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A Dynamic Alignment Approach to the Leverage Design in System Dynamics Models: Use Strategem-2 As an Example

Showing Young
Department of Business Management, National Sun Yat-sen University, Taiwan, R.O.C.,
886-7-5252000 ext. 4625
young@cm.nsysu.edu.tw

Yi-ming Tu
Department of Information Management, National Sun Yat-sen University, Taiwan, R.O.C.,
886-7-5252000 ext. 4717
ymtu@mis.nsysu.edu.tw

Ya-tsai Tseng
Department of Business Management, National Sun Yat-sen University, Taiwan, R.O.C.,
886-3-5562959
m8342607@mis.nsysu.edu.tw

Abstract

This paper attempts to develop a dynamic alignment approach to leverage design of system dynamics models. The approach developed in this research is a flow-based design, different from traditional macro designs of aggregated system structures or loop analysis. It is grounded on some major concepts in Synchronous management at plants and uses the Drum-Buffer-Rope (DBR) system to align the various operations of rate decisions. We take the famous long wave model (Strategem-2) as an example to examine the performance of the proposed leverage design method. The redesigned system shows that the original oscillation behavior is fully eliminated. By better alignment and streamlining of flows, the discrepancy between the production rate and desired production in Strategem-2 is dramatically reduced, even in higher degree than some previous leverage design approaches proposed by other system dynamists (e.g., Sterman (1989), Ozveren and Sterman (1989)).

1. Introduction

System dynamics is a methodology to investigate the information-feedback characteristics of complex managerial, economic, or social systems. The goal of system dynamics is to obtain deep understanding of systemic behaviors and to help for the design of improved system structure. The assumption that system behavior results from interacting feedback loops, which force variables to grow or to decline, enables one to understand how unwanted behavior arises and to analyze how a proposed policy design may affect the dynamics of the system. System dynamics models are not sets of poorly understood mathematical functions, but a formulation of acceptable formal decision policies that describe how decisions result from the available information streams. Nonlinear decision equations specifying the momentum of tangible and intangible flows interact each other and constitute the underlying structure of dynamic systems. Hence, the original decision policies and the proposed policies to improve system behavior are no longer black boxes with poorly known operations and limits.

According to Macedo (1989), current methods used to conceive the best policy of a system dynamics model can be classified into three families: the heuristic methods, the modal methods, and the optimization methods. Heuristic methods largely rely upon a sufficiently deep, intuitive understanding of the problem or by some simple principles and rules of thumb (Forrester, 1961; Graham, 1976). Thus, heuristic methods do not offer formal mechanisms to develop new policies for its lack of theoretical basis. Relative to the heuristic methods, policy design methods of the modal and optimization categories are too difficult for managers and designers to understand. Most of modal methods build the desired policy with applications of modern control theory. These methods require linearization of the system dynamics model, a procedure that is in variance with the basic idea of system dynamics and limits these methods to be applied in high dense complex problems (Mohapatra and Sharma, 1985). Optimization methods use mathematical programming techniques to optimize a certain objective function and to obtain the improved policy. Most researches in this category propose “black box” policies. This is in variance with the basic principle of system dynamics (Burns and Malone, 1974; Keloharju, 1982; Coyle, 1985). In summary, none of the existing methods is fully satisfied and researchers continuously devote to develop better leverage design methods.

This paper proposes a “dynamic alignment approach” which can be classified into the heuristic methods, but has a more rigid theoretical basis. It is focus on the synchronization of rate’s operation to generate the expected systemic behaviors. The synchronization mechanism is derived from the Drum-Buffer-Rope (DBR) system in Synchronous management. The DBR system is designed to manage work centers at plants to streamline multiple flows. This research adopts this mechanism to manage the relationships of the various rate policies within and between flows in system dynamics models. We will introduce some major concepts in Synchronous management and DBR system in more detail later. Principles and steps in the proposed dynamic alignment approach will also be described further.

2. A Dynamic Alignment Approach

2.1. Theoretical basis and Guiding Principles of the Dynamic Alignment Approach

Synchronous Management is a time-oriented description of the manufacturing process, which is consistent with system dynamics as a dynamic analytic methodology. “Synchronous management” is a newly developed manufacturing management approach and is established on the theory of constraints (TOC), which is developed by a physicist named Eliyahu M. Goldratt (Goldratt, 1987). Theory of constraints analyzes systemic problems at plants by checking the consistent operations between constraint resources and non-constraint resources. A constraint is defined as “any element that prevents the system from achieving the goal of making more money”. With the consideration of constraint capacity resources, Synchronous management identifies several manufacturing principles to examine and manage the operation of plants. Traditional way of thinking about a manufacturing plant reflects a resource focus or resource orientation. Managers try to balance each work center’s output and input by the balance of capacity (Srikanth and Podzunas, 1990; Umble and Srikanth, 1997). Different from traditional management methods, synchronous management shifts from a resource focus to a product-flow focus and stresses on the balance of flow between the constraint resources and non-constraint resources. In the perspective of theory of constraints, synchronous management manages a factory by coordination and harmonization of the operations of critical work centers to streamline various flows. And it is the Drum-Buffer-Rope (DBR) logistic system that is used in Synchronous management to be responsible for the coordination work.

There are three components in the Drum-Buffer-Rope system. The first one is the drum. Drum reconciles customer requirements with the system’s constraints. And a drum is responsible for setting the pace for material release into the system. Usually the drum at a plant is the schedule of master production plan. The second component is buffer. Buffer refers to time buffers or stock buffers used at a few critical points in the process to protect the system throughput. Because factories and plants designed by the synchronous management approach are tightly coupling systems. Buffers are needed to protect the tightly coupling systems from variations in customer requirement and work centers. The last component is the DBR system is rope. Ropes are designed to provide effective communication throughout the organization of those actions that are required to support the master production schedule. Every aspect of the operation must be synchronized to the requirements of the drum so that the planned product flow may be executed. Ropes in the DBR system act as the communication link from the demand to the drum, as well as from the drum to other schedule release points. A single rope replaces the series of short ropes. It means that the pace of drum is directly transmitted to those control points linked by ropes. With the drum, buffers, and ropes, critical material release points operate at the same pace with the constraint resource, which also runs synchronously to reflect market demand variations. It means that all the control points or material release points centrally controlled by the drumbeat are responsive to the demand variations at the same time. That's why synchronized flows are possible in synchronous management.

For system dynamics models, synchronous management to make each flow synchronized has a much deeper implication. System dynamists have found that it is phase-lag subsystems that transform the sinusoidal signal and allow it to continue propagating (Graham, 1977; Mass and Senge, 1975). A phase-lag subsystem is defined as a subsystem (possessing one or more levels) that produces a phase lag between its input and its output, so that when the input reaches its steady-state value, the output reaches its steady-state value only later. The phase-lag subsystem is identified to be essential to producing oscillation. In a phase-lag subsystem, if the input to the subsystem goes to its equilibrium value, the output goes to its equilibrium value only afterwards. That suggests the disturbance propagates around a loop: an exogenous input or initial condition disturbs a subsystem way from its equilibrium value, and even when that subsystem returns to its equilibrium value, the loop has nevertheless transmitted the disturbance to leave another subsystem out of equilibrium (Graham, 1977). A synchronized-flow design can eliminate the phenomenon of propagation in sub-lag system effectively, because all the streamlining flows operate at the same time and at the same pace. When sudden exogenous changes occur, a synchronous system can return to its stable state quickly. The dynamic alignment approach developed in this research is built on such a synchronous concept.

The goal of the dynamic alignment approach is to design a synchronous system that can adapt to the environmental change as soon as possible. A synchronous system in this research means a system that is not only synchronous to the external requirements but also synchronous in the actions of the rates' operations. From the macro and systemic perspective, a synchronous system is a system that generates exactly the quantity that external environment demands at exactly the time that the demand is happened. In the analysis of the micro decision rules and policies, operations of rates are designed to be responsive to the external disturbances and changes at the same speed and at the same time. Based on the concepts of synchronous management and the concept of propagation of variations in previous system dynamics research, several principles guiding the dynamic alignment design are derived.

First, each level in the synchronous system has to remain its original state or its proportion relationships to other levels in the system, unless some necessary changes planned by designers. This principle is to maintain the original relationships among levels and among rates to prevent any non-synchronous rate operations. Second, rates to be synchronous with exodogenous input change must be the overt decisions and the pseudo overt decisions. In this paper, pseudo overt decision is a finer classification derived from the implicit decisions (Forrester, 1961). It is one kind of implicit decision influenced by those resources that can be decided consciously by decision makers. When resource limitations change at the same pace with the drumbeat, and these kind of overt decision generated by the synchronous design are called as pseudo overt decisions. In the dynamic alignment approach, such decisions can be treated as overt decisions. So, this kind of decisions is called as pseudo overt decisions. This principle claims that designers can manage and design only those decision rules of overt decisions and pseudo overt decisions in synchronous systems. Third, to avoid any non-synchronization due to the time delay between planned policy and actual actions, pipeline stocks have to be supplemented. Fourth, a good synchronous design has to maker sure all the rate that may be influenced by the exogenous change are taken into account, including rates that are influenced directly and indirectly through the relationships between each rate, connect directly by information wires or flows, or by the wires and flows both.

2.2. Steps in the dynamic alignment approach

As mention above, the dynamic alignment approach is to design a system that can prevent any oscillations due to the inconsistent actions of individual rates. The main mechanism to align rate policies and to streamline flows used is the DBR logistic system in synchronous management. With the DBR system, one can focus on the synchronization design among rates within each flow and between different flows, thus make sure the whole system react to the external disturbances as a whole. In the dynamic alignment approach developed here, three major stages can be identified. Firstly, one needs to decide the basic drumbeat and the pace of the system. Secondly, those control points to be synchronized with the drumbeat have to be found out and the quantity of each rate operation relative to the drumbeat has to be computed properly.

What is more important is this stage is to make sure the actual synchronization among rates and flows are at present and avoid any fluctuations arise from the time lag between the planned quantity and actual quantity of rate operations. Therefore, one needs to design and implement a mechanism to solve the problem of time delay. Lastly, a buffer size adjustment mechanism is designed to satisfy the buffer size and stable level adjustment requirements to protect the system from internal variations of rates and to offer the system a certain degree of flexibility in confrontation of external disturbances.

According to the guiding principles and the three major stages, there are eight synchronous steps for the basic design of a synchronous system. We introduce the eight-step basic synchronous design first. As to the advance mechanisms to make the synchronous system more stable will also be described later.

(1) **Choose the rate influenced directly by exogenous input as the drum.** This step is based on one assumption that only one exogenous variable is at present in most of system dynamics models. Exogenous variables are variables that are generated independently of the system. Seldom will more than a single exogenous variable be justified, because using more than one exogenous variable impli3es a rather unlikely condition that the exogenous variables are interlocked by control mechanisms between themselves but all are free of interlocking ties with the variables of the system under study (Forrester, 1961). Therefore, one can make sure that there is only one drumbeat in the designed system. Because rate directly influenced by the exogenous variables passes the change further to influence other levels and rates in the system, that is chose as the drum and the change speed of the drum is the drumbeat of the entire system.

(2) **Choose the level directly influenced by the rate as the focus level.**

(3) **Make one of the rates influencing the focus level as the focal control point and make it synchronize with pace of the drumbeat.** This step is to make the focus level influenced directly by the drum rate stay in its original state. According to guiding principle 1, each level in a synchronous system should sustain its relative state compared to other levels in the model. To make the focus level remain unchanged, one should select one control point from all possible rates that make the focus level decrease or increase directly. And according to guiding principle 2, the control point selected should be an overt decision or a pseudo overt decision. The quantity of this control point is the same as the drumbeat, because the drum and the control point are of the same flow and have the same unit dimension. This step is a synchronization of rates within a specific flow.

(4) **Search for candidate rates influenced by the focus control point, make all of the rates to be control points, if there is no more new focus level can be found.** This

step is a synchronization design of rates belonging to different flows. These rates connect to each other through information links, though rates seldom connect to other rates directly in system dynamics models. Because the synchronization objects in this step are of different flow, the unit consistency should be take into account. That means the synchronized points in this stage move at the same time as the drumbeat, but may not move at the same speed as the drumbeat. The speed of the synchronized points depends mainly on the unit of the flow.

(5) **Search for rates that influence the focus control point in original model, make them be the control points.** This step means also the synchronization design of rates belonging to different flows. A little different from step 4, this step is to make those rates influencing the focal control point to be synchronous with the drumbeat.

(6) **Check if the focal control point is a pseudo overt decision in the original model. If it is, make the source limit the pseudo overt decision to change in synchronous with the drumbeat.** This step is also a synchronization design for different flows, but only applied in the pseudo overt decisions. Because pseudo overt decisions are decisions that have some operational limitation. To disable these limitations, one can make them also increase or decrease as the drumbeat.

(7) **Choose one of control points set in previous steps to be the newest focal control point.**

(8) **Reorient the focus level to the level influenced by the new focus control point. And repeat step 3 to step 7 until all control points are fully taken into account for the synchronization within and between flows.**

The eight steps described above constitute the basic synchronous design of a dynamic system. There lies a basic assumption in the basic synchronous design. That is the information about the exogenous variable’s impact on the drum can be directly acquired by those control points, thus synchronizations between external environment and the system as a whole can be achieved. Information technology developments, such as shard databases and high speed of communication networks can make this assumption reasonable and practicable. In addition to the basic synchronous design for rate operations, two supplement mechanisms are developed in the dynamic alignment approach to make the synchronous design more stable. The first supplement mechanism is for time delay problems in synchronous systems. In fact, Time delay has been a bothering problem for it generates various kinds of oscillation behaviors. There are two kinds of time delay problems in a dynamic system. One is information delay, and the other is physical delay. The former is no more a problem in synchronous systems, for information is shared in real time by each control points. The latter is the major problem to be solved. Consistent with the basic assumption in the dynamic alignment approach that rates can be connect directly to each other, one simple method and mechanism is used to supplement quantity gap due to the time lag between decision points and actual action outputs. The core mechanism to solve the time delay problem can be illustrated by figure 1 listed below:

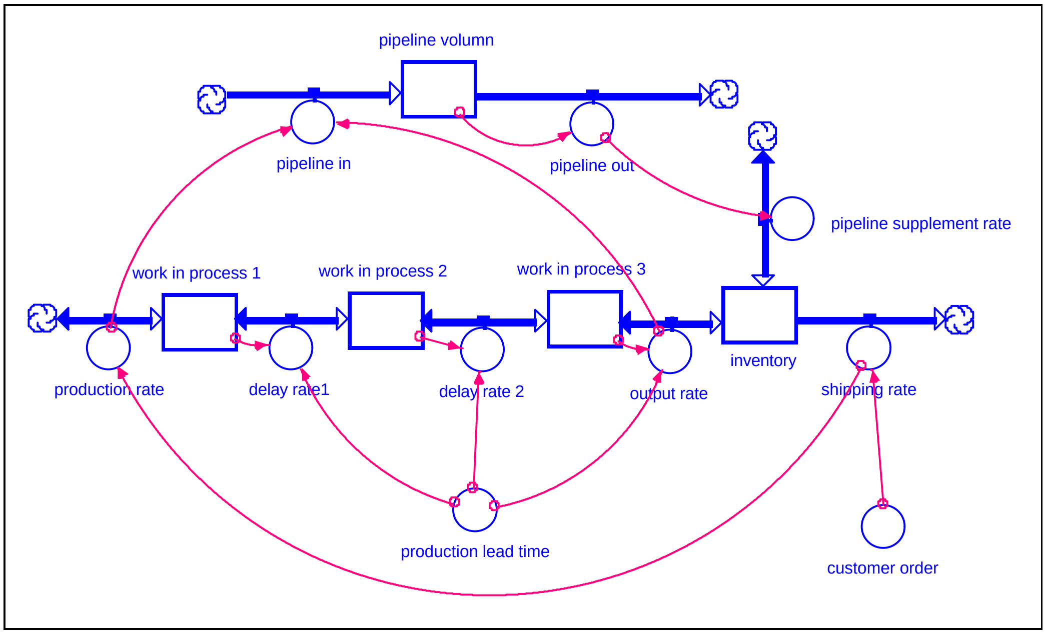

Figure 1 supplement mechanism to solve time delay problem

In the example in figure 1, customer order rate is the only one exogenous variable influence the balance state of the system. Shipping rate is the drum to guide the pace of production rate. The information of shipping rate is transmitted directly to production rate so that production rate is to be synchronous with the shipping rate. However, there is a time lag between production rate and output rate. Without no management actions to the time lag, behaviors of the synchronization design system would like inventory change pattern in figure 2. From figure 2, one can observe that without synchronous design, the system is oscillating due to a sudden increase of customer order rate. After a basic design of the synchronous system, inventory quickly achieves its new equilibrium point without any oscillation phenomenon, but inventory does not return to its original state due to the pipeline lost. The logic to solve the time delay problem in synchronous system is to capture the pipeline change in "every time interval (variable of "pipeline in" in figure 1) and to supplement the pipeline change with a new double flow rate. After the redesign of the synchronous system, the new behavior of inventory change is as curve 3 in figure 2. From figure 2, one can observe that inventory goes back to its initial state quickly without any lost.

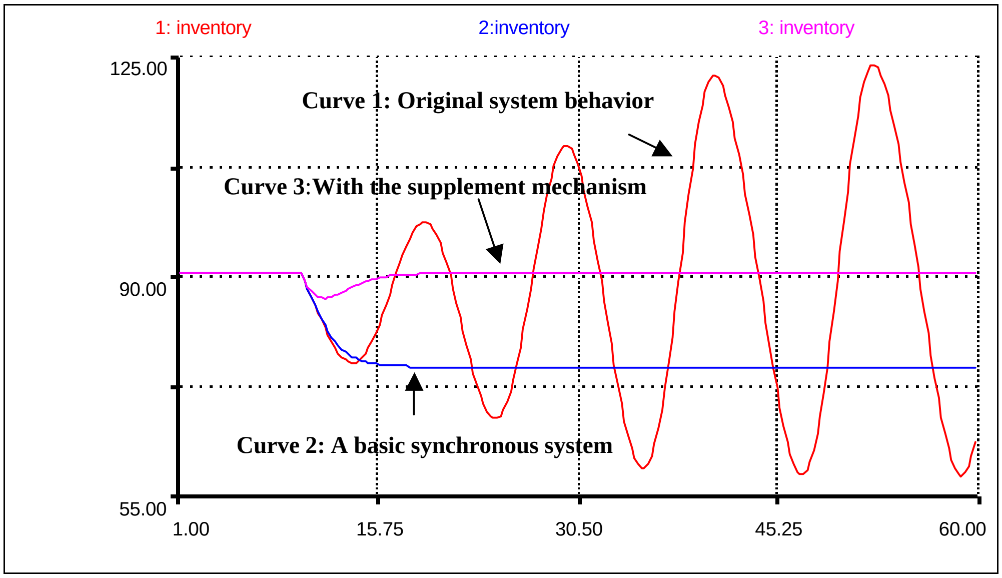

Figure 2 Comparison of behaviors with and without time delay

Lastly, this paper discusses another supplement mechanism in the dynamic alignment approach. Because the synchronous system is a tightly coupling system, variations in any operation of the synchronous rate will have impacts directly and indirectly to other rates. To design a strong synchronous system, this research also develops related mechanisms to adjust buffer size and the equilibrium level of variables. The buffer size adjustment mechanism can be shown as figure 3.

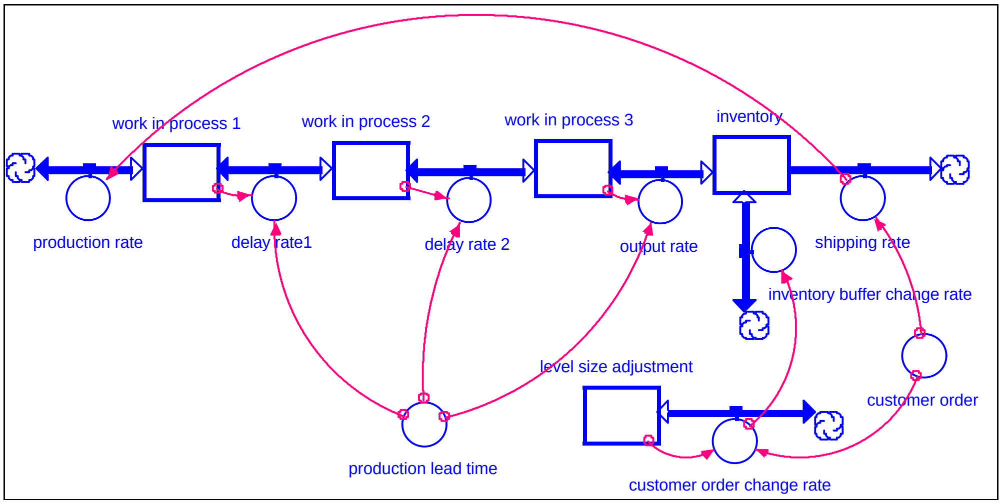

Figure 3 mechanism of buffer size adjustment

Figure 3 is also a simple example of production chain. In that example, managers may want to adjust the inventory level as the customer order rate change. For example, per unit of customer order rate change may trigger 0.5 units adjustment of safety inventory quantity at the same direction. Logic of the adjustment mechanism in figure 3 is to capture the first differential value, which is added by the inventory buffer change rate to change the inventory level. Simulation result of the adjustment can be shown as figure 4.

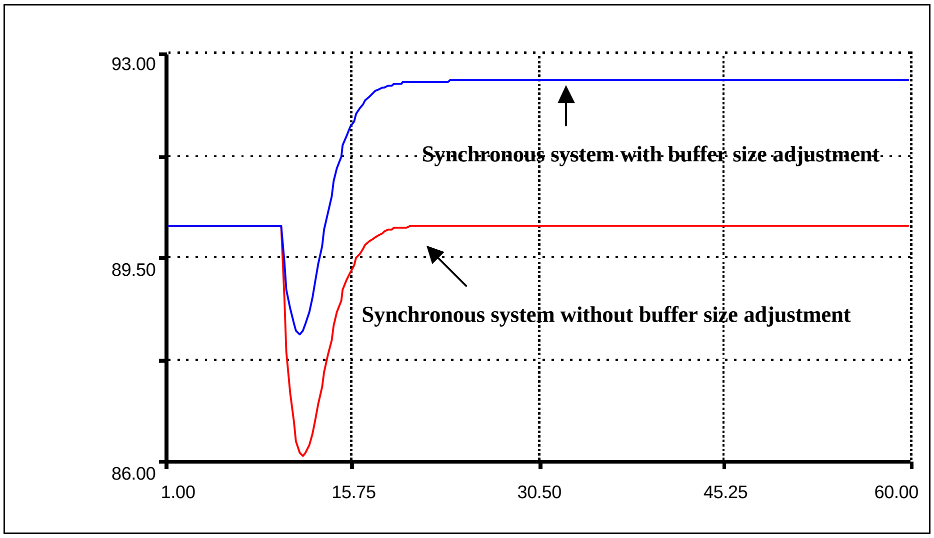

Figure 4 simulation behaviors with and without adjustment mechanism

In this section, we described the complete dynamic alignment approach. The dynamic alignment approach contains three parts: basic synchronous design procedures, time delay adjustment mechanism, and buffer size adjustment mechanism. With these procedures and mechanisms, the synchronous designed system can be responsive to the environmental change and has the ability to maintain its stability. In next section, the dynamic alignment approach will be applied to the famous long wave model (Strategem-2) and the redesigned system will be simulated and compared to other leverage design methods to test the performance of the dynamic alignment approach.

3. A Case Study

Strategem-2 is a simulation game of the long wave model. It represents the capital self-ordering feedbacks created by the fact that capital is an input to its own production. The decision point in Strategem-2 is to balance the supply and demand for capital. That is to minimize the average absolute deviation between supply (production capacity PC) and demand (desired production DP) over the T periods of the game. Several system dynamists have used the Strategem-2 as the experimental case in their research. With Strategem-2 model, Sterman (1989) experimented human being's misperception behaviors of dynamic problems. In that research, Sterman suggested an optimal policy to minimize the average score and got an average score that equals to 19. Ozveren and Sterman (1989) proposed an optimal leverage design approach with control theory techniques. With their approach, the average score lows down to 15. To compare with these researches, this article uses the same values NCAT=2, ALC=20, COR=2. Also, the score function is the same with previous researches in order to make the present results easily comparable to the simulation results designed by Sterman (1989) and Ozveren and Sterman (1989). But notice that DT is set to be 0.1 in this paper for the consideration of the length of minimum delay in the redesigned model (Forrester, 1968). Because there is no buffer size required in the Strategem-2 model, this article only illustrates synchronous procedures and adjustment mechanism of time delay problem.

At initial, all variable in Strategem-2 are in equilibrium. The exogenous variable arouses disturbance and oscillations is NGS (New orders of the Goods Sector). It is a rate containing the exogenous changes, thus is the drum of the synchronous design in the Strategem-2 model. Then, the next step is to decide control points to be synchronous with the drumbeat of NGS. In Strategem-2, there is only one decision point NKS (New order of the Capital Sector) for players to control. How to make NKS move synchronously with the change of NGS is the main problem to solve. In our synchronous design with the dynamic alignment approach, the policy of NKS is formulated as below:

NKS=CD + order change New orders of the Capital Sector (units/year)
Order change=original order state-NGS (unit/year)
Original order state=NGS (unit/year)

In Strategem-2, just a new policy of NKS is not sufficient to make the system sustain its stable state, for there are some positive loops hidden in the structure. Those positive loops can amplify minor oscillations generated from the discrepancy between production capacity (PC) and desired capacity (DP). Though NKS and NGS are set to be synchronous, there still exists a delay to increase capital stock. To avoid any unwanted behaviors that may be generated from that delay, we apply the adjustment mechanism of time delay to reduce the discrepancy between PC and DP. One supplement rate is added to the model. The supplement rate depends on two factors. One is the discrepancy between NGS and GCA and the other is the discrepancy between NKS and CA. The former is to reduce the impact of delay impact between capital orders and capital acquisition, and the latter is to reduce delay of goods orders and the capital acquisition rate of consumer goods sector. Related equations are listed as below:

Order supplement = pipeline of NGS and GCA out +
pipeline of NKS and CA out

pipeline of NGS and GCA out = pipeline of NGS and GCA

pipeline of NKS and CA out = pipeline of NKS and CA

pipeline of NGS and GCA = pipeline of NGS and GCA + (pipeline
of NGS and GCA in - pipeline of NGS
and GCA out)

pipeline of NKS and GCA = pipeline of NKS and GCA + (pipeline
of NKS and GCA in - pipeline of NKS
and GCA out)

pipeline of NGS and GCA in = NGS-GCA

pipeline of NKS and GCA in = NKS-GCA

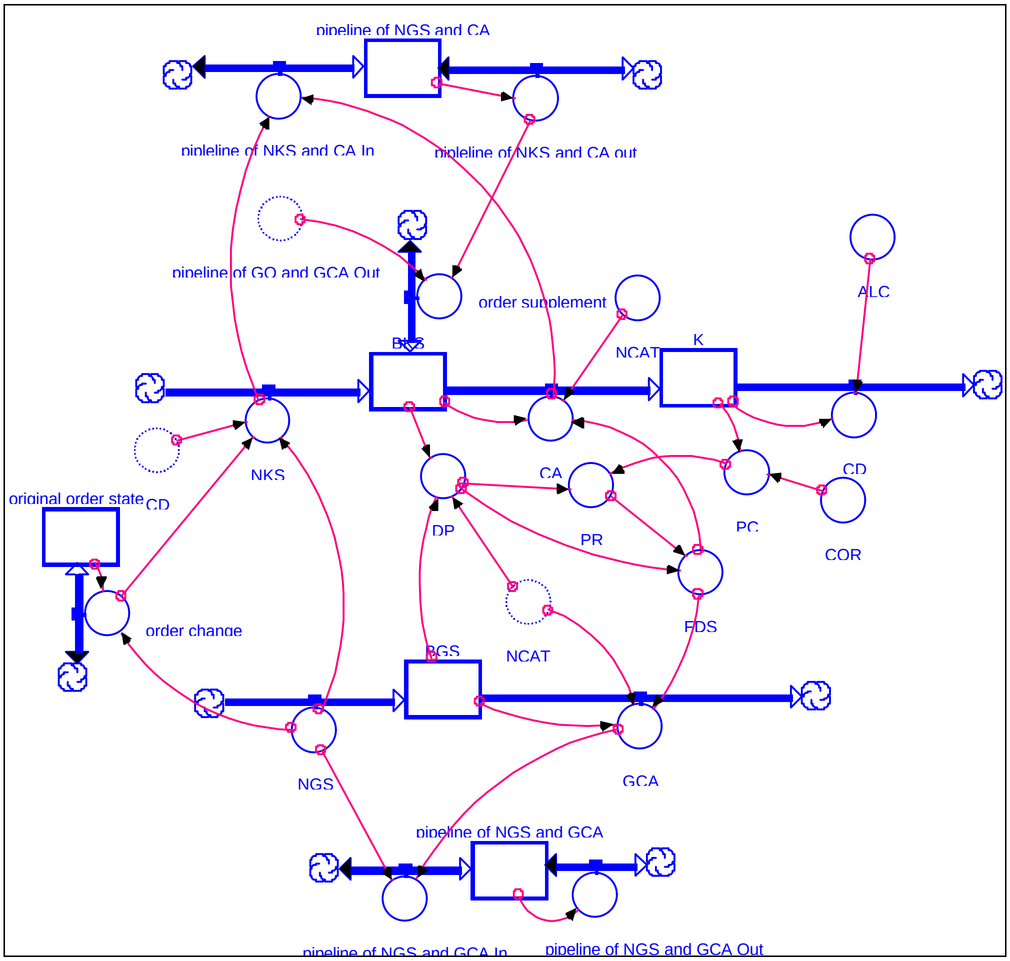

Figure 5 Structure of the synchronous designed Strategem-2 model

The redesigned system structure is shown in figure 5. With the synchronous designed Strategem-2, we further test its stability in confrontation with environmental changes. The step input is used to compared with previous researches. Simulation results of key variables are shown in figure 6 and figure 7. To compare with the other researches, value of NKS is multiplied 2 times in figure 6 and figure 7, because the DT in this experiment is just 0.1 year. From the two figures, one can observe the oscillation phenomenon is completely eliminated in the redesigned system. All the variables go to equilibrium quickly. For example, the FDS returns to 1 after the 4-year deviation. Table 1 is the summary of key variables and it also compares the simulation result to previous researches.

Table 1 Comparison of the simulation result

Approach	FDS	Average Score
Sterman (1989)	62%	19
Ozveren and Sterman (1989)	80%	15
The dynamic alignment approach	81%	13

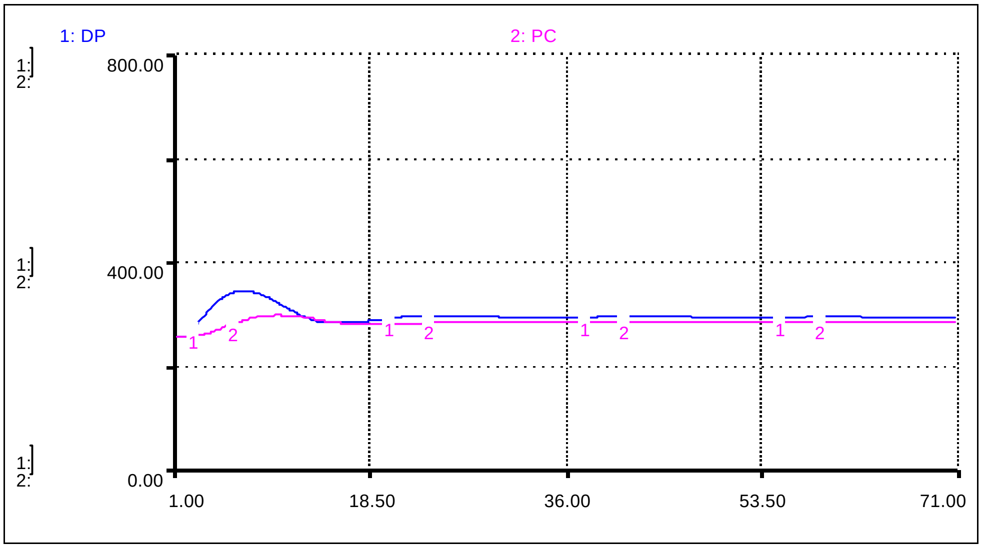

Figure 6 Simulation results (1)

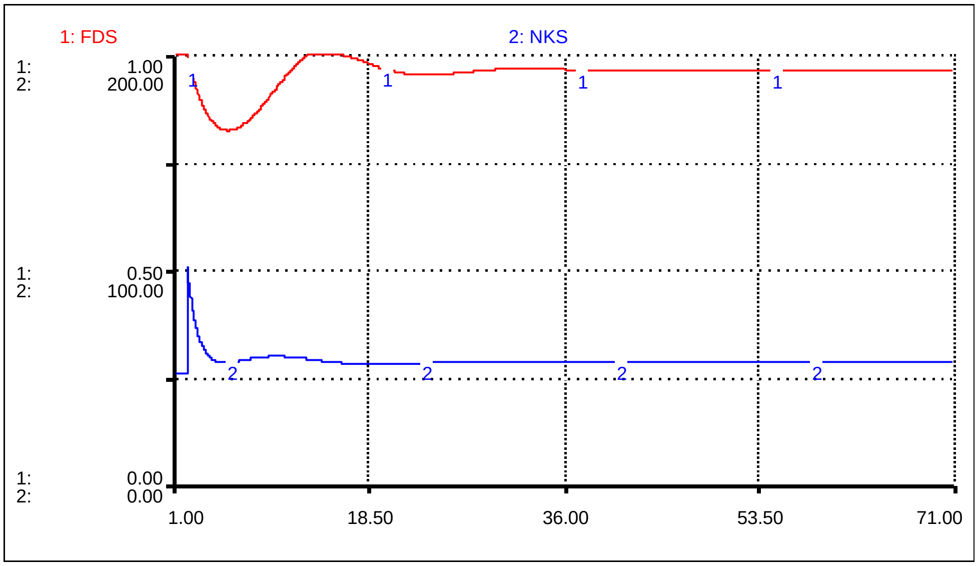

Figure 7 Simulation results (2)

In addition to the step input , we also test other kind of demand variations, such as the sin-wave test as Ozveren and Sterman (1989) do. The result shows that the average score in the redesigned system can be dramatically improved also. In fact, other than the Strategem-2 model, the dynamic alignment approach is experimented in other system dynamics model, for example, the industrial dynamics model by Forrester (1961) and market growth model (Forrester, 1968). All the experiments show that system behaviors can be improved dramatically.

4.Conclusion

Most of current high leverage related researchers use modern control theories and complex mathematic algorithms to find optimal solutions. They focus on system dynamics as a generic theory and methodology to solve dynamic complexity problems. This paper attempts to connect system dynamics with other social science domains other than mathematics and control theory to develop a leverage design approach. Different from these researches, this paper focus on the tangible flows only. The dynamic alignment approach developed in this research is proved to be effective in the dynamic problems with tangible flows mainly. The dynamic alignment approach is built on the one assumption that each rate is responsive to the exogenous input change at the same time. This implies that the objective and limitation of this approach is focus on the tangible flows, and the extensive usage of information technology and inter-net or intra-net applications is the premise.

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