POLICY DESIGN IN OSCILLATING SYSTEMS

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ABSTRACT

Policy design is a key issue in System Dynamics. It consists in the introduction of changes into the system, in order to track the objectives trajectories. Those changes are either numerical or structural. Oscillations require more structural than numerical changes.

Oscillatory systems are are usually undesirable because of the ups and downs they bring into the system components. For instance, the labor instability in the Labor Backlog model.(Lyneis 1980, pp 182-210).

Oscillations have been found very insensitive to numerical changes in the parameters (Graham(1977)); but, they have been found very sensitive to changes in the sign, and the presence of them. Where presence denotes changes from zero to something. Therefore, the design of effective policies to control oscillations is a problem that goes beyond the Classical Optimal Control Theory of nonlinear systems (Coyle 1985), and it belongs to the Structural Control Theory. However, the Optimal Control Theory is a valuable tool to model the control structure. (Ozveren; Cuneyt; Sterman J., 1989, pp 130 - 147), (Keloharu 1982).

In this paper, some guiding principles for policy design in oscillatory systems are presented. The construction of the management structure is illustrated.

Two classical models: Labor- Backlog and the version of Kondratieff cycles presented by (Mosekilde; Rasmussen; Sterman (1985)), serve as prototypes to try the proposed principles on.

INTRODUCTION

In the last thirty years System Dynamics has shown two main lines of work: modeling and analysis. The modeling paradigm was introduced by Jay Forrester at the end of the fifties. It has experienced practical enhances over the years but it has experienced no significant change. Industrial Dynamics (Forrester 1961) is still a futurist book .

The analysis have been performed either by computer simulation or by mathematical theory.

Simulation was introduced by Pugh Roberts with their DYNAMO, greatly improved over the years.

The Mathematical Nonlinear System Theory for the analysis of System

Dynamics models have been introduced, mainly by several European Scientist, to the System Dynamics Community. Ilya Prigogine(1977), (Aracyl; Mosekilde 1988), (Nathan Forrester 1982) and Others have presented their findings enhancing the analysis of dynamic models.

Modeling and Analysis are distinct processes in the understanding socioeconomic systems; therefore, they can not constitute two different schools of thought, but two faces of the same coin.

Nevertheless, there is an apparent controversy regarding the sensitivity to changes in parameters(Mosekilde; Rasmussen; Sterman (1985)).

Forrester suggests that System Dynamics models are usually insensitive to changes in parameters; but, Prigogine and his followers have presented a wide diversity of behavior of nonlinear dynamical models, very sensitive indeed to changes in parameters. However, stable nodes are found insensitive to changes in parameters Porter(1966, p340.).

Forrester has incorporated managers within the models. Managers have to lead the system toward objectives, so the resultant system, that includes effective management, will exhibit a stable node at the objectives, very insensitive indeed to parameter changes. That does not mean that the system can not, for instance, growth exponentially if the managers want to do so; But, the gap between the trajectory of the model, and the trajectory of the objectives will die out. Managers track the objectives trajectory.

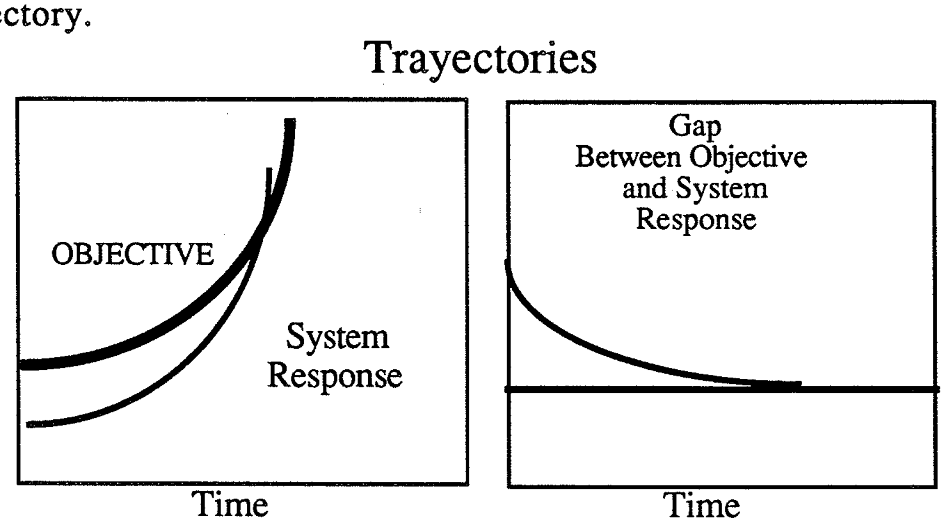

Figure 1. Dynamic Behavior of System plus Managers

Sometimes the system behaves counterintuitivelly, achieving objectives contraries to intuition(Forrester 1975, p 211). But those unexpected objectives are consequences of management structure. Sometimes, managers create a stable node around those undesired objectives, which are also very reluctant to changes in parameters, even though they are achieving the wrong objectives, because the managers are not aware of the logical consequences of their way to structure their decisions.

Sometimes, unpurposefully, managers build a stable node around the wrong objectives.

A stable node around the right or wrong objectives is a particular case of the wide variety of possible behaviors that have been extensively studied in the mathematical theory of nonlinear systems. But, it is very common case in management.

In recent years there have been a considerable mixture between modeling and analysis. STELLA and STELLA STACK, in the area of computer simulation are outstanding examples of such a synthesis. All the models worked out in this paper have been simulated using this wonderful tool.(Richmond 1989).

The mathematical analysis of System Dynamics Models are solid basis for counterintuitive behavior of the decision makers. They can be used to design the piece of structure to control the system.

This paper explores the use of mathematical techniques to model structures to control oscillations. First, the mathematical theory is explained within the System Dynamics context. Two classical examples are presented to illustrate the application of the technique: the Kondratieff model and the Labor Backlog. The size of the paper does not allow to present more illustrations; nevertheless, the reader is encouraged to work his own examples out.

THE OSCILLATING STRUCTURE

The oscillating structure around a critical points occurs when the eigenvalues of the linearized system around the objectives are complex numbers, if the system is structurally stable.

$$\frac{dy}{dt} = Q(x,y)$$

$$\frac{dx}{dt} = P(x, y)$$

Rosen (1970) has shown that a sufficient condition for sustained oscillations is to have the self-couplings, $\partial Q/\partial y$ and $\partial P/\partial x$, and the cross-couplings, $\partial Q/\partial x$ and $\partial P/\partial y$, in opposite sign; besides the product of the cross-couplings, in absolute value, must be greater than the absolute value of the product of the self-couplings. If the self couplings change in sign around the region, then the sum of them must change in sign too.

To depart from the conditions established in the theorem, is a way to depart from oscillations.

In System Dynamics notation this theory can be expressed has:

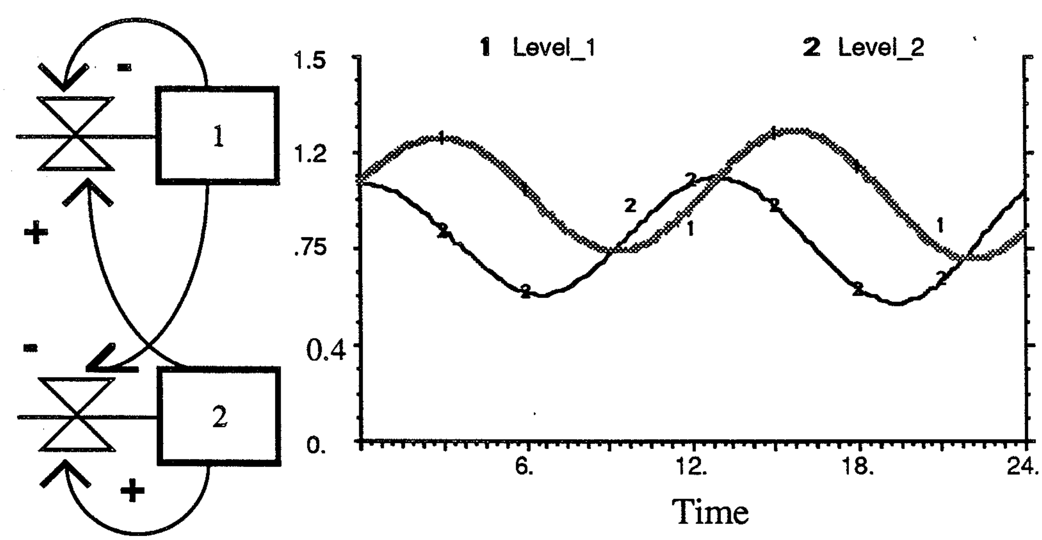

Figure 2. Sustained Oscillations

Figure 2 summarizes the structure and the encountered behavior. This structure can be represented by different alternatives of interaction between input and output rates. A negative influence of one level over the other can be achieved either by a negative interaction to the input rate or by a positive interaction to the output rate. Similarly, a positive influence either favors input rate or inhibits output rate. Some of this alternatives are shown in the figure 3.

There are others ways to interact having self and cross couplings with opposite sign; but, the purpose is to show the equivalence, rather than to enumerate all the alternatives.

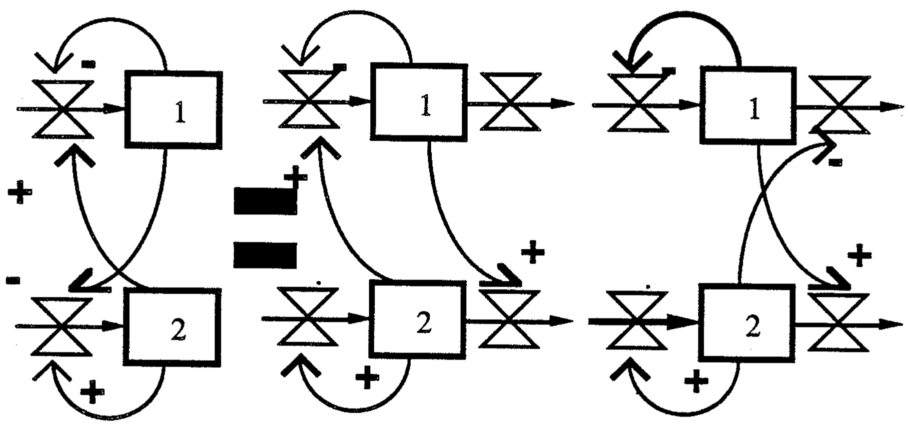

Figure 3. Equivalent Oscillating Structures

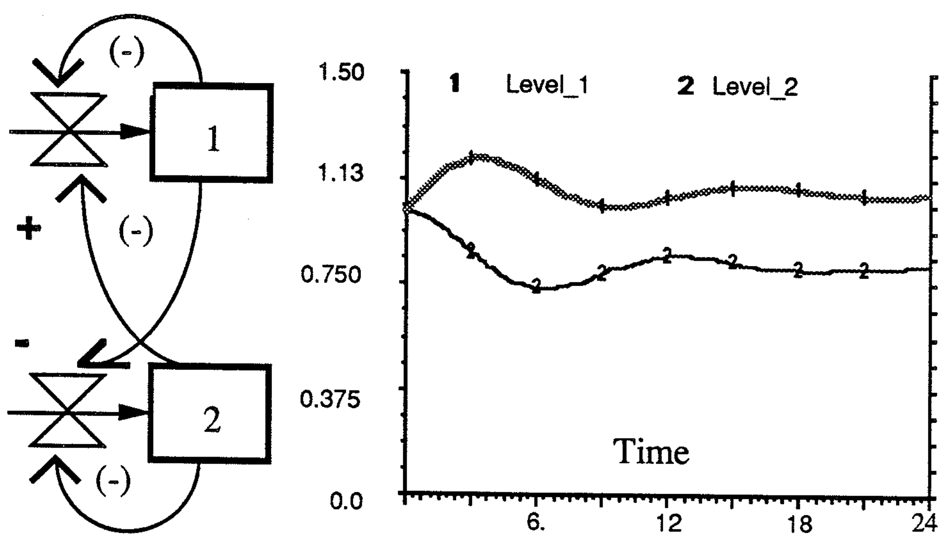

Figure 4. Damped Oscillations by Negative Self-interactions

Changing the sign of the self interactions is one of the potential sources of control; Besides, if the product of the self interactions is stronger than the product of the cross interactions, then the control of oscillations is improved. This policy remind us the one used by the Americans cowboys to stop the bull oscillations: **taking the bull by the horns.**

HIGH ORDER DELAY (HOD)

One common structure often encountered in System Dynamics is the High Order Delay. It consists in several levels in succession.

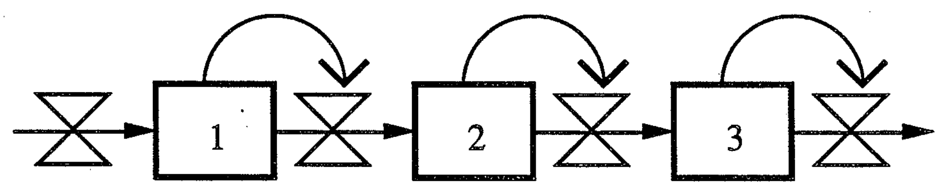

Figure 5. Third Order Delay

The High Order Delays are not Oscillating Structures, because there is only a positive interaction among each level and the following one. But, an inhibition in any direction will make the oscillations to appear; because, the cross interactions of opposite sign are present.

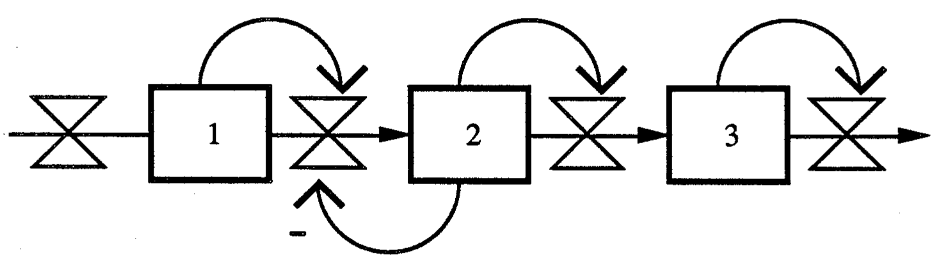

Figure 6. Backward Inhibition

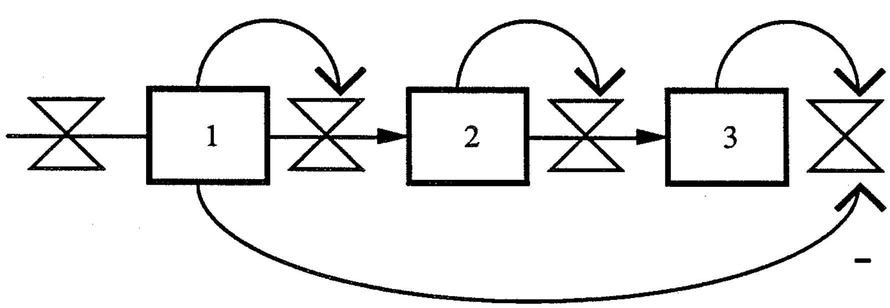

Figure 7. Forward Inhibition

A version of the Kondratieff Cycle is going to be used to illustrate this simple case of policy design .

KONDRATIEFF CYCLE

The following diagram shows the simplified version of the Kondratieff cycle presented by Mosekilde, Rasmussen and Sterman (1985). It is presented as a second order delay, the back inhibition darkened in the figure 8, completes sufficient conditions for oscillations.The time plot is presented in figure 9 .:

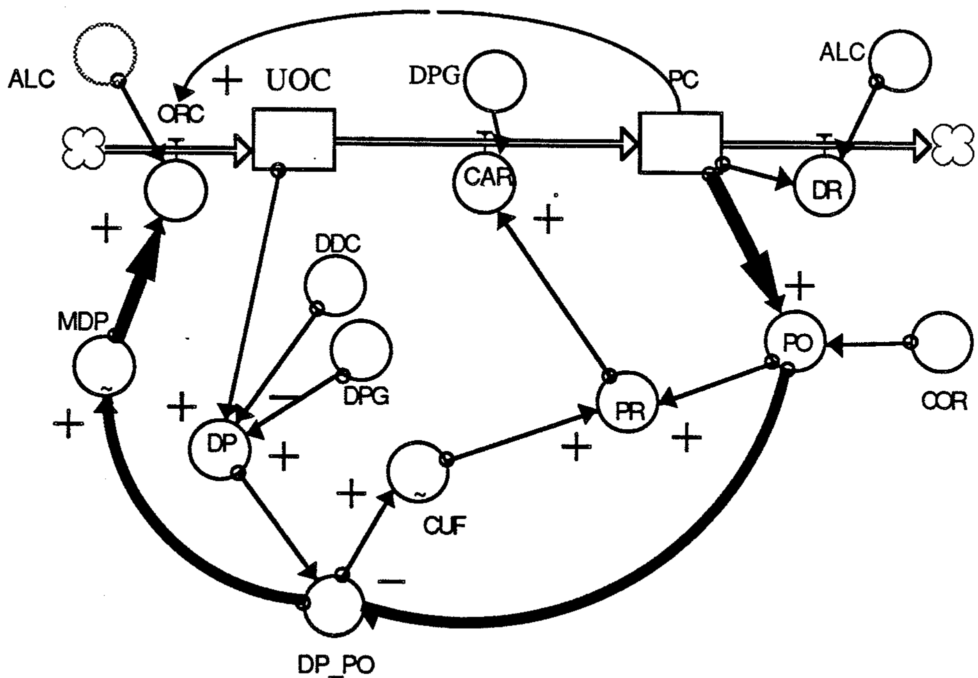

Figure 8. The Kondratieff Cycle

There is also an activation link between the capital and the orders for capital, this activation link represents the ordering of new capital, as the existing one is depreciated. If the activation link is strong enough; then, there will be a net activation from **PC** to **UOC**, rather than inhibition; so, the oscillation will tend to disappear. So, this link constitutes a potential source of changing the oscillatory character into an exponential growth as presented in figure 10.

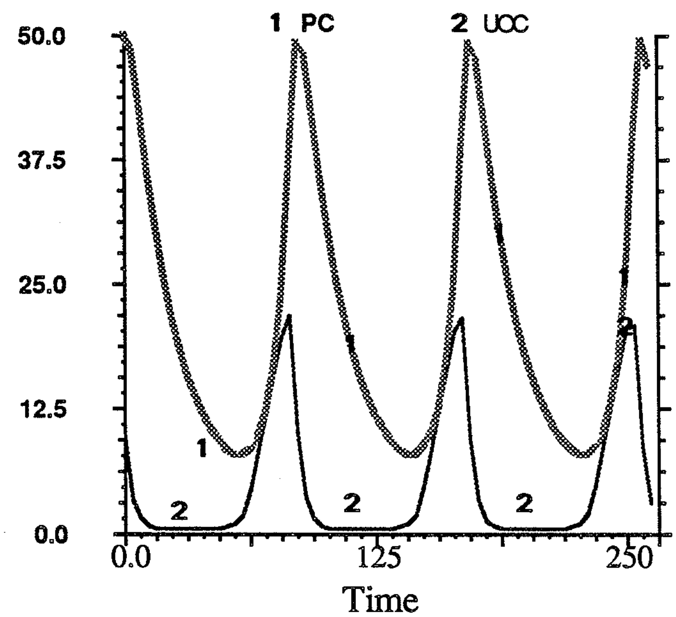

Figure. 9 Kondratieff Oscillations

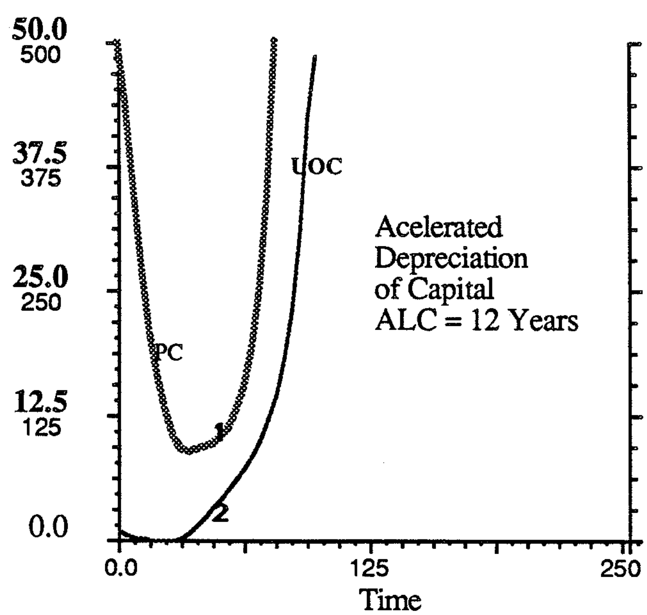

Figure 10 . Backward Activation instead of inhibition

The Capital Output Ratio affects directly a negative link in the backward inhibition, main responsible of the oscillating character of the model. Therefore, a decrease in the value of **COR** weakens the backward inhibition, making the oscillations to damp, as presented in figure 11.

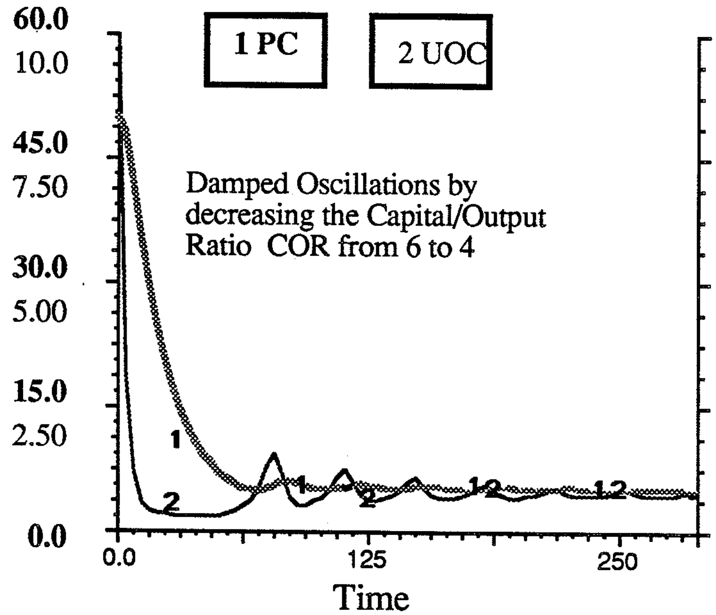

Figure 11. Damped Oscillations by Decreasing the capital Output Ratio

If the backward inhibition is suppressed, then the oscillations die out, and the system goes to equilibrium. Note that the self ordering loop of the capital is still present; but, it does not cause oscillations.

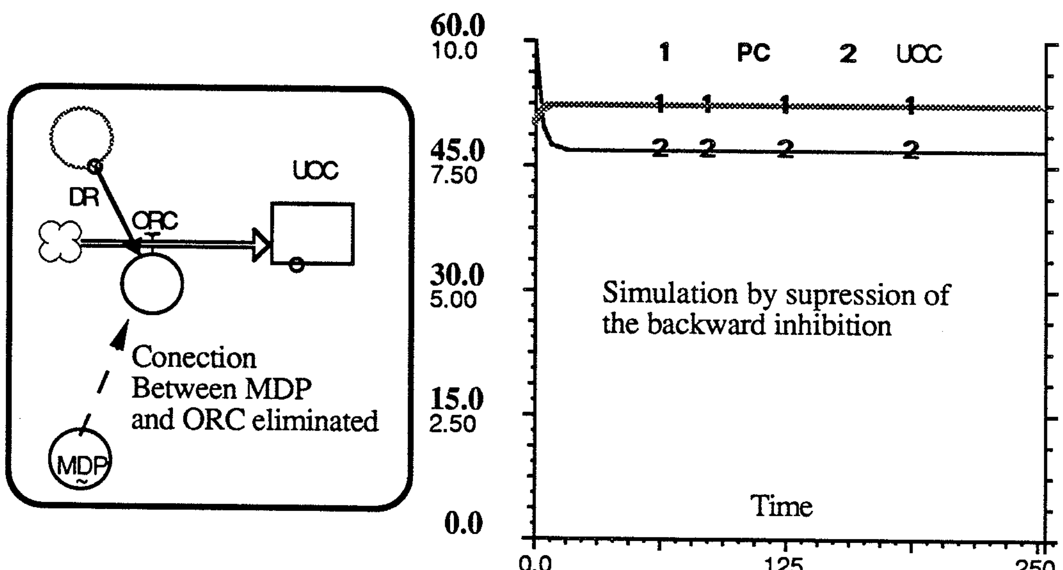

Figure 12. Suppressing the backward inhibition eliminates the oscillatory character

LABOR BACKLOG

A company receives orders for its products which accumulates in a Backlog until the orders are filled. If the order backlog becomes too high, the company hires more people to produce the goods more rapidly to reduce the backlog.

The backlog stimulates the hiring of more workers, the level of labor increases production, depleting the backlog.

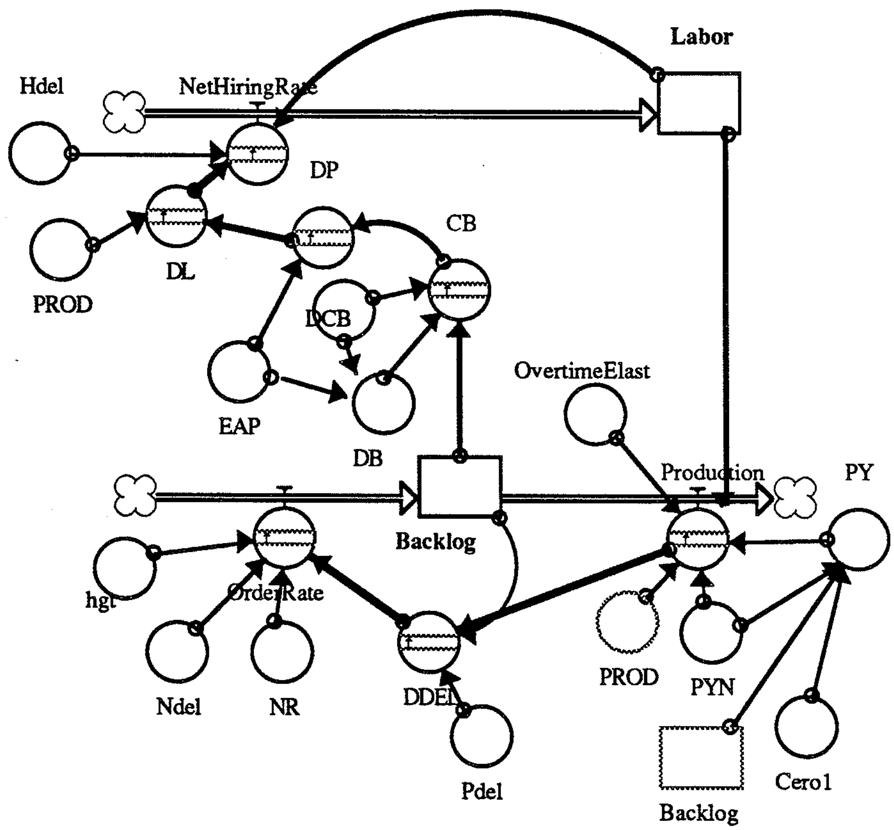

Figure 13. Labor Backlog Model

The structure of the interactions and the results of the simulation are shown in the figure 14. The Backlog stimulates more orders, because there is a need to preserve the delivery delay. The Level of labor inhibit the recruiting of more people. The model has cross and self couplings of opposite sign; So, it will oscillate.

One of the options to control this system is turn both self couplings to inhibiting ones: to take the bulls by the horns. In this case, there is a need for an inhibiting self interaction in the backlog, for instance, the more backlog, the more production. Note the stimulating interaction between the backlog and the order rate, it is a response of the customers, very difficult to control by the company. But, the increase in production as a result of an increase in the order backlog is controllable by the company.

So, the production has to be stimulated by the backlog, with no more hiring. This can be achieved by working overtime.

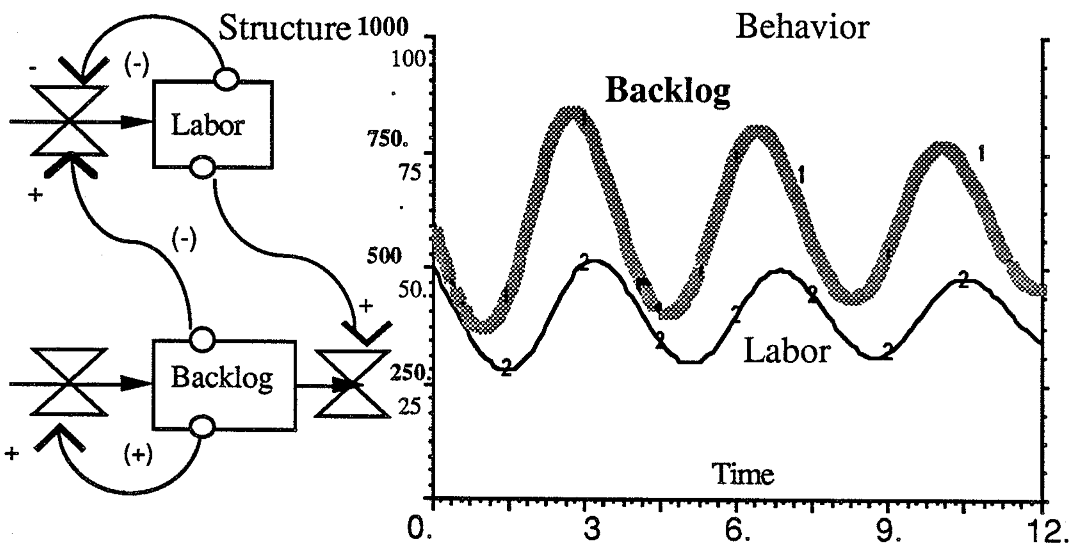

Figure 14. Labor Backlog Model Oscillations

Overtime also has an impact in the delay necessary to hire people, because less effort has to be devoted to hire more people in response to extra backlog. So the strength of the cross interaction **HDEL** is diminished.

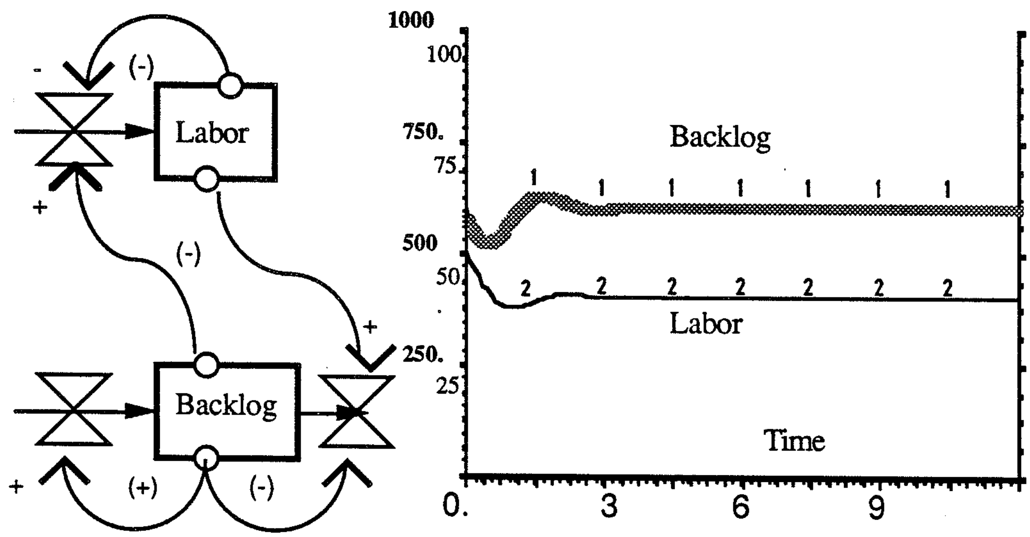

Figure 15. The Oscillatory Character Disappear with the Overtime Management

CONCLUSION

Departures from self and cross interaction of opposite sign; Besides, forcing the product of self interactions to be stronger than the product of cross interaction(taking the bull by the horns) have been shown to be a guiding heuristic principle for structural intervention aimed to control oscillations. The proposed methodology as been presented only for two level systems. One of the reasons is that complex eigenvalues of the linearized system come in pairs, usually related to two interacting levels. Therefore, the principles can be applied to more complex structures. However, there are a lot of available results in the mathematical theory of nonlinear systems that can be applied to multilevel systems. (Othmer(1976); and Graham(1977,pp 97,186,234)) have encountered that positive multilevel loops of less than five levels, provides sources to control oscillations. Negative loops of less than five levels favor oscillations. Loops of more than five levels may have any impact over behavior. In any case, the pattern of activation - inhibition responsible for oscillations has to be identified, then a synthesis of the structure able to depart from such a pattern can be achieved. It is important to emphasize that the loops have to be identified over level and rates diagrams. The causal loop diagrams without showing explicitly levels and rates may lead to inconsistencies.

Policy Design continues to challenge System Dynamicists. Design requires more than choosing the right parameters, it takes choosing the right structure. System Dynamics is a discipline of structure, rather than a branch of optimization. However, the mathematical theory of nonlinear systems, provides the basis for the counterintuitive behavior of the decision makers, necessary to model the management structure.

APPENDIX

LABOR BACKLOG MODEL EQUATIONS
{Initialization equations}
INIT(Backlog) = 600 {Units}
INIT(Labor) = 50 {Men}
EAP = 1200 {Units}
DCB = 0.5 {Years}
DB = EAP*DCB {Units}
CB = (Backlog - DB)/DCB {Units/Year}
Cero1 = 0 {Zero with no control, One activates the control structure}
PROD = 30 {Productivity Units/Men-Year}

OvertimeElast = 0.80 {%Labor Elasticity}
PYN = 2080 {Days/Year}
PY = MIN(Backlog/init(Backlog),1.3)*PYN*Cero1+(1-Cero1)*PYN
{Overtime Production Units/Year}
Production = PROD*Labor*EXP(OvertimeElast*LOGN(PY/PYN))
{Units/Year}
Pdel = 0.2{Years}
DDEL = SMTH1(Backlog/Production,Pdel,.5){Years}
DP = CB+EAP
DL = DP/PROD{Men}
Hdel = 0.5 {Years}
hgt = 300 {Units}
Ndel = 0.5{Years Normal Delivery Delay}
NetHiringRate = if Labor >0 then (DL-Labor)/Hdel else 0 {Men/Year}
NR = 1200 {Units}
OrderRate = (DDEL/Ndel)*(NR+STEP(0,hgt)) {Units/Year}

{Structure equations}

Backlog = Backlog + dt * (OrderRate - Production)
Labor = Labor + dt * (NetHiringRate)

{Auxiliary equations}

DB = EAP*DCB {Units}
CB = (Backlog - DB)/DCB {Units/Year}
PY = MIN(Backlog/init(Backlog),1.3)*PYN*Cero1+(1-Cero1)*PYN
{Overtime Production Units/Year}
Production = PROD*Labor*EXP(OvertimeElast*LOGN(PY/PYN))
{Production Units/Year}
DDEL = SMTH1(Backlog/Production,Pdel,0.5) {Years}
DP = CB+EAP
DL = DP/PROD {Men}
NetHiringRate = if Labor >0 then (DL-Labor)/Hdel else 0 {Men/Year}
OrderRate = (DDEL/Ndel)*(NR+STEP(0,hgt)) {Units/Year}

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