type of optimization</th>
<th>Scope of parameters</th>
<th>Optimized values of parameters</th>
<th>Objective function</th>
<th>Initial value</th>
<th>Final value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>MIN</td>
<td>CUD=3</td>
<td></td>
<td></td>
<td>CUD=3</td>
<td>CD=4.89912</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CLO=30</td>
<td></td>
<td></td>
<td>CLO=30</td>
<td>CZ=3285.4</td>
</tr>
<tr>
<td>2.</td>
<td>MAX</td>
<td>CWG1=100</td>
<td>PF=1.286e+006</td>
<td></td>
<td>PF=1.286e+006</td>
<td>PF=1.417e+006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SKW=45</td>
<td></td>
<td></td>
<td>SKW=45</td>
<td>SKW=45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WSP=80</td>
<td></td>
<td></td>
<td>WSP=80</td>
<td>WSP=80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PRD=2</td>
<td></td>
<td></td>
<td>PRD=2</td>
<td>PRD=2</td>
</tr>
</tbody>
</table>

The possibilities of such experimentations are practically unlimited, however, the scope of our paper does not allow to extend the analysis.

**Figure 8.** Optimization setup by Vensim

**Figure 9.** Optimization setup by Vensim
### Table 2. Results of optimization experiments for logistic problem

| Problem (no.) | Type of optimization (MIN, MAX) | Scope of parameters | Optimized values of parameters | Objective function
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>MIN</td>
<td>CUD є (3,5)</td>
<td>CUD=3</td>
<td>CD=4.89912</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CZPM є (0.5,1)</td>
<td>CZPM=0.545774</td>
<td>CD=4.2645</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CWG є (0.5,1)</td>
<td>CWG=0.595165</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>MIN</td>
<td>CLO є (10,30)</td>
<td>CLO=30</td>
<td>CZ=3845.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CWG є (90,100)</td>
<td>CWG1=100</td>
<td>CZ=3285.4</td>
</tr>
<tr>
<td>3.</td>
<td>MAX</td>
<td>SKW є (45,50)</td>
<td>SKW=45</td>
<td>PF=1.286e+006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WSP є (70,80)</td>
<td>WSP=80</td>
<td>PF=1.417e+006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PRD є (2,2.66)</td>
<td>PRD=2</td>
<td></td>
</tr>
</tbody>
</table>

The possibilities of such experimentations are practically unlimited, however, the scope of our paper does not allow to extend the analysis.

### Discussion of results

The comparison of the initial and final values of objective functions in Table 2 allows us to ascertain that the choice of parameters and their scope was quite good, since the value of objective function has improved in all considered cases. The interesting fact is that the choice had “local” meaning (in the sense that parameters were from the sectors that were similar to objective functions).

Łukaszewicz (1975) ascertains that in large scale models there are few sensitive parameters and a lot of insensitive parameters. It is vital to detect those sensitive parameters and thus improve the behavior of the system. Naturally the ‘trial-and-error’ process is time and labor-consuming. This sensitive analysis by Vensim allows us to estimate the sensitiveness of selected variable for the choice of given parameters in an easier way and prepare the basis for optimization process.

It should be stressed that the obtained results are in line with specific assumption about the characteristics of the model entrance. Łukaszewicz in his paper (Łukaszewicz, 1975) recommended that the analysis of the model behavior should be under a wide spectrum of entrances, not only the classic “step” functions (like in our case) but the sinusoidal or linear ones (for example: trapezium). In books of Forrester (1961) and Łukaszewicz (1975) there are many examples of the analysis using the “trial and error” method. As a result of such analysis, the model behavior has been improved. In our paper we suggest the process of “automatic” sensitivity analysis and optimization by
Vensim. Obviously, this simulation language was not known by Forrester or Łukaszewicz, and their results of simulation were time and labor-consuming, and impressive in their times.

**Conclusion**

Firstly, we would like to draw a number of theoretical conclusions:

- as Jackson (2006) said: “creative holism is necessary in the modern world. Managers are facing ever increasing complexity, change and diversity, and the solutions they have at their disposal to cope with these issue are inadequate”. Thus we can say that the possibilities presented by SD are adequate for solving logistics problems in the firm.

- simulation – optimization experiments, on System Dynamics models allows to find sensitivity parameters and consequently conduct the search for optimal solution for multi-criteria problems (objective functions are modelled like inner elements of the model, with feedback in its structure),

- searching for optimal solutions can take into consideration different preferences of decision makers (different form of objective function, with possibilities of weighting parameters for their factors).

Secondly, we would like to offer some practical conclusions:

- logistics problems in the firm can be investigated using sensitivity analysis and optimization by Vensim,

- the Vensim language should become popular in the environment of System Dynamics modellers, because it is an effective tool for such experiments as: simulation – optimization: its sensitivity and optimization setups allow almost automatic search for confidence bounds or optimal value of objective functions,

- doing simulation with complex, large scale models, requires seeking many versions of structures, many parameters (especially sensitive parameters), including random elements. All of this is offered by Vensim. Moreover, a new version of this language (see: Vensim 2013) allows its users to create interactive games. This constitutes a new direction of future investigations for the authors.
References


**Słowa kluczowe:** Dynamika Systemowa, analiza wrażliwości, optymalizacja, Vensim.