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Modeling and Simulating Supply Chain Management

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Abstract

Uncertainty in Supply Chain Management can lead to unsuitable services to customers, but it can be overcome through having an emergency inventory. Due to high costs of inventory, a general inclination exists towards a minimum inventory. So, one of the objectives of Supply Chain Management is to coordinate all activities throughout the chain, so that simultaneously with reducing commodity inventory, they can be supplied to customers when is needed. In addition, it is required that negative effects of changes in demand on order rate to be decreased. If order rate is considered constant, large changes will be seen in the inventory which will cause increase in inventory costs. Also, if the inventory is considered is considered constant, it will cause unstable production processes which will lead to increase in production costs. Existing static models for Supply Chain Management seem to be insufficient encountering with dynamic specifications of the supply chain system. The present article uses linear control method and transfer function analysis to offer a method for modeling Supply Chain Management in continuous-time condition in order to provide the best situation for exchanging order rate and inventory. Simulation has been conducted using Vensim software and results have been described.

Keywords: Supply chain management, control, modeling, dynamic systems

Introduction

Supply chain is a network of inventory and distribution factors (producers, suppliers, distributors and retailers) involving in transforming natural resources, raw materials and components into a finished product and delivering to the end customer. The supply chain is specified mainly as a forward process of raw materials and a backward process of information. Supply chain management is one of the newly emerge branches of management science and it is developing day by day. It discusses ways to shorten production processes and delivery times of supplying finished products to customers, while improving quality of products and services. To this end, it benefits from cutting-edge breakthroughs in management and technology sciences. In fact, all countries are inevitable to utilize supply chain management. Situations which have led to definition and development of supply chain management are the daily increasing competition and efforts for the survival of organizations, which have been obtained as a result of expansion of communication and technology networks.

Enterprises have become recently very interested in improving efficiency of supply chain management due to rising production and distribution costs, globalization of markets and demands of customers for diverse products with short lifecycle. These all boost competition among companies. Uncertainty in all the supply chain stages has complicated supply chain management process. Uncertainty can cause halts in a supply chain as wrong predictions, late information, and transportation problems. Any halt in supply chain can lead to unsuitable services to customers, i.e. in timely delivery of goods to customers. Companies overcome the uncertainty usually through holding an emergency inventory. All the companies maintain the inventory to minimize the effect of uncertainty and to keep a streamlined, stable and profitable process form suppliers to customers. But due to high inventory costs, companies are inclined to minimize the inventory as well.

So, coordinating all different activities across the chain is an important responsibility of Supply Chain Management, so that goods can be delivered timely to customers at a time when inventory and costs are low. An efficient Supply Chain Management will reduce production costs, inventory and supply costs as well as service costs in each phase.

Different methods have been developed to model supply chains which can be divided into four categories:

- Deterministic models in which all parameters of the model are determined.
- Stochastic models in which at least one parameter is not determined, but it follows a probability distribution function.
- Economic games theory models.

- Simulation based models.

Most of the models are steady state models based on average performance or steady state conditions. But, static models encountering dynamic specifications of Supply Chain Management seem to be insufficient due to demand fluctuations, delivery time delays compared to order time (lead time) and sale prediction.

The above issue indicates that studying dynamic specifications is a competitive advantage in modeling supply chain systems. No surprise analyzing and designing supply chain management systems as a whole has attracted attention of academicians and industrialists, as well.

Control theory is a suitable mathematical tool for analyzing, designing and simulating supply chain management systems based on dynamic models. In fact, the control theory has been used to find solutions for solving problems of supply chain systems. The article discusses the control theory's application in inventory and production control issues based on order in supply chain systems.

Control Theory

Using control methods in supply chain management issues dates back to the early 50s. Simon applied the continuous-time theory to manipulate production rate in a simple system with only one product. This idea was expanded for discontinuous-time models through using Z Transform methodology for inventory control purpose.This methodology has been used for dynamic systems such as production-inventory system as well as for other complicated systems, including social, planning and strategy developing, educational, medical, biology, energy and environment and dynamic decision-making systems.

Considering the dire need for establishing a new framework based on control and feedback regulations in production-inventory systems, a production control system based on Inventory and Order Based Production Control System (IOBPCS) can be presented in the form of a block diagram.

Dynamic System Methodology

Dynamic system is a method for understanding behaviors of complicated systems through simulation and is used to show behavior of a system against different strategies and policies in order to be utilized in planning and decision-making processes. This methodology was introduced 35 years ago by Forrester in his first book titled Industrial Dynamic (1971), focusing on industrial applications. Initial works paid attention to managerial issues such as instability in production and employment, deficit or problem in union's growth and decline in market share. During a short while, this method was used in a broader range of affairs extending from research and development management to understanding exponential growth concept in a limited world and reduction in natural resources.

The initial term of industrial dynamic was substituted with a more general term of "dynamic system". The study of dynamic systems does not focus on a system but on a problem (Forrester, 1985). Problems in the viewpoint of dynamic system have at least two specifications. Firstly, they are dynamic. For instance, they deal with amounts which vary in time. They can be depicted and displayed using timevariant charts. Fluctuations of employment levels in an industry, reduction in urban municipal taxes base don quality of life, excessive increase of costs in a construction project, expansion in government's size, and cancer are some examples of dynamic system problems. Capability in defining dynamic problems is the first step for learning approaches of dynamic systems (Richardson and Pug, 1981).Secondly, feedback concept is used in dynamic system problems. A good example for a feedback system is the automatic mechanism in CNC machinery and closed circuit cameras. All the human systems are basically feedback systems (Goodman, 1983).

Dynamic system focus on structures and behaviors of combined systems comprised of mutual feedback loops. The cause-and-effect chart is a simple tool which helps the modeler in depicting and conceptualizing real world models. In a cause and effect chart, arcs show the direction of effect and plus and minus signs show the kind of effect. If a change in a variable causes a change in another variable in the same direction related to the initial amount of the variable, the relation between the two variables is positive. If a change in a variable causes a change in another variable in the opposite direction related to the initial amount of the variable, the relation between the two variables is negative.

The difference between this chart and other charts, such as flowchart, is in showing relations which can not be easily depicted in other charts. If a feedback loop related to a variable causes an increase in the original deviation, it is called a positive feedback loop. In a positive feedback loop, increase or decrease is exponential. If a feedback loop changes amount of a variable opposite the direction of the original deviation, it is called a negative feedback loop. The negative feedback loop is recognized through a directed behavior toward the goal. A negative feedback loop is expected to cause an asymptotic increase or decrease toward the goal (Goodman, 1983).

The abovementioned cause-and-effect is the initial viewpoint toward the problem. It is basically created to establish a link between the modeler and the system. Formulating the executive model of the system based on structural details such as policymaking rates or variables, state variables, secondary variables, information flows and delays is more specific. Flowcharts provide more details and viewpoints regarding structure of the model (Richardson and Pug, 1981). The dynamic system model includes state variables, secondary variables, fixed amounts, rate variables and initial amounts. Cumulative amounts of state variables are totally different from effective flows over them in terms of concept. Forrester (1985) described state variables as accumulators inside the system. These variables can be inventories, products to be manufactured, factory environment and number of employees.The presented model for production control system based on order and inventory control have been shown in the below block diagram:

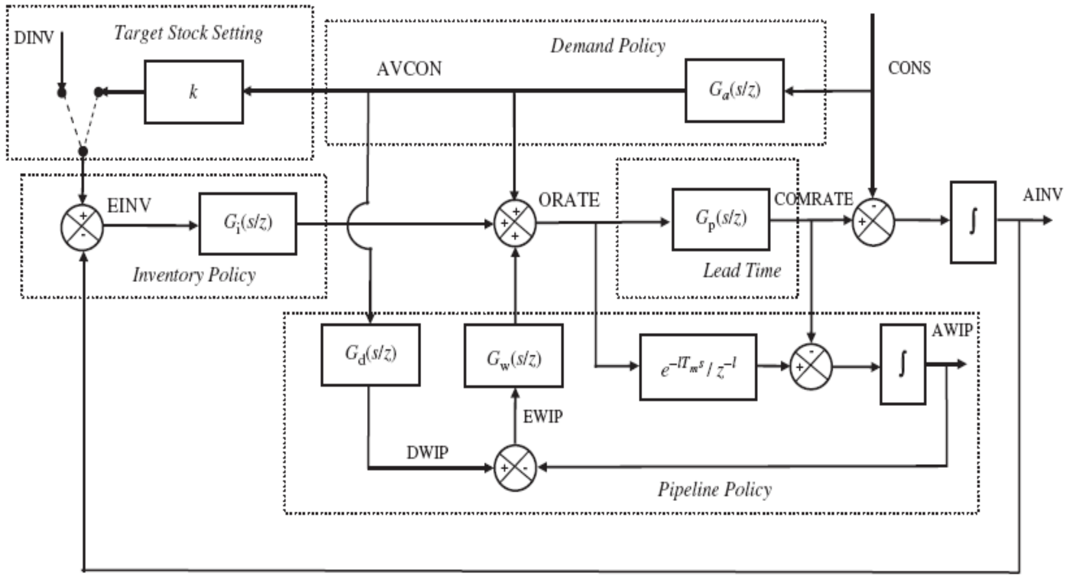


Figure 1: IOBPCS family model

In which:
AINV: Actual inventory
AVCON: Average consumption
AWIP: Assembly work-in-progress
COMRATE: Completion rate
CONS: Consumption
DINV: Desirable inventory
DWIP: Desirable work-in-progress
EINV: Error in inventory
EWIP: Error in work-in-progress
ORATE: Order rate

This model can be applied to various products or to a single product. Using control words, the actual inventory (AINV) is a controlled variable. Meanwhile, the consumption (CONS) is distortion and the order rate (ORATE) is a manipulated variable. Two integrals have been used to add deficits in inventory and work-in-progress (WIP) during time. Each of the IOBPCS family members has been made based on using a portion or all the five factors which are described below:

- Waiting time: Waiting time is referred to the time period between production order and delivery dates. In fact, it also includes the production delay time. It acts as a smoothing factor in production process which, in fact, shows the adaptability of production with changes in order rate.
- Target stock setting: This value can be fixed or a multiple of the average current selling rate.

- Demand policy: Current demand is a very important factor, because if it is removed from the planning algorithm, permanent shortages will be created with step rise in demand. If we use current demand without average-taking form, it will cause growing changes and fluctuations in the production rate, which in turn, will raise production costs. The best and the most appropriate method for this purpose is the exponential smoothing method because it requires lower data and is precise for short-term prediction. This can be described using Laplace transform in control theory. The question is how much weight should be allocated to the recent data in order to minimize demand fluctuations and simultaneously respond important changes as well?
- Inventory policy: The inventory policy is important because the rate of inventory changes has a great effect on production changes and fluctuations. There is a wrong belief in industries which describes production targets as factors that can improve inventory deficit for a short period of time, while a much more time was required to show the manufactured product in the inventory. Once the product is manufactured, a significant rise will occur in the work-in-progress assembling and inventory will exceed the desirable level. The problem should be removed through producing less than the market demand average in order to near the inventory to the desirable amount. Anyway, some overshoots occur here which affect the production rate. In fact, the inventory policy is a feedback loop which controls the rate to improve and modify the inventory shortage or surplus.
- Pipeline policy: The desirable work-in-progress production is a function of the market demand average and the required time for production (the waiting time). During times in which work-in-progress production shortage occurs as a result of an increase in step demand, deficits should be compensated through increasing demand for production. Contrarily, if the work-in-progress production increases in comparison with the desirable amount (due to non-consideration of the waiting time in demand and inventory policies), the problem should be removed through reducing the production. In fact, the pipeline policy is a feedback loop which controls the rate that improves and modifies the inventory shortage or surplus.

Model behavior analysis

The waiting time is a parameter of the system which should be controlled. Although designer of the system can not manipulate it, but it is important to delay it as best as possible. A model of the waiting time with 2 parameters has been mentioned below:

$$G_P(s) = \frac{1}{((T_P/n)s+1)^n}$$

$$\begin{aligned} &n=1: \quad \textit{first order delay} \\ &n=3: \quad \textit{third order delay} \\ &n=\infty: \quad \textit{pure delay} \end{aligned} \tag{1}$$

For the two first cases Tp, n=1,3 equals the waiting time average for each unit, while for the third case Tp, n=∞ is a fixed delay time. For the third case, the transform function is changed as below:

(2) $$G_P(s) = e^{-T_P s}$$

The system designer should decide how to adjust the target inventory level (a fixed amount or a multiple of the average sale) as well as the three policies (demand policy, inventory policy and pipeline policy) so that it optimizes the system considering the two objectives of the operation.

A- Improving inventory level

B- Weakening effects of changes and fluctuations on order based demand rate

These two objectives are in contrary with each other. So, for a definite supply chain, the system designer should find the best inventory and order rate and exchanging these two factors. If a fixed order rate is used, great changes are seen in the inventory, increasing inventory costs. Also, if a fixed inventory is used, production plans are greatly changed, increasing production costs.To this end, the dynamic system has been tested through applying a step signal related to the demand rate. The response of inventory is analyzed considering performance parameters such as rise time and settling time and overshoot. (Charts 1 to 4).

Using feed forward related to the demand policy in the model, it can be seen both empirically and mathematically that if a step signal is applied as the consumption rate, the zero steady state error can be attained between the real and the desirable inventory levels. But, if the market demand is applied to the system without the average-taking from, a rising fluctuation will be seen in the order rate/production. In fact, this is a factor in non-realization of the second goal.

The inventory policy defines a rate by which the inventory deficit is improved through manipulating the order rate. The inventory policy should consider the system's dynamism and waiting time. The applied change in a specific time on the order rate will cause a change in the real inventory after a specific period of time, equaling the waiting time. The inventory policy will lead to rise in the work-in-progress production and eventually the completion rate and the inventory level are obtained with a sinusoidal behavior.Results of such a dynamic system will raise production costs due to non-smooth order rate. Also, inventory fluctuations will lead to rise in inventory costs (in the case of inventory surplus) and reduction in services to customers (in the case of inventory deficit). So, only a portion of the inventory deviation should be modified by the inventory policy.

Te pipeline policy is a correction mechanism which does not use the data related to the real inventory. In fact, the WIP signal undoes the inventory signal and increases the average consumption's share in reaching the steady state. The WIP deficit is obtained by deducting the real signal from the desirable signal (based on the market demand average).

The pipeline policy is in fact effective for reducing the inventory balance which is considered as a third element besides the inventory policy and the demand policy. It is used to calculate the order rate.

In comparison to the inventory policy, the pipeline policy responds faster to the requirements of order rate increase and decrease, especially when sharp changes are seen in the market demand.
Eventually, it can be said that the WIP control loop will reduce rise time and also fluctuations related to the order rate. Also, it will also reduce the time to reach the steady state.
Differences of the two cases are shown in the charts (3) and (4).
Various models which are included in the IOBPCS have been mentioned in the table below:

Table 1: Various models of IOBPCS

Model		Target stock setting	Demand policy	Inventory policy	Pipeline policy
IBPCS	Inventory based production control system	Constant	$G_a(s)=0$	$G_a(s)=\frac{1}{T_i}$	$G_w(s)=0$
			$G_a(z)=0$	$G_a(z)=\frac{1}{T_i}$	$G_w(z)=0$
IOBPCS	Inventory and order based production control system	Constant	$G_a(s)=\frac{1}{T_a s+1}$	$G_a(s)=\frac{1}{T_i}$	$G_w(s)=0$
			$G_a(z)=\frac{a}{1-(1-a)z^{-1}}$	$G_a(z)=\frac{1}{T_i}$	$G_w(z)=0$
VIOBPCS	Variable inventory and order based production control system	Multiple of average market demand	$G_a(s)=\frac{1}{T_a s+1}$	$G_a(s)=\frac{1}{T_i}$	$G_w(s)=0$
			$G_a(z)=\frac{a}{1-(1-a)z^{-1}}$	$G_a(z)=\frac{1}{T_i}$	$G_w(z)=0$
APIOBPCS	Automatic pipeline, inventory and order based production control system	Constant	$G_a(s)=\frac{1}{T_a s+1}$	$G_a(s)=\frac{1}{T_i}$	$G_w(s)=\frac{1}{T_w}, G_d(s)=T_p$
			$G_a(z)=\frac{a}{1-(1-a)z^{-1}}$	$G_a(z)=\frac{1}{T_i}$	$G_w(z)=\frac{1}{T_w}, G_d(z)=T_p$
APVIOBPCS	Automatic pipeline, variable inventory and order based production control system	Multiple of average market demand	$G_a(s)=\frac{1}{T_a s+1}$	$G_a(s)=\frac{1}{T_i}$	$G_w(s)=\frac{1}{T_w}, G_d(s)=T_p$
			$G_a(z)=\frac{a}{1-(1-a)z^{-1}}$	$G_a(z)=\frac{1}{T_i}$	$G_w(z)=\frac{1}{T_w}, G_d(z)=T_p$

The designer can manipulate the four mentioned elements based on the table and gain different models. It should be noted that the model mentioned in this article has been simulated using MATLAB and SIMULINK softwares and results have been analyzed and compared in charts 1 to 4.
For example, for the IOBPCS model, the WIP feedback loop has not been applied, a first-order delay has been considered for the demand smoothing policy and the target stock has been set to a fixed level. The production waiting time is a delayed model from the order rate which has been shown by a first-order lag with Tp as the time constant. Also, the demand average-taking process (demand policy) has been shown by a first-order delay with Tp as the time constant.
So, the order rate is obtained by adding average consumption rate and a portion (1/Ti) of inventory deficit.
The transform function of completion rate variables (COMRATE), actual inventory (AINV) and consumption fluctuations (CONS) is described as follows:

$$\frac{AINV}{CONS} = -T_i \frac{T_a T_P s^2 + (T_a + T_p)s}{(T_a s + 1)(T_i T_p s^2 + T_i s + 1)}$$

(3)

(4) $$\frac{COMRATE}{CONS} = \frac{(T_a + T_i)s + 1}{(T_a s + 1)(T_i T_p s^2 + T_i s + 1)}$$

The characteristic equation is a third-order polynomial which is written as the multiply of a first-order term by a second-order term. Considering the Routh-Hurwitz criterion, the system will be stable if all the closed system roots are located at the left of the jw axis. So, because all the constants of the two terms are positive, the transfer function for all the non-zero adjusting parameters will be stable. It should be mentioned that the adjusting parameter related to the feed forward element (Ta) does not exist in the second-order term, so it has no effect in oscillatory behavior. The second-order term can be written in the standard form of and gain the adjusting parameters. To gain stability, we set Δ<0, so:

(5)

$$\Delta = T_i^2 - 4T_i T_p < 0 \qquad \Rightarrow \qquad T_i < 4T_p$$

Supposing that and placing in the second-order equation, a good design can be achieved and the relation between Ti and Tp will be obtained as:

(6)

$$T_i \in [T_p \quad 2T_p]$$

Through applying the pipeline policy to the model and simulating behaviors of AINV and ORATE signals for Tw=Ti=Tp=Ta=2 the difference between non-using the pipeline policy (figure 3) and using the pipeline policy (figure 4) in the mentioned charts can be seen.

As it can be seen in the figure 3, all the three policies of inventory, demand and production have been used, so it has reduced rise time, settling time and fluctuations compared with the figure 3 which uses inventory and demand policies.

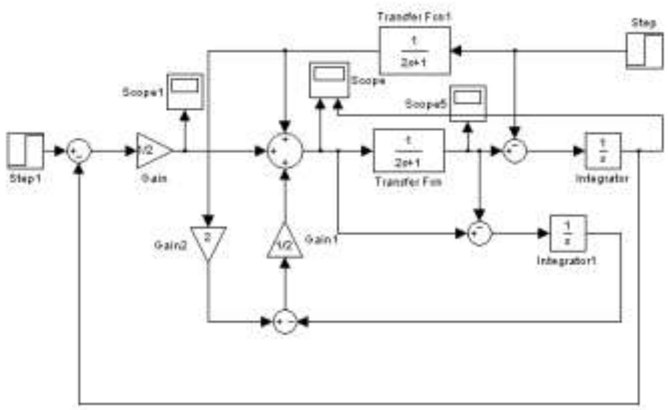


Figure 2: The APIOBPCS block diagram in MATLAB (SIMULINK) software with Tw=Ti=Tp=Ta=2

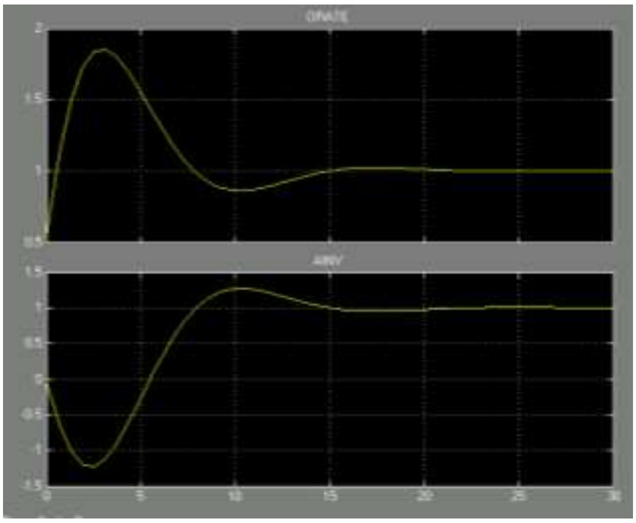
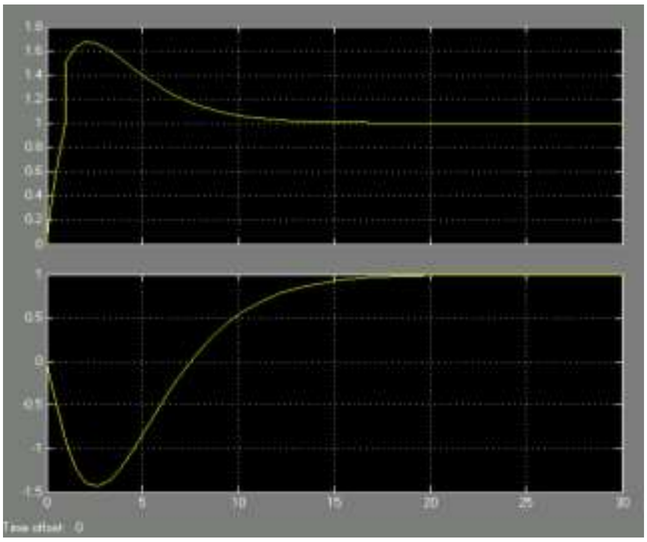


Figure 3



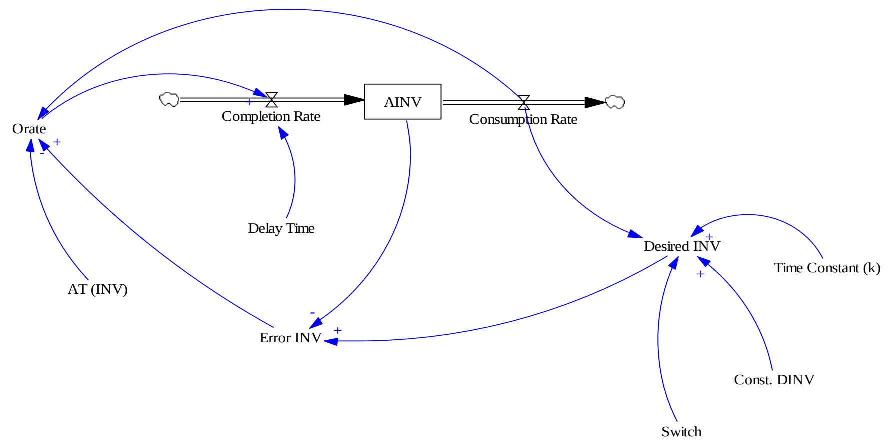


Figure 5: The schematic IOBPCS dynamic system in Vensim software

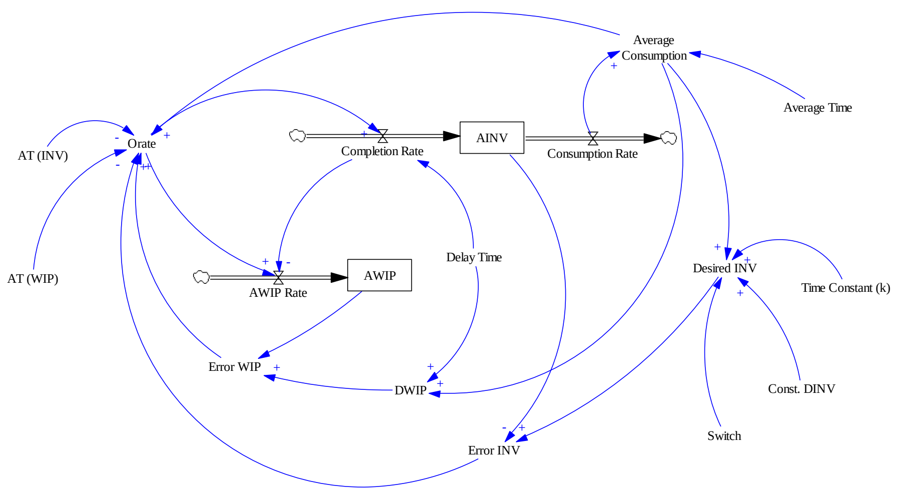


Figure 6: The schematic APIOBPCS dynamic system in Vensim software

As it is seen, the problem has been simulated by Vensim software for two case of only the inventory policy and all the three policies. Results for the two cases are similar.

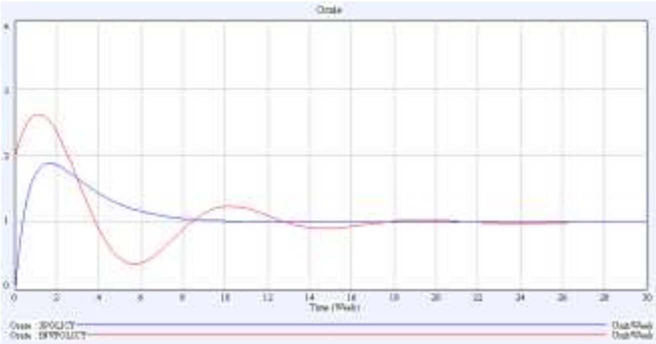


Figure 8

Conclusion

The article has used the linear control method and transfer functions analysis for modeling the supply chain in time-invariant situation, so that it creates the condition for exchanging the order rate and the best inventory level. Results have been simulated using Vensim software.

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