UDK 005.4:004
Original scientific paper

DEVELOPING SYSTEM DYNAMICS MODELS WITH „STEP-BY-STEP“ APPROACH

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Abstract: *System dynamics is a powerful tool that enhances learning about company, market and competitors; portrays the cognitive limitations on the information gathering and processing power of human mind; facilitates the practice of considering opinions; and supports building of "What if" scenarios. Although the literature on system dynamics modeling is very rich with applications in many fields, not many papers on developing system dynamics models were published so far. In this paper we portray current approaches to the development of system dynamics models. These are (1) model development based on influence diagram, (2) model development based on the identification of resources and their states, (3) usage of generic structures for specific domain field, and (4) component strategy for the formulation of system dynamics models. Validation is an important issue that none of these approaches tackles. We propose a "step-by-step" approach that integrates validation with developing process of system dynamics models. This approach will be demonstrated on the example of development of a simple inventory model.*

Keywords: *system dynamics, model development, validation, inventory.*

1. INTRODUCTION

The process of system dynamics model development is not simple, and a not many papers about this topic were published so far. Those who are just beginning to deal with system dynamics can easily be mislead by the simplicity of the system dynamics development software, and may attempt to develop the model in one step. However, this type of approach often results with the model containing various faults which are difficult to correct.

System dynamics models can help in understanding structure and behavior of the system with nonlinear links and feedback. However, experience in development of system dynamics model teach us that proper understanding of the model behavior is very hard to achieve if the approach to the development of the model is not gradual. Therefore we recommend "step-by-step" approach to system dynamics model development which integrates the evaluation of the model with the process of model development. Such approach enables better understanding of the model behavior, as well as establishing better confidence in the model.

The goal of this paper is to describe the "step-by-step" approach to development of the system dynamics model, and demonstrate it on the example of the inventory model. The paper consists of the following parts. After the introduction, in the second part of the paper current approaches of system dynamics model development are shown. In the third part "step-by-step" approach of system dynamics model development is described, while the fourth part presents development of the inventory model using this approach. The last part of the paper gives conclusion.

2. DEVELOPMENT AND VALIDATION OF SYSTEM DYNAMICS MODELS

Current approaches to the development of system dynamics models are: (1) model development based on casual-loop diagram (Coyle, 1996), (2) model development based on the identification of resources and their states (Wolstenholme, 1990), (3) usage of generic structures for specific domain field (Wolstenholme, 2004), and (4) component strategy for the formulation of system dynamics models (Forrester, 1968; Goodman, 1975). Validation is an important issue that none of these approaches tackles.

*Model development based on influence diagram*s proposes building quantitative model with system dynamics software using causal-loop diagrams. Casual-loop diagrams are very suitable for explaining model structure to management at the beginning and at the end of the modeling process. However, some problems may arise in causal-loop diagramming, both in development of causal-loop diagrams and in the deriving system behavior from them. The main problem is that causal-loop diagrams obscure the stock and flow structure of systems (Richardson, 1986). Casual-loop diagrams are then used for deriving of both stock and flow diagrams, as well as system dynamics equations.

System dynamics approach is based on *identification of resources, their states and rates* at which resources change their states. Resources (levels or stocks) could be material, people, cash, orders, etc. A state of the resource can be defined as any accumulation of the resource which is relevant to the purpose of the model. The rate at which resources are converted between states is represented by rate variables. Wolstenholme (1990) proposes creating the structure of systems with the goal of recognizing resources and states. He proposes identification of relevant resources related to the modeling goal, as well as states and rates at which resources change. Based on this, stock and flow diagram and model equations are derived.

Generic structures are relatively simple structures that occur in various situations (Albin et al., 2001), and can help with the creation of dynamic hypotheses at the front end of the modeling process as well as with communication on systemic insights at the back end of the modeling process. In practice, it is often beneficial to use the archetypes in parallel throughout the process to guide high-level thinking whilst detailed modeling is taking place (Wolstenholme, 2004). In that way, stock and flow diagrams are created without any preliminary preparation. However, by simply fitting the system to a generic structure, the inexperienced modeler can easily use wrong generic structures that are not suitable for particular system. (Breirova, 2001).

The most recent concept is the *component strategy* to the development of system dynamics models. This approach concentrates on the formulation of the Forrester stock and flow diagram, and incorporates the concept of an interaction matrix to assist in formulation of such models (Burns, et al., 2002). In this strategy the quantities that will be included in the model and their associated interactions are generated simultaneously. The goal of introducing this strategy was to develop computer aids that could facilitate model formulation in order to speed up the process of system dynamic model formulation. This strategy would then divide the labor of modeling into human and computer part, where computer part could be automated.

System dynamics models are used in analyzing the structure and the behavior of the system as well as for designing efficient policies of managing the system. For example, using system dynamics model of decisions can help in finding appropriate decisions for the company (Merten, 1991; Morecroft, 1984). Moreover, these models have a significant role in the education of managers (Graham *et. al,* 1992). Clients and other potential users obviously want to be sure that they can trust the system dynamics model, because model with significant flaws can lead them to wrong decisions (Richardson, 1996).

Tests for acquiring confidence in the system model dynamics can be divided into two groups: (1) structure tests and (2) behavior tests (Forrester, *et.al*, 1979). *Structure tests* (structure verification test, parameters verification test, extreme conditions test, model border adequacy test and dimensional consistency test) compare the structure of the system dynamics model with the structure of the real system so that every relationship between the elements of the real system is being compared with the relationship between corresponding elements of the model which is described by mathematical equation. *Behavior tests* (behavior reproduction test, behavior prognosis test, behavior anomaly test, generic behavior test, extreme policy test, border adequacy test and behavior sensibility test) are conducted to determine whether the behavior of the model matches the behavior of the real system, and here the relationship between the structure and the model behavior is analyzed with particular care.

Interviewing was introduced as another strategy for assessing of system dynamics models (Diker et al, 2005), based on importance of using expert judgment for assessing purposes. The paper presents four illustrations about the use of interviews in the validation of system dynamics models. These four methods differ in a number of points: who was interviewed, technology of delivery, type of questions, how behavior was presented, how structure was presented, data processing and data analysis. These methods provide a number of question formats and analysis techniques that could be used in the validation process.

3. "STEP-BY-STEP" APPROACH

Evaluation is a process in which users acquire confidence in the system dynamics model (Richardson *et.al*, 1981). The experience shows that it is very important that the process of model evaluation is conducted in parallel to the development of the model, rather than after the model completion. It means that evaluation of the model should be an iterative procedure conducted during all phases of the simulation modeling. This is especially important since it is well known that too fast model development is the common beginners' mistake. Most frequently beginners develop whole models in a single stage, and conduct evaluation tests only when the model is already finished. This approach cannot guarantee development of high quality and robust model whose behavior and structure matches reality. Because of the formerly mentioned problem with the use of casual-loop diagrams (causal-loop diagrams obscure the stock and flow structure of systems) we recommend the development of the stock and flow diagram right after the system analysis.

Because of all these we recommend development of the system dynamics model in several steps:

1. Development of the basic model
2. Conducting the basic evaluation tests – extreme condition tests, behavior sensibility test and dimension consistency test
3. Expansion of the model with one or more feedbacks

4. Re-conducting aforementioned evaluation tests for the new version of the model
5. If (a) these tests are not giving satisfactory results or if (b) the user on the basis of understanding the system reach the conclusion that it is necessary to expand the model with new feedbacks, step two is repeated and the whole procedure is continued
6. If the results of the aforementioned tests are satisfying, and the modeler concludes that the model is complete, the other evaluation tests mentioned before are carried out

Therefore "step-by-step" approach to system dynamics model development proposes the use of the three basic evaluation tests which point out to the modeler the existence of errors and oversights (dimensional consistency test and extreme conditions test), and also help in understanding the influence of every variable on the model behavior (behavior sensibility test). Short description of these tests follows.

Dimensional consistency test

In the system dynamics model it is important that the units of measure of variables on both sides of the equation are equal. This test also checks whether dimensions of variables in the model correspond to the unit in which they can meaningfully express the real variables which exist in the company. The test is conducted using built-in function of program language used for system dynamics model development.

Extreme conditions test

This test checks whether the structure of the model is such that the behavior of the model in extreme conditions matches the behavior of the real system in same situations. For example, if the demand for the company products is equal to zero during the whole simulation, then the number of delivered product should also be zero, and there should not be any revenues from the product sales as well as no directs costs related with the sales.

Behavior sensibility test

This test is focused on detecting the parameters whose small changes cause significant change in the model behavior. The fewer such parameters, the higher the credibility of the model is. However, the model behavior sensibility is acceptable if in the real system small change of the parameter values also causes significant change of the system behavior. The goal of the system dynamics is to find the parameters which have most effect on system behavior, and can thus be used for.system management policies. If this test shows that the model is not sensible to the changes of some parameters, it can be concluded that for assessment of these parameters subjective judgment is reliable enough.

4. EXAMPLE: DEVELOPING SIMPLE INVENTORY MODEL BY "STEP-BY-STEP" APPROACH

We describe here development of the inventory model in the company which solely imports products, and doesn't have any production capability. Model was developed using Vensim system dynamics software.

The development of the inventory model is carried out through three steps. In the first step the simple model of the inventory with supply and delivery is analyzed. This model's disadvantage is that in it the inventory can become negative. In the second step feedback is added, which prevents the inventory to become negative. In the third step ordering new products is added into the model.

4.1. SIMPLE INVENTORY MODEL

Inventory model in the beginning of the modeling process consists only of the inventory level and the speed of supply and delivery (Figure 1). Supply equals 1000 product per month, the same as the monthly delivery of the products. In the beginning of the simulation there are 1000 products in the inventory, and the model is balanced, i.e. during the whole simulation inventory contains 1000 products.

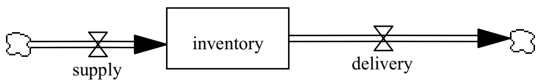

Figure 1. Simple inventory model flow diagram

The equations of the model are:

delivery=1000
Units: P/Month (P = products)
The number of products which company delivers to customers every month.

suppy=1000
Units: P/Month
The number of products which company buys from the supplier every month.

Inventory= INTEG (+supply-delivery, 1000)
Units:JP
The number of products currently in the company's warehouse.

Evaluation of the model is done in the following way. Dimensional consistency test is conducted by the Vensim's built-in function, and it shows that the level units and the speed are dimensional consistent. Extreme conditions test is carried out with two assumptions: (1) delivery=0 and (2) supply=0.

It was shown that when delivery=0, inventory grows linearly (Figure 2). This kind of behavior is consistent with the situation when company does not succeed in selling the products, but still keeps on buying new ones. Since this kind of behavior is not realistic, the model needs to be expanded so that the process of buying new products is formulated on the basis of the demand information.

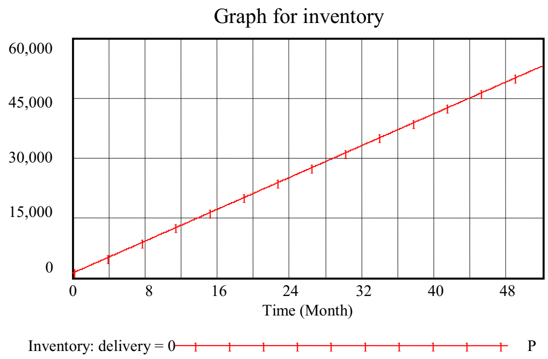

Figure 2. Model behavior when delivery =0

If the company does not succeed in supplying new products (i.e. supply is equal to zero), the inventory will be depleted and number of products decreases until it falls to zero. However, in the model inventory keeps on decreasing and even becomes negative (Figure 3), and this is unreal. Because of that the model needs to be corrected so that the delivery of the inventory is limited, and this is done in the next step.

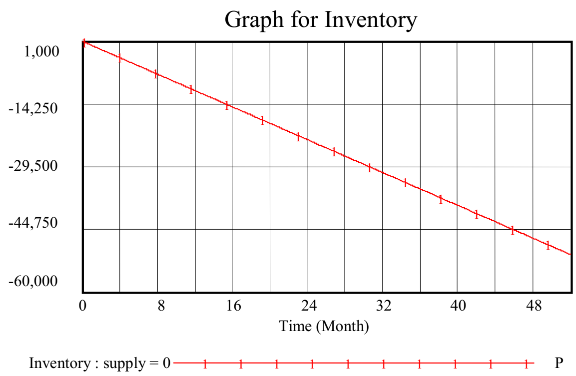

Figure 3. Model behavior when supply=0

4.2. LIMITING INVENTORY DELIVERY

In inventory modeling we should take in consideration that the company will not always be able to satisfy the demand for its products, and that it can sell only the amount of products that it has in warehouse. Until the number of products in inventory is higher than the desired number of products in inventory, sale equals demand. When the inventory decreases, management restricts delivery. However, it does not deliver products to the first customers that appear, but always keeps a few products for its permanent buyers. If the demand is constantly higher than the supply, the inventory will gradually decrease until the effect of the inventory state doesn't stop further delivery (Figure 4).

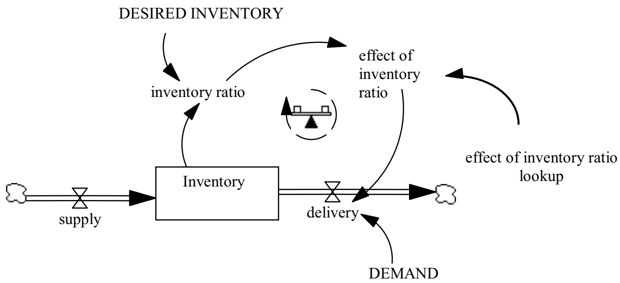

Figure 4. Flow diagram of the inventory model with delivery constrains

The model is expanded with following equations:

DESIRED INVENTORY=1000
Units: P
The number of product management would always want to have in warehouse.

the effect of inventory ratio= effect of inventory ratio lookup (inventory ratio)
Units: dmnl
The effect of the inventory status on delivery depends on ratio of inventory/desired inventory.

*delivery=the effect of inventory status on delivery*sales*
Units: P/Month
The number of products that the company can deliver to its customers every month.

Inventory ratio=inventory/DESIRED INVENTORY
Units: dmnl (without dimension)
The ratio of current to desired company inventory.

DEMAND=1000
Units: P/Month
Demand for the company's products.

effect of inventory ratio lookup
([(0,0)-(1,1)],(0,0),(0.05,0.3),(0.1,0.55),(0.15,0.75),(0.2,0.9),(0.25,0.97),(0.3,1),(1,1))
Units: dmnl
Non-linear function of the inventory state effect on company's product delivery.

The function of the inventory status is presented as follows (Figure 5). The abscissa shows a current/desired inventory ratio, while the ordinate shows the effect of the inventory state. The number of delivered products is calculated as a product of inventory state effect and demand. The effect of inventory state depends on the ratio of current/desired number of products on stock. For example, if the current/desired number of products ratio is 3/10, the effect of inventory state is 0.5, what means that the management delivers half of the desired quantity. The smaller current/desired inventory radio, management delivers a smaller part of the requested quantity. If there inventory is empty, current/desired inventory radio equals to zero. In this case the effect of inventory status also equals to zero, and management does not delivery any products.

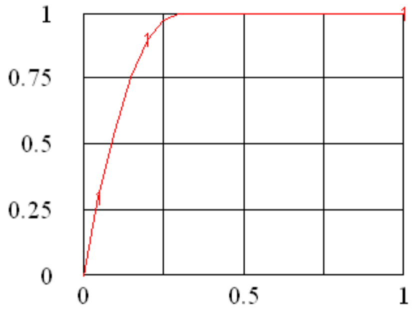

Figure 5. Effect of inventory ratio lookup

If both the demand for the products and its supply is equal to 1000 products per month with, the model would be balanced during the entire simulation. Now let us assume that the demand is 1100 products monthly instead of 1000 products. At he beginning of the simulation management has 1000 products in inventory, i.e. equal to the desired inventory. Although demand is 1100 products, management keeps on supplying only 1000 product per month. Since the delivery is larger than supply, inventory is gradually decreasing. Assume that the company's policy is to delivery requested number of products until inventory decreases to approximately 1/3 of desired inventory, and after that management reduces delivery until the number of 1000 products monthly is attained and inventory reaches equilibrium value (Figure 6).

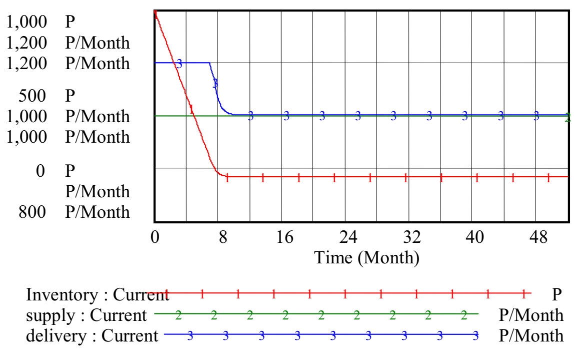

Figure 6. Inventory model behavior with the demand of 1100 product per month

As in the previous step of model development dimensional consistency test is conducted with the Venism software built-in function, and it is shown that the level units and the speed are dimensionally consistent.

Extreme conditions test is conducted again, with two assumptions: (1) supply = 0 and (2) demand = 0.

If the management stops buying the products and all other parameters are left unchanged (inventory and desired inventory are 1000, demand is 1000) the inventory will decrease until all he products are sold, i.e. until they reach the value 0, as seen in Figure 7.

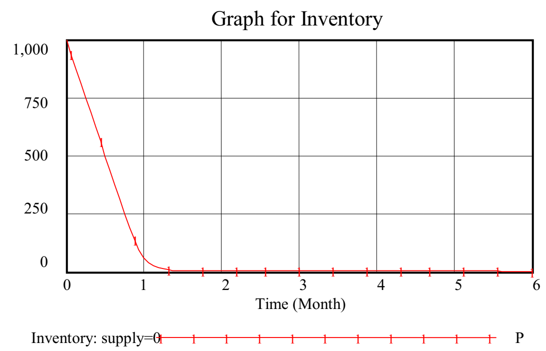

Figure 7. Model behavior when supply=0

If the demand is 0 and the management keeps on supplying 1000 products every month, the inventory should linearly increase, which is visible from the graph of Figure 8.

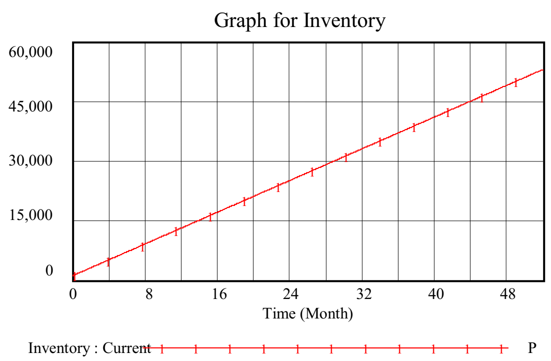

Figure 8. Model behavior when demand = 0

In order to conduct the sensitivity test the value of "function of inventory status effect on delivery" was changed (Figure 9). Current form of the function reflects the position of management on backup inventory. However, there are no exact rules in the company concerning backup inventory for permanent buyers. So the function is changed in order to reflect both liberal and restrictive policy of keeping the backup inventory. If the nonlinear function is shifted to the right, it reflects the restrictive policy of keeping the backup inventory, because delivery is starting to decrease with the larger value of inventory ratio. In this case the management will keep higher level of inventory if the delivery increases. The reverse is true if the nonlinear function is shifted to the left.

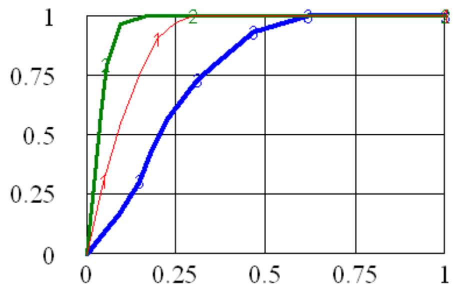

Figure 9. Function for the basis of sensitivity test

The simulation is carried out with changed function of inventory status effect on delivery, which reflects current, liberal and restrictive policy of keeping backup inventory. It is assumed that the demand for the products is 1100 products during the whole simulation. The model behaves according to expectations. When the policy of inventory delivery is more liberal than the current one, the equilibrium value of inventory is lower. The reverse is true if the policy of inventory delivery is more restrictive (Figure 10).

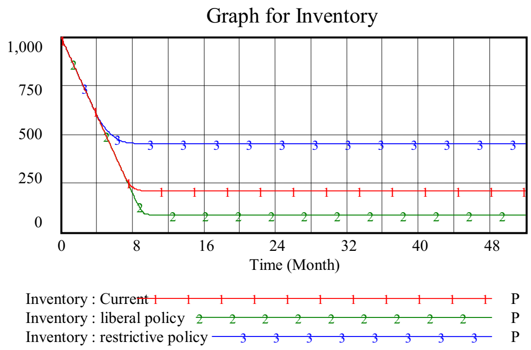

Figure 10. Model behavior with sensitivity test

4.3. ORDERING PROCESS

In previous step it was assumed that management always orders the same amount of products regardless of the change in the demand. This kind of assumption is not realistic, and therefore the model will be expanded in order to represent the process of ordering in the company.

Suppose that company's management orders every month the amount of products that was sold in the previous month in order to fill the inventory. The supplier needs approximately 6 weeks to delivery the ordered goods. Management takes into account the desired inventory, compares current inventory with desired inventory and orders product every month to eliminate the difference between them. The desired inventory depends on the demand for the products, and management wants to keep the quantity of products that is enough to settle the demand during 6 weeks. The ordering process is developed (Figure 11) according the Guided Study Program in System Dynamics (1999).

The model contains two negative feedbacks:

1) Increasing the inventory causes the increase of inventory ratio. The higher the inventory ratio, the larger the effect of inventory status on delivery, and delivery grows. Because of increased delivery, the inventory decreases.
2) Increasing the inventory decreases inventory deviation. The smaller the inventory deviation, management orders less new products. Because of the smaller supply, inventory decreases.

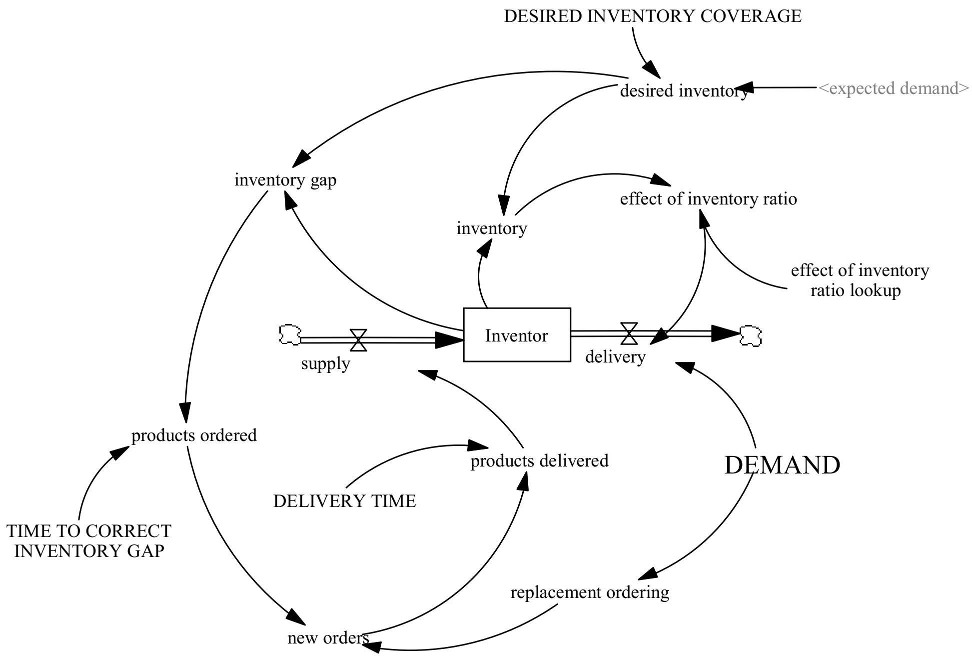

Figure 11. Flow diagram of inventory model with constraint of delivery and ordering

Evidently no company works under ideal condition in which demand is always constant and inventory always equals desired inventory. Therefore we will test the behavior of the model in conditions where demand increases only once. It is assumed that demand increases after 10 months from 1,000 products monthly to 1,500 products monthly, and it remains unchanged until the end of the simulation. It this case the demand equation is

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DEMAND=1000+step(500,10)
Units: P/Month
Demand for the company's products
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After the demand increases from 1,000 products to 1,500 products monthly, desired inventory also changes from 1,500 products to 2,250 products (Figure 12). Since for the first 10 months inventory equals 1,500 products, the management has to order new products so the inventory could grow to the desired level. However, when management orders product to remove the deviation of inventory it does not take in consideration the time necessary for delivering products from the supplier, what causes system oscillations. After the demand increases, the sales also grow and the inventory diminishes. Management compares current inventory with desired inventory, and orders products to eliminate the difference. Upon next order, management again compares current with desired inventory. However, the problem is in that the products ordered in previous month have not still arrived. Because of that management orders too many extra products. After the ordered products finally begin to arrive, management realizes that the inventory grows too much so they order fewer products. However, again they didn't take in account the products which are still on their way to inventory, and they cut back on orders too much and this results in a large decrease of inventory. So, because of the delay in delivery of products, management at first orders too much, and later not enough products. However, inventory oscillations become smaller and smaller, and inventory reaches new equilibrium level of 2,250 products.

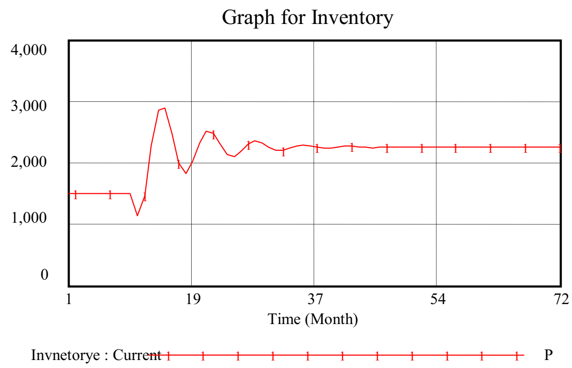

Figure 12. Model behavior with the increase in demand

The dimensional consistency test, extreme conditions test and the sensibility test are conducted again. Because of the limited amount of space here, only one sensibility test results; the extreme conditions test, will be shown.

The model sensibility test is conducted under the assumption that the DEMAND equals 1000 products during first 10 month, after which it grows to 1500 products. The values of the next parameters are changed:

- TIME OF CORRECT INVENTORY GAP (Ordering time) = 1, 3 and 5 months
- Initial value of inventory = 1000, 1500, 3000 products
- DESIRED INVENTORY COVERAGE = 1, 3 and 6 months
- DELIVERY TIME = 0.5, 1.5 and 3 months

Inventory is an important issue for every company. Large inventory represent cost and decrease liquidity, and small inventory can cause the loss of company's market. Therefore, inventory should oscillate as less as possible. This is why the goal of above sensitivity tests is to find out optimum combination of parameters that would ensure lowest oscillations.

Ordering time

Ordering times represent the speed of reaction on deviation of current from desired inventory. The inventory model shows that management can influence only the value of time of ordering stocks, while initial value of inventory, desired coverage of inventory, and the time of delivery depend on many external factors. They could intuitively believe that it is better to react faster in ordering inventory, and that this would bring larger stability of inventory. However, the sensitivity test shows that inventory oscillations are higher with the shorter time of ordering, and vice versa (Figure 13).

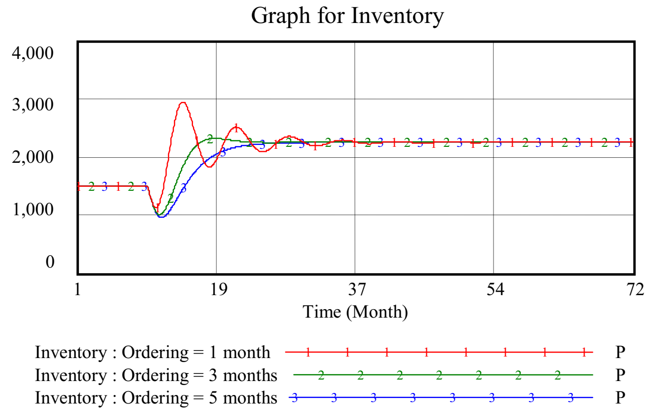

Figure 13. Behavior of inventory with the ordering time of 1,3 and 5 months

Initial value of Inventory

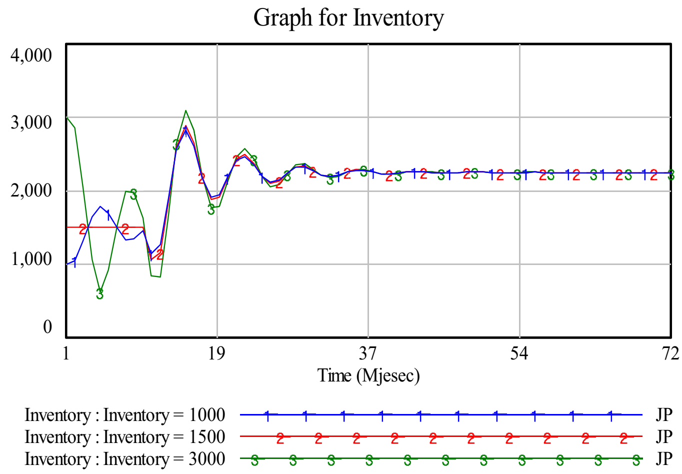

Figure 14. Behavior of inventory with the Initial value of inventory of 1000, 1500, 3000 products

Desired Inventory Coverage

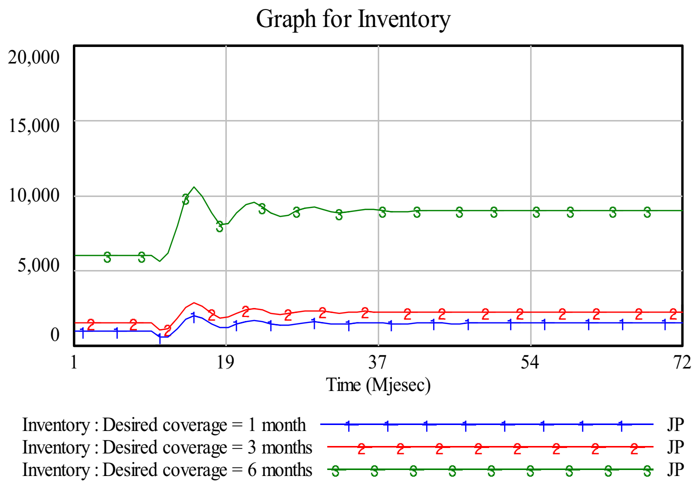

Figure 15. Behavior of inventory with desired inventory coverage of 1, 3 and 6 months

Delivery time

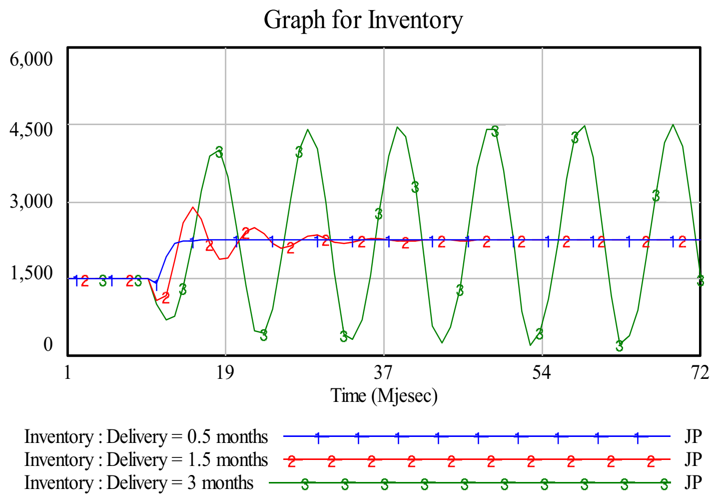

Figure 15. Behavior of inventory with delivery time of 0.5, 1.5 and 3 months

5. CONCLUSION

In the paper "step-by-step" approach to developing system dynamics model was shown. This approach consists of the following steps. In the first step the initial version of the model is designed, which is tested by basic evaluation tests: dimensional consistency test, extreme condition tests and behavior sensibility test. In the second step the model is expanded with feedbacks, and the expanded version of the model is tested using the aforementioned tests. The second step is repeated until the model functions satisfactory. After that the other standard structure and behavior tests are applied. This approach helps in achieving significant degree of confidence and understanding of model behavior. The "step-by-step" approach is shown on the example of development of the simple inventory model.

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Received: 16 March 2007

Accepted: 26 October 2007