A new approach for finding dominant feedback loops: Loop by loop simulations for tracking feedback loop gains

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Traditionally, feedback loops have been analyzed in two ways. First, as in causal loop analysis, the positive or negative relationships between variables are summed up to judge the polarity of feedback loops. This approach can be said as a qualitative method. Second approach for analyzing feedback loops are analytic methods mainly developed for dealing with linear models.

For the problem of understanding the behavior of feedback loops, the qualitative methods and analytic approaches give little help to modellers. In this paper, third approach for understanding the behavior of feedback loops are suggested. That is a loop by loop simulation method for tracing the feedback loop gains.

First parts of this paper explain the concept of a feedback loop gain and the loop simulation method. Second parts of this paper experiment the loop simulation method with two S.D. models; the commodity cycle model which shows equilibrium forces and the two shower model which shows fluctuating system behaviors without external shocks. Last parts of this paper discuss about the danger of understanding S.D. model with qualitative analysis of causal loops and raise a question on the way of interpreting cyclic or chaotic behavior as shifts in dominant feedback loops.

A new approach for finding dominant feedback loops: Loop by loop simulations for tracking feedback loop gains

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From the beginning of the system dynamics, feedback loops have been regarded as a starting point to understand dynamic and complex systems. In general, causal loops and the polarity of feedback loops have been used as a major tool for explaining model behavior. However, system dynamists have found that it is not an easy work to find and understand all feedback loops in a model. Furthermore, as George Richardson pointed, system dynamists are really in need of a general tool for finding dominant feedback loops (Richardson 1986).

Traditionally, feedback loops have been analyzed in two ways. First, in causal loop analysis, the positive and negative relationships between variables are summed up to judge the polarity of feedback loops (Weick 1979; Hall 1994). This approach can be said as a qualitative method. However, the qualitative method has following defects.

1) It cannot deal with the conditional or complex relationships, polarities of which are determined by variables located out of the feedback loop.

2) The strength of a feedback loop cannot be determined.

3) As a result, it cannot find which loops are dominant in system behavior.

Second approach for analyzing feedback loops are analytic methods mainly developed for linear models. Although the analytic methods are useful in some area, to my knowledge and to the knowledge of George Richardson in 1986, its applications in analyzing nonlinear feedback loops are severely limited (Richardson 1986).

For understanding the behavior of feedback loops, the qualitative methods and analytic approaches give little help to modellers. As a general rule, one should simulate his problems for which qualitative insights and analytic formula are of no use. In this paper, third approach for understanding the behavior of feedback loops is suggested. That is a loop by loop simulation method for calculating feedback loop gains.

First parts of this paper explain the concept of a feedback loop gain and the loop simulation method. Second parts of this paper experiment the loop simulation method with two S.D. models; the commodity cycle model which shows equilibrium forces (Meadow 1970) and the two shower model which shows fluctuating system behaviors without external shocks (Morecroft et al 1994). Last parts of this paper discuss on the danger of understanding S.D. model with qualitative analysis of causal loops and raise a question on the way of interpreting cyclic or chaotic behavior as shifts in dominant feedback loops.

1. Definition of feedback loop gain

SD models have many feedback loops. One can conceive a feedback loop as an independent entity or structure with its own property emerged from individual variables. In this perspective, a feedback loop is regarded as having its own attributes which are protected from the change of individual variables. Within this perspective on the feedback loop, its numerical property cannot be observed, because only individual variables have a real numerical value.

In order to catch the numerical property of the feedback loop, one should focus on linking points between the feedback loop and individual variables. By definition, a variable in the feedback loop produce effects on itself. This feedback effects may be strong/weak and positive/negative according to the nature of the feedback loop. From the standpoint of a particular variable, one can calculate the feedback effects numerically. In this paper, **a feedback loop gain** is defined as 'a magnitude of feedback effects from the viewpoint of a particular variable'. It can be described as following mathematical form.

$$G = \Delta Xf / \Delta X \qquad (1)$$

G : a feedback loop gain
ΔX : a magnitude of change in the original variable
ΔXf : a magnitude of feedback effect to the original variable

In this equation X is an original variable in the loop from which we start to calculate the feedback loop gain. The magnitude of feedback effect to the original variable (ΔXf) can be defined as

$$\Delta Xf = Xf - Xm \qquad (2)$$

In this equation, Xf is an updated value of the original variable which reflects a feedback loop effect resulting after the introduction of change (ΔX) into the original variable. Xm is an another updated value of the original variable which reflects the feedback loop effect without the change of an original variable.

In a closed feedback loop, each variable is updated every time by the feedback loop effects. **Xm** reflects this momentum of feedback loops which is generated by the previous value of the original variable. In order to obtain a pure loop gain of ΔX, this momentum should be subtracted from the feedback loop effect of ΔX. In a word, ΔXf can be interpreted as a net feedback effect which is generated by the change of an original variable (ΔX).

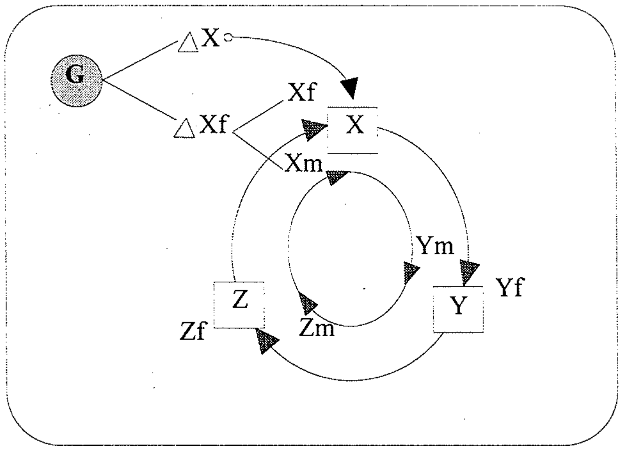
From the equation (1) and (2), we can define a feedback loop gain as follows.

$$G = (Xf - Xm) / \Delta X \qquad (3)$$

This is an operational definition of a feedback loop gain. Equation (3) can be programmed straightforwardly into computer languages.

The logic behind the Equation 3 can be demonstrated by figure 1. Figure 1 shows the calculation process of the feedback loop gain which is composed of three variables; X, Y and Z. In figure 1, an inner circle represents a momentum of a feedback loop. Xm is generated from the momentum of a feedback loop.

For calculating the feedback loop gain, ΔX is inserted into the loop. That is, a small fraction of X is added to the previous value of X. By simulating variables of the loop after the introduction of ΔX, we can get Yf, Zf and Xf sequentially. However, Xf contains the momentum of the feedback loop. In order to calculate the net feedback effect of ΔX, the momentum (Xm) should be subtracted from the Xf. As a result, a feedback loop gain (G) of ΔX is calculated from the Xm and Xf.



[Figure 1] Calculation process of a feedback loop gain

2. Computer implementation of feedback loop gains

Note that a feedback loop gain is not static, but dynamically changes with the time. The amount of Xf and Xm changes as external variables affecting the feedback loop do change. For this reason, we should not assume the feedback loop gain (G) as a static value. We should trace the feedback loop gain as the system evolves. We can trace several feedback loop gains simultaneously by simulating model equations, and then we can select a dominant feedback loop which has the largest gain in the specified periods.

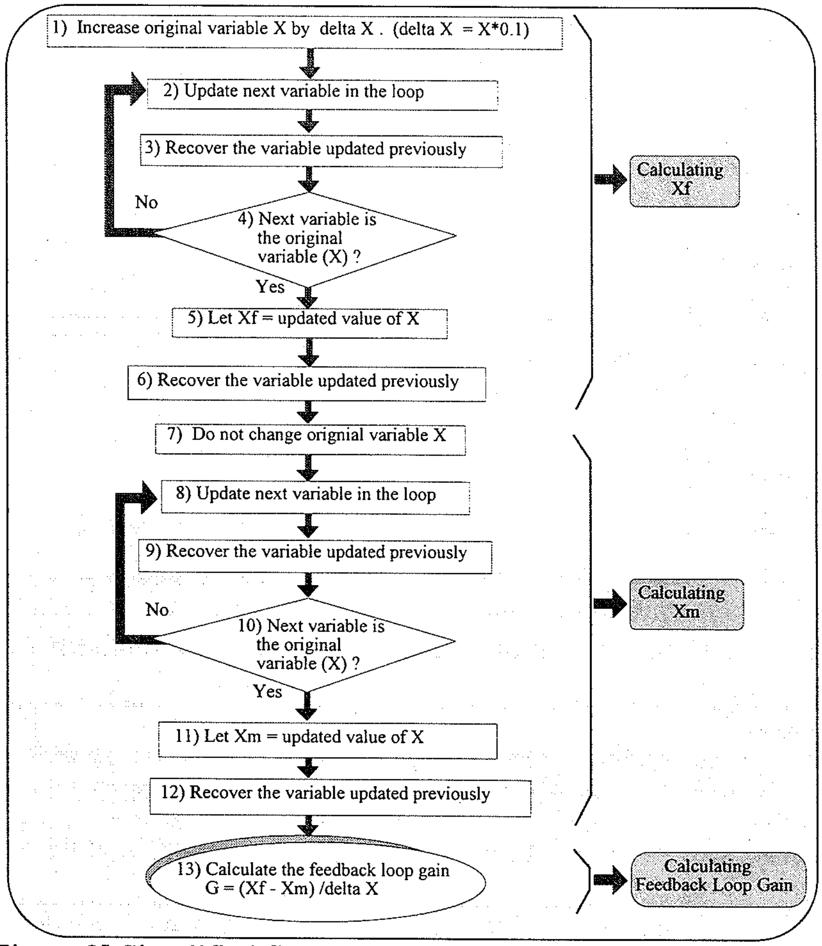
The amount of Xf and Xm can be calculated by a loop by loop simulation. The procedure of loop simulation is somewhat different with that of a system dynamics simulation in which level variables and auxiliary variables are updated separately. In the loop simulation, each value of variables in the loop is updated sequentially in order of causalities. This is for excluding external effects which come into the feedback loop during the simulation. With the loop simulation, one can get the feedback loop gain which is not contaminated from other effects.

In this research, the algorithm for finding feedback loops and their gains is implemented in EGO (**E**quations as **G**raphic **O**bjects) which is an object-oriented simulation environment for system dynamics (D.H. Kim 1995). Figure 2 shows a simplified flow chart for calculating a gain for a given feedback loop.

First six steps in figure 2 are for calculating Xf of equation 3. At first step the amount of delta X (ΔX) is calculated as 10 % of the value of original variable (X) and is added to the original variable. From second step to fourth step, all variables in the given feedback loop are updated one by one. In this process, updated variables are recovered to their original value as soon as next variables of them are updated.

From seventh step to twelfth step, the momentum of the feedback loop (Xm) is calculated. Calculation processes for Xf and Xm are identical. Both are different only in whether or not the original variable is increased.

At last step in figure 2, one can calculate the feedback loop gain according to the equation 3. Its polarity represents the polarity of the feedback loop. Moreover, the amount of the gain means the strength of the feedback loop, because it indicates how much feedback the original variable receives.



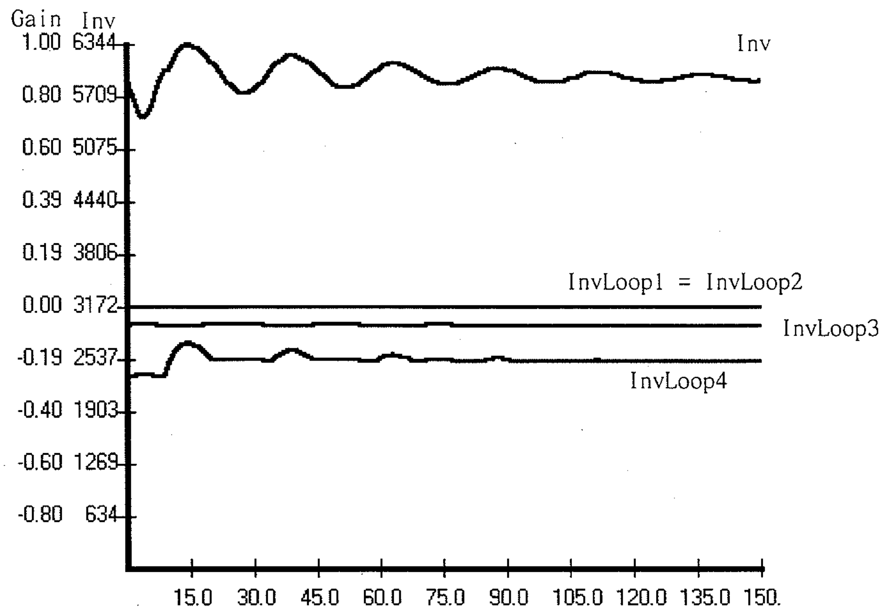
[Figure 2] Simplified flow chart of calculating a feedback loop gain

This loop by loop simulation is performed for every specified feedback loops at every time interval of recording model behaviors. Even in a small model, a variable may have hundreds of feedback loops. Accordingly, the loop by loop simulation method requires a lot of times. However, it can help modellers to find out dominant feedback loops and can provide many insights for understanding fundamental structures of system behaviors.

3. Experimenting with the commodity cycle model

For experimenting the performances of feedback loop gains algorithm, the commodity cycle model was selected, because it shows the forces toward equilibrium state. Generally speaking, systems characterized by the equilibrium states are expected to have the negative feedback loops as their dominant feedback loops. Figure 3 shows the time behavior of feedback loop gains about inventory (Inv) variable.

In commodity cycle model, EGO found out four feedback loops containing 'Inv' variable. One can inspect contents of the feedback loops in a text window as figure 4. EGO automatically makes names for each loops. A name of a feedback loop is constructed as 'variable name + Loop + sequential number'. For example, 'InvLoop2' is a name for the feedback loop on 'Inv' variable which EGO found at second time.



[Figure 3] Time behavior of feedback loop gains in commodity cycle model

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*** Feedback Loops of Inv
InvLoop1 :: Cov => Rcov => Price => Ep => Dpcap => Rdac => Cuf => Inr => Pr => Inv
InvLoop2 :: Cov => Rcov => Price => Ep => Dpcap => Ctir => Ctcr => Pcap => Rdac => Cuf => Inr
            => Pr => Inv
InvLoop3 :: Cov => Rcov => Price => Ep => Dpcap => Ctir => Ctcr => Pcap => Inr => Pr => Inv
InvLoop4 :: Cov => Rcov => Price => Eppc => Pccr => CR => Inv
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[Figure 4] Feedback loops in commodity cycle model

In figure 3, one can observe three important points about the dynamic nature of feedback loop gains.

1) Some feedback loop gains are not stable, but dynamically change with time.

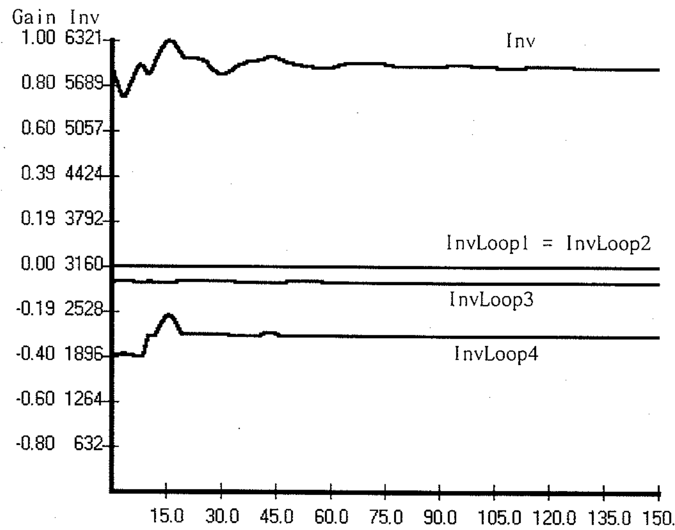
2) As the commodity system goes to the equilibrium state, all feedback loop gains tends to be stabilized.

3) The cyclic behavior of 'Inv' variable in the initial period can be explained by the fluctuation of the InvLoop4.

Comparing the time behavior of 'Inv' and that of 'InvLoop4', one can conjecture that 'InvLoop4' is a dominant feedback loops. In figure 3, 'InvLoop3' and 'InvLoop4' tell us that the feedback loop gain changes as the system evolves. From these observations, one can conclude that the dynamics of feedback loops can be used as an explaining tool for dynamic behavior of system variables.

InvLoop4 was experimented for inspecting the power of a dominant feedback loop. As can be seen in figure 3, InvLoop4 is a dominant negative feedback loop. In order to stabilize the 'Inv' variable, one must add more strength to InvLoop4. In this experiment, 'consumption requirement adjustment delay (Crad)' was reduced from 3 months to 2 months. The results are displayed in figure 5.

The feedback loop gain of InvLoop4 was enforced from -0.2 to -0.3. However other feedback loop gains are identical with those of figure 3. While 'Inv' was stabilized after 135 months in figure 3, the stabilization of 'Inv' starts from 45 months in figure 5. From these results, one can conclude that the dominant feedback loop really has the power of changing system behaviors.



[Figure 5] Results of enforcing InvLoop4

When Meadow said that "a change in the consumption loop has a greater impact on the stability of the system", he was aware that InvLoop4 is a dominant feedback loop (Meadow 1970, p.70). However, he has not used a systematic and convenient method to find this fact. With the analysis of the feedback loop gains, one can find the dominant feedback loops without time-consuming trials and errors and furthermore one can understand how the dominant feedback loops can be exploited to achieve policy goals.

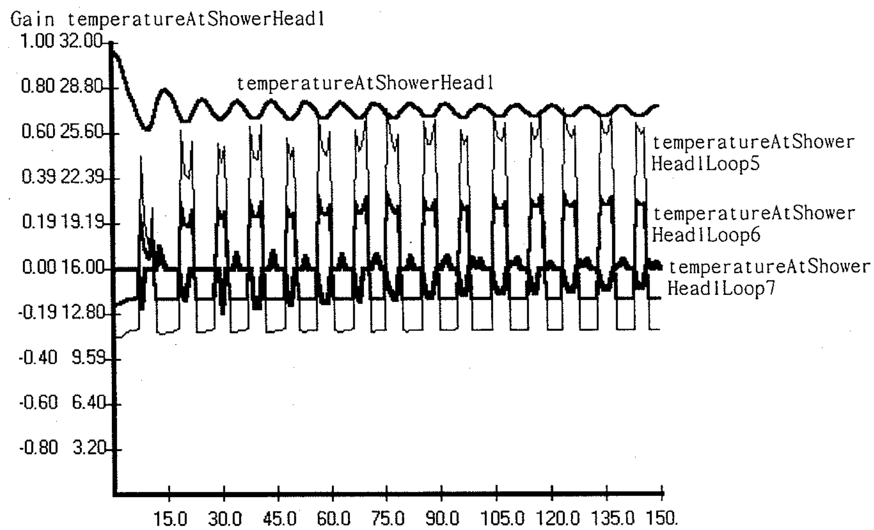
4. Experimenting with the two-shower model

Previous experiments was performed to investigate the feedback loops in a stable system. In this section, two-shower model is experimented to investigate the time behavior of feedback loop gains in the system which shows fluctuating behaviors.

As Morecroft et al presented, system behaviors of the two-shower model depend on whether or not two person have the same desire for temperature of water (Morecroft et al 1994). First, the model with different desire for temperature at shower head (27 and 25 respectively) is experimented. It shows fluctuating behaviors. Results of experiments are presented in figure 6.

In figure 6, all feedback loop gains fluctuate with the time. Moreover, the polarities of feedback loops change with regularities. All feedback loop gains graphed in figure 6 fluctuate between the negative polarity and the positive polarity. In this situation, the polarities of feedback loops should be understood as dynamically.

As graphed in figure 6, fifth feedback loop (temperatureAtShowerHead1Loop5) is dominant. Note that a shift of dominant feedback loops did not happened during entire simulation period! It seems that one dominant feedback loop generates the cyclic behavior of 'temperatureAt-ShowerHead1'. In this example, the fluctuating system behavior should not be explained by the shifts in dominant feedback loops, but by the oscillation of one dominant feedback loop from negative polarity to positive polarity and vice versa.



[Figure 6] Time behavior of feedback loop gains in two-shower model

*** Feedback Loops of TemperatureAtShowerHead1
TemperatureAtShowerHead1Loop5 :: TemperatureGap1 => FractionalAdjustment1 => RequiredAdjustment1 => ChangeInTapSetting1 => TapSetting1 => TemperatureAtTap1 => TemperatureAtShowerHead1
TemperatureAtShowerHead1Loop6 :: TemperatureGap1 => FractionalAdjustment1 => RequiredAdjustment1 => ChangeInTapSetting1 => TapSetting1 => FracHotWaterAvaiableTo1 => MaxFlowOfHotWater1 => TemperatureAtTap1 => TemperatureAtShowerHead1
TemperatureAtShowerHead1Loop7 :: TemperatureGap1 => FractionalAdjustment1 => RequiredAdjustment1 => ChangeInTapSetting1 => TapSetting1 => FracHotWaterAvailableTo2 => MaxFlowOfHotWater2 => TemperatureAtTap2 => TemperatureAtShowerHead2 =>TemperatureGap2 => RequiredAdjustment2 => ChangeInTapSetting2 => TapSetting2 => FracHotWaterAvaiableTo1 => MaxFlowOfHotWater1 => TemperatureAtTap1 => TemperatureAtShowerHead1

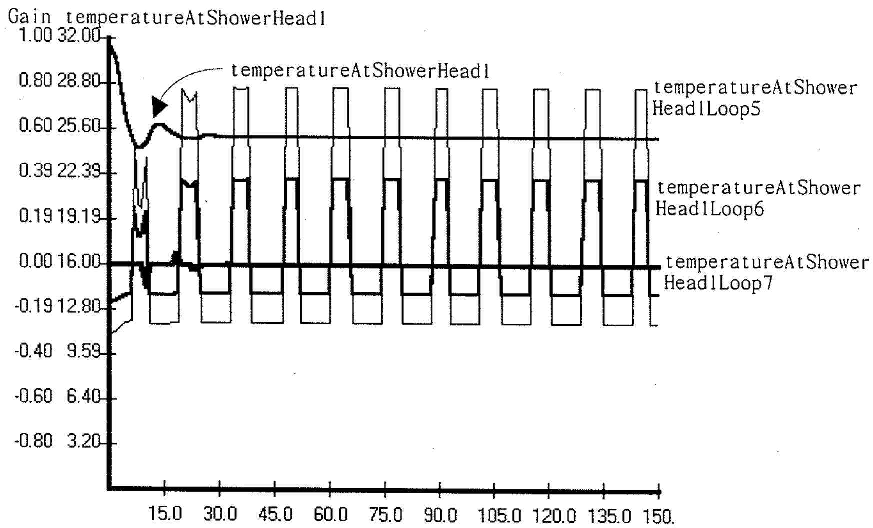
[Figure 7] Feedback loops in two-shower model

The dynamics of feedback loops found in figure 6 is somewhat different with the explanation provided by George Richardson (1986, 1991). The explanation for the cyclic or chaotic behavior by the shifts in dominant feedback loops seems to be not applicable to this case. With regard to the systems like this example, one should explain the cyclic or chaotic behavior by the fluctuation of some dominant feedback loops.

As a second experiment with the two-shower model, a model on two persons with identical desire for temperature at shower head was experimented. The experiment was performed to find out what differences are there between the stability of a commodity model and the stability of two-shower model.

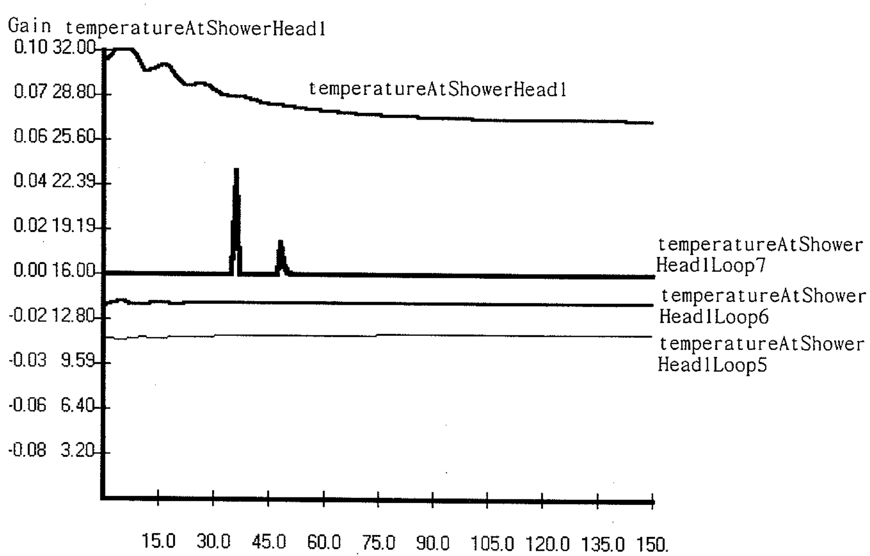
Figure 8 shows the time behavior of feedback loop gains in two-shower model with identical desire for water temperature. As demonstrated by Morecroft et al (1994), 'temperature-AtShowerHead1' comes to an equilibrium state. However, this equilibrium state is not robust. It is very weak to external shocks.

This point can be explained with the feedback loop gains. In figure 8, feedback loops are fluctuating in spite of the stable behavior of 'temperatureAtShowerHead1'. Only seventh loop remains stable after initial fluctuations. The oscillating behavior of feedback loops implies that the temporary equilibrium state is weak. If there is any change in fifth or sixth feedback loops, its effect will be fluctuating with that of feedback loop gains.



[Figure 8] Feedback loop gains in two-shower model with identical desire for temperature

How can one achieve stability in the face of different desires for shower temperature? From figure 6, one can observe that the unstable system behavior comes from the oscillating nature of feedback loops. If one can reduce the power of the dominant feedback loops, one can increase the stability of shower system. The power of dominant feedback loops can be reduced by decreasing 'judgementalCalbration' from 0.1 to 0.01. The results are displayed in figure 9.



[Figure 9] Results of reducing 'judgementalCalbration' from 0.1 to 0.01

In figure 9, all feedback loops are stabilized to the negative side so that the shower temperature comes to stable stage. Note that polarities of feedback loops can be changed by adjusting one parameter! These results raise a new research question on the relationship between parameters and the polarities of feedback loops.

5. Discussions and Conclusion

In this paper, a new method for finding dominant feedback loops was introduced and their practical implications in system dynamics models were presented with two examples. I think that a loop by loop simulation method for tracing feedback loop gains may provide a new tool for analyzing and understanding S.D. models.

Through this research, some questions have been raised. First question is on the qualitative analysis of causal loops. If feedback loops fluctuate from positive to negative polarities with the time, qualitative analysis of causal loops may be incorrect in interpreting model behaviors and even might suggest wrong policy recommendations. Second question is on the notion of shifts in dominant feedback loops. If unstable systems can be explained by the fluctuation of one dominant feedback loop, we should pay more attentions to the parameter adjustment than the system restructuring. Third question is on the dynamic relationships between parameters of variables and polarities of feedback loops. Studies on their relationships might give much more understandings on the dynamic interactions between system structures and parameters in determining system behaviors. I think that more experimentations and technical developments on using dominant feedback loops to find policy levers should be performed in the future.

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