THE CAUSAL LOOP DIAGRAM: A DYNAMIC PROFILE

by

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ABSTRACT

The Causal Loop Diagram, a signed digraph which shows the variables and interactions of a system Dynamic model, has been studied. It has been found convenient to start with the levels and their interactions. Then signed interactions between levels and rates may proceed. The transformation from signed level digraph into Causal Loops, in terms of levels and rates, is presented.

Dynamics properties such as stability, oscillations, controllability, and observability are related to the information contained in the Causal Loop Diagram. These dynamic properties have been found very useful in the synthesis of policies aimed to manipulate structure. Illustrations and examples are inserted in the exposition.

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INTRODUCTION

The Causal Loop Diagram (CLD) expresses visually the variables and the signed interactions that constitute the structures of the model. However, the expression of the CLD in terms of level to rates interactions facilitates consistency with System Dynamic Theory.

It is recommended to start with the levels, visualizing the interactions among them by the traditional signed digraph. Next, when rates are included then the standard System Dynamic flow diagram is more appropriate to depict the signed interactions because it provides a convenient way to incorporate the System Dynamic relational constraints. Besides, it is the natural transition from the signed digraph to the full SD model. A discussion of the brokendown level-to-level interactions depicted in the signed digraph in terms of more simple level-to-rate interactions is presented.

A conceptual discussion of the relations that may go into the CLD is offered. In addition, the CLD is compared with Interpretative Sructural Modeling. Moreover, fundamental dynamic properties such as stability, controllability, observability and oscillations are related to the information contained in the Causal Loop Diagram. The strategy used to achieve this goal is outlined because it provides a means for further additions. Thus, the set of principles presented here is not intended to be exhaustive. Finally, computer routines are provided to simulate the information contained in the causal formulation.

1. VARIABLES AND RELATIONS THAT GO INTO THE CAUSAL LOOP DIAGRAM

Any relation that goes into the Causal Loop Diagram requires an explanation of the reasons that support the links between the cause and the effect. Perhaps the major drawback in the social sciences and one of the many important contributions of System Dynamic, has been to establish a clear distinction between casual and causal links.

The casual or coincidental observations can be confused with causality mainly through three mechanisms:

1) Because the variables appear simultaneously or coincide in some point in time or space or both.

2) Because there are relevant variables which are omitted, making the causal relation, Y(t+DT) = CAUSE (X(t)), between cause X and effect Y, arbitrary.

3) Because there are inconsistencies among the models used to characterize causality in the different components of the system.

The first mechanism corresponds to the phenomenon of conditioning, which has been extensively studied by Skinner (1969). In this case, the cause has nothing to do with the effect, but they appear together and therefore contribute to the building of an intuitive link between them. Skinner called it superstition, and even though it appears to be absurd, it is an integral part of any living organism. At least some behavioral attributes, whether in a bacteria or a decision maker, will be partially determined by their previous conditioning. Superstition is perphaps the most difficult pitfall to overcome because it is a property of living mater-and humans, after all, are living organisms.

The second kind of coincidental observations are those in which causality is inferred from empirical observations of the variables that intervene in the causal link, without holding the rest of the variables constant. The observed relation, therefore, does not respond to the sole cause-effect interaction but to the simultaneous variations of many other variables as well.

It has been shown that having all the variables included will not suffice. Consistency between the models that link the system variables is also necessary. System simulation, as a multidisciplinary activity, sometimes gathers components whose model structures are incompatible. System engineers have avoided these inconsistencies by specifying general formats for the mathematical models to be used. Then all the components are cast under that general format. For instance, one of the formats commonly used is $\dot{X} = AX + BU + CW$, where the X are state vectors, U the input vector, W a pink noise, and A, B, C, constant matrices. Other form is $\dot{X} = f(X,U,W)$. However, the writings about socioeconomic simulation, with the exception of System Dynamic, usually do not present modeling categories that should be used to avoid inconsistencies.

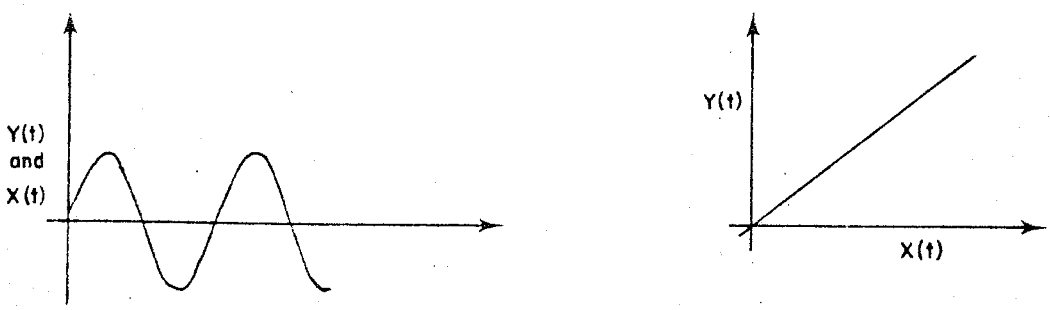
The following example illustrates this point. Suppose that the following model represents adequately the component of the system that is required for study.

$$\frac{d}{dt}\begin{pmatrix} Y \\ X \end{pmatrix} = \frac{1}{\sin B}\begin{pmatrix} \cos B & -1 \\ 1 & -\cos B \end{pmatrix}\begin{bmatrix} Y \\ X \end{bmatrix}$$

with the initial conditions: $Y(0) = \sin B$, $X(0) = 0$

A solution to that system is: $Y(t) = \sin(t + B)$; $X(t) = \sin t$

Suppose that there is an observer who wants to use regression techniques to infer causality between X and Y. That outsider observes essentially the phase portrait of the system, namely, the functional relationship between Y and X. Now, suppose, for instance that $B = 0$. Then the observer will regress observe values of Y(t) and X(t). The time dynamic and the regression are shown in Figure 1.



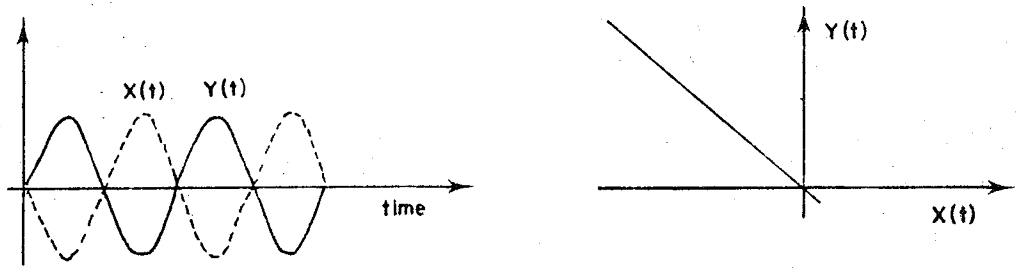
(a) Time dynamics:both X and Y coincide in the sinusoidal wave.

(b) Y as a function of X will appear as a straight line.

Figure 1. Dynamic and Causality in regression (1)

The increase in X will originate increase in Y and vice versa. Therefore, the observed causality between X and Y will be $X \xrightarrow{+} Y$.

On the other hand, if B is, for instance, equal to 3.1416, then the case would be as shown in Figure 2.



(a) Dynamics: Y is disphased from X.

(b) Straight line with negative slope.

Figure 2. Dynamic and Causality in regression (2).

In this case, increases in X will lead to decreases in Y and vice versa; in causal terms, $X \xrightarrow{-} Y$. If B varies, a variety of contradictory causal relations can be drawn. Moreover, the fitting of Y to X does not put the problem in an adequate perspective. It obscures the potencial sources for control such as the values of the parameter B.

Of course it may be claimed that any relationship among two variables is not causal if analyzed within the context of a more elaborate model for which that association is just a particular case, a coincidence. But the modeler should be cautious verifying that all the mathematical components of the model appear under compatible formats. This, of course, does not exclude particular cases of the general format. For instance, linear algebraic equations can be regarded as particular cases of nonlinear differential equations, in which the changes of the dependent variables are zero and the relationship among the variables can be linearly approximated. However, the modeler should verify under what set of assumptions a particular component fits into the general format that has been adopted for the model. Naturally, all the assumptions have to be justified. (For more details see Andersen (1975)).

Summarily, the model builder should:

1) Try not to be driven by conditioning when checking to see that all the relevant variables are included.

2) Be sure of the mathematical consistency of the model components by casting the causal links within the System Dynamic Method.

3) Remember that no statistical hypothesis is true because the experiential evidence does not contradict it.

2. THE CAUSAL DIAGRAM

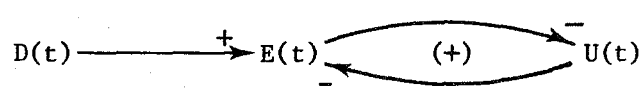
The Causal Loop Diagram (CLD) starts with a digraph composed of a set of simple interactions between causes C, at time t, and the effects E, at time, $t + DT (DT \geqslant 0)$. In mathematical terms: $E(t + DT) = CAUSE\ (C\ (t))$ where CAUSE is a continuous functional relationship. The interaction is positive if the changes in C lead to changes in E in the same direction. It is negative otherwise.

Even though the CLD is described in terms of relationships between changes in the variables, the levels and not the rates will go primarily into the diagram. However, if you want to include rates then your Causal Formulation has to be expressed in standard Dynamo flows Diagram with the signs of the interactions written on it.

The SD literature is full of examples where the causal links have been shown on the Dynamo flowchart. (See for instance Forrester, 1971). However, by departing from the original framework of System Dynamic some researchers have made up obscurities in the methodology. A good example of this is presented by Sharp and Stewart (1980). They pointed out supposed pitfalls in System Dynamic concepts. The System in question can be expressed mathematically as:

$$\frac{dU(t)}{dt} = \frac{(K-1)}{T} * U(t) - \frac{K*D(t)}{T}$$

Where U(t) is some sort of inventory of goods which they called supply. D(t) represents the level of desire for consumption of that particular good. Using Laplace transform and rearranging the variables they have made up a positive Loop, claiming that such a Loop is misleading in the inference of the dynamic properties of the system. Here, no Laplace transform will be used; but, the essence of their argument will be discussed to show where their obscurities arise. Thus let Error be the difference between demand and supply: Error = E(t) = D(t) - U(t). Then the following loop diagram can be drawn:



They argue that according to System Dynamic methodology the system will grow forever; which is not true, because it only grows for values of K greater than one. A claim of SD inconsistency is requested. Naturally this argument has many flaws that can be presented with no difficulty. Nevertheless, our interest is to cast this example, or any other, in a general framework of SD where its "obscurities" will be elucidated. Then the Causal Loop will be:

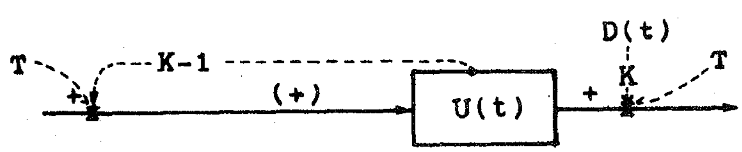


Figure 3. The System Dynamic Positive Loop.

As it can be clearly seen, this loop is positive only for values of K greater than one. It is negative otherwise.

3. THE SYSTEM DYNAMIC CAUSAL INTERACTIONS

This section introduces some simple interactions between the level cause C(t) and the rate effect . Later on, the link depicted previously in the digraph (level-to-level) are related to the simpler level-to-rate links.

3.1 Activation.

The presence of the level C or stimulus, stimulates the effect E or Response. Whenever C is available, E changes positively. If C can take negative values, then those negative values will encourage E to decay. This usually happens when there is a threshold for C. In this case, the stimulating force is the excess of E above the threshold. If C can only be positive then it can only provoke positive increases in E even if C decreases. For instance, the level of rain can only increase the moisture of the soil. If C decreases, E will continue growing as long as C remains positive.

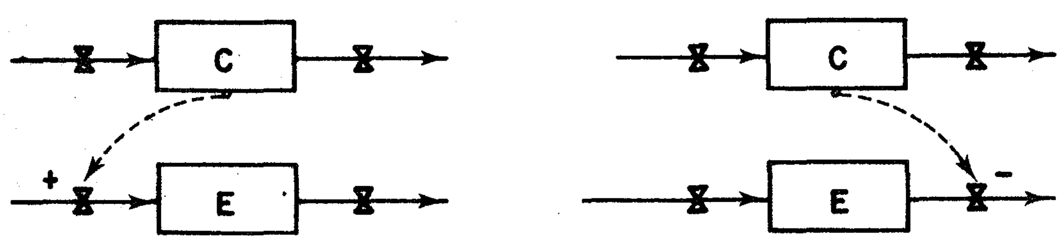


Figure 4. System Dynamic Activation.

3.2 Inhibition.

The presence of C inhibits the response E; therefore, the level C provokes a decrease in the net input rate of E. For instance, the level of pollution inhibits population (World Dynamics, Forrester (1971)).

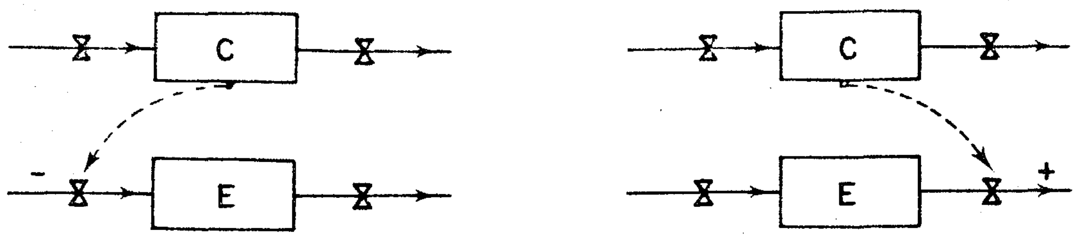


Figure 5. System Dynamic Inhibition.

3.3 <u>Decay and Growth.</u>

Figure 6. Decay and Growth.

Decay is one of the simple structures used many times in the SD literature. But, it usually does not appear in the digraph. The growth, like the population growth is also common but it does not appear in the digraph either.

The causal interactions which are present in the digraph can be broken down into simpler causal structures, such as activatations and inhibitions. For instance, the positive causality can be brokendown as follows:

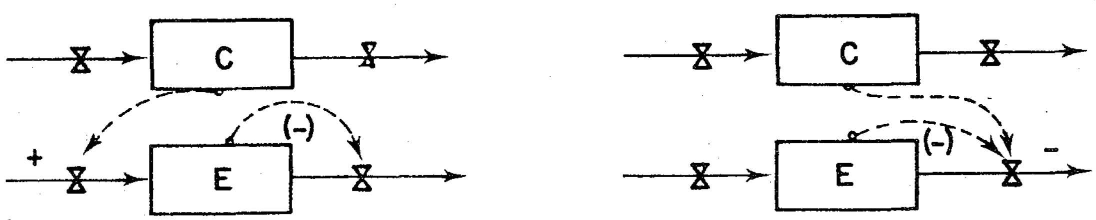


Figure 7. Activation plus Decay.

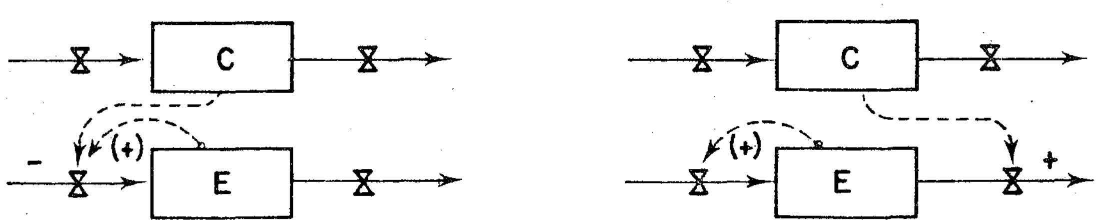


Figure 8. Inhibition plus Growth.

For instance, in Figure 7 can be asserted: $C \xrightarrow{+} E$

If C is diminished then E will go down, if the decay predominates over the activation. But if C is increased the E will be increased too, if the activation predominates over the decay. Of course these effects are overall effects. Tey are only true in a gross way. The Figure 8 shows the brokendown of the negative interaction. **C** $\longrightarrow$ **E**

There are other more elaborated interactions that can be responsible for positive or negative causal relationships. Sometimes, the level **cause** activates the **effect** through some mechanism and at the same time inhibits effect through another mechanism. This is some sort of Dialectic interaction.

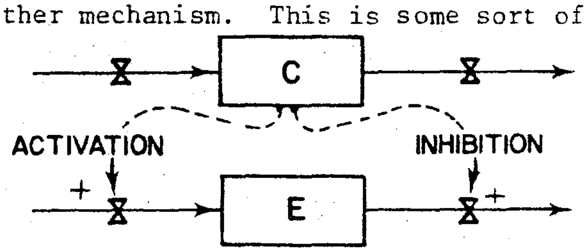


Figure 9. Dialectic Interaction.

If the cause is increasing and activation predominates over inhibition, then the effect rises too. If the cause decreases then the effect also decreases, since inhibition may eventually predominate over activation. Therefore:

An alternative way of writing this mechanism is to establish an equilibrium or normal value for the cause (activation= inhibition) then the stimultus comes from the cause being above the threshold. Inhibition comes from the cause being under the threshold.

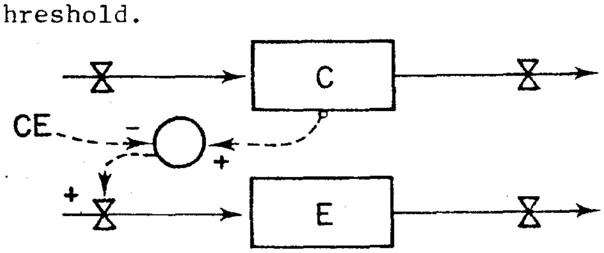


Figure 10. Activation given an equilibrium value CE.

E is stimulated by the excess of C over the equilibrium value, either by a multiplier that depends on the ratio C/CE, or by a factor that depends on the difference, C − CL. This representation is fine as long as there is only one cause. But when several stimuli are present, the equilibrium value may depend on the joined presence of the causes. Therefore the overall equilibrium or normal value moves along with the changes of the causes. This is clear when the influences of the different causes are additive.

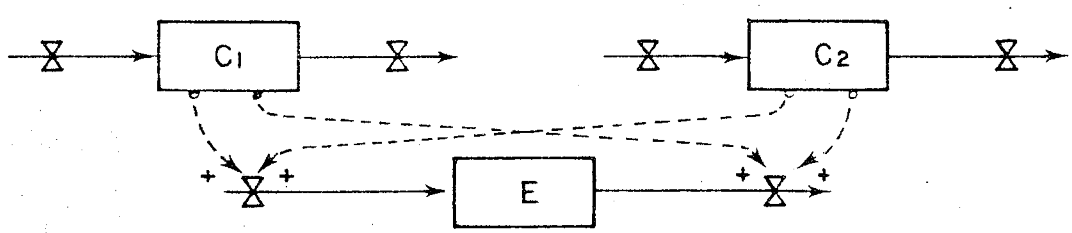


Figure 11. Activation and Inhibition of many causes treated separately.

The threshold of C_1 that stimulates E depends upon C_2. Consequently the mechanism that activates and inhibits should be treated separately. An example of this mechanism is provided by the limits-to-growth interaction.

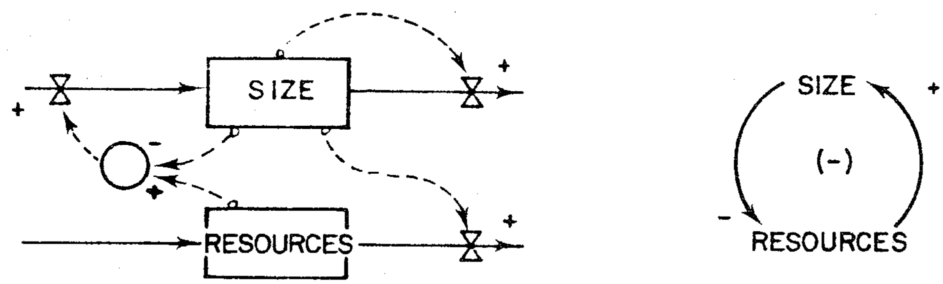


Figure 12. The limits to Growth Causal Interactions.

The size of the system grows at the expense of resource consumption. Therefore, the rate of growth responds to the effects of the abundance of resources above those required by the actual size. The actual size determines the threshold under which no stimulation occurs. Therefore, the system growth depends upon the joined influence of Size and Resources.

4. DYNAMIC PROPERTIES OF THE CAUSAL LOOP DIAGRAM

There are similar or parallel techniques to Causal Loops that are also used for similar purposes. Particularly Interpretative Structural Modeling (ISM) has received considerable attention in literature. ISM constains information which is similar to the information depicted in the Causal Diagram. However, the ISM does not make a clear distinction between direct and indirect relationships. For instance, when a level V_i affects a level V_j, then there is not a reliable way of deciding whether this relationship is direct or indirect by means of other variables already included in the model. In CLD, this kind of error is more difficult to be made. Besides the connectability among variables is evident in CLD, while it requires the elevation of the matrix of coefficents to different powers in ISM. This adds more flexibility to CLD over ISM. There are also more fundamental advantages of CLD over ISM. The first one is that CLD is closer to the Mental Data Base of Human beings where, according to Forrester (1979), most of the information about structures resides. The second one is that when the causal Loops are formulated in terms of levels and rates, then a whole theory of system behavior is incorporated. The System Dynamic Theory.

The strategy adopted for relating dynamic properties to the Causal Loop Diagram, has been the following:

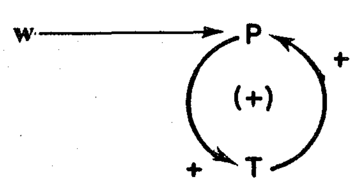
Suppose the system is described by the model $\dot{X} = f(X,U)$ **(1)**

Suppose that a steady state exists X^*, $f(X^*,U) = 0$ and f continuous, where X is the state vector and U are external disturbances. In these systems the rates X, depend on the levels X and the external disturbances U. Naturally, these systems represent the mathematical structure of a System Dynamic Model (Forrester 1961,p66). Now, around X^* the model can be linearized in the form $\dot{X} = A + Bu$ **(2)** ; where $a_{ij} = (\partial f_i / \partial X_j)_{X = X^*}$.

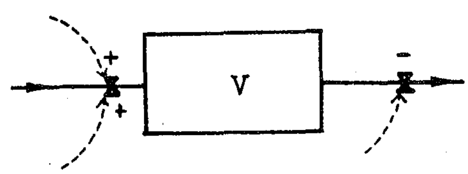
The stability properties of (1) are analogous to (2) if zero is not a real part of an eigenvalue of two. (2) (For the proof see, for instance, Rosen 1970, p.118). The important point to notice is that the sign of the a_{ij} represents the level-to-rate interactions in the CLD and its magnitude the gain which sometimes is available. This strategy is fruitful and provides avenues for further incorporation of principles to guide the synthesis of control structures.

4.1 The Unstable and Stable Causal Diagrams.

The positive Loop, formulated in terms of level to level interactions, is the most common unstable diagram. Therefore, the existence of negative loops will be a necessary condition for stability. Based on the definition of positive loops it can be stated that any disturbance will make the system grows. So, the system will not return to its steady state condition. These ideas will be labelled rule 1. They are shown in figure 13.



a) Positive Loop



b) Unstable Level

Figure 13. Unstable Causal Diagrams, rules 1 and 2.

In terms of level to rate interactions, a level is unstable if its rates are only activated by positive levels (rule 2). Therefore, there will be no way to make the level decrease.

A sufficient condition for stability is provided by a mathematical theorem presented by Othmer (1976, p.316), based on an earlier work by Maybee and Quirk (1969, p.39). This theorem, in the language of causal diagrams, can be stated as: In a Causal Loop Diagram, that shows level-to-rate interactions: there must be at least one negative Loop, no positive second order loops and no third order loops. (in the linearized matrix, $a_{ii} \leq 0$, $a_{ii} < 0$ for some i, $a_{ij}\ a_{ji} \leqslant 0$ for $i \neq j$, $a_{ij}\ a_{jk}\ a_{kl} \ldots a_{pi} = 0$, for $i \neq j \neq k \ldots \neq p$). This will be called rule 3. Unfortunately the violation of the theorem does not guarantee instability.

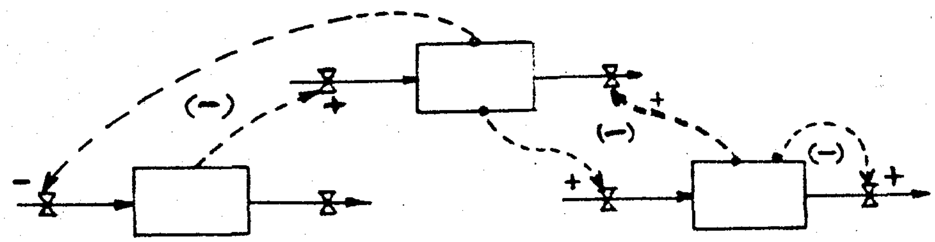


Figure 14. A Sufficiently Stable CLD. Rule 3.

4.2 Oscillatory Causal Loop Diagrams.

The Oscillatory behavior usually comes in packages of two levels. Therefore, the discussion about oscillations will start with a two level system and it will be referred to causal formulations that include level to rate interactions. The oscillation occurs when the cross interactions are of opposite sign ($a_{12} = -a_{21}$). Moreover, the self interactions are of opposite sign or both vanish ($a_{11} + a_{22} = 0$) and the product of the gain of the cross interactions is greater than the product of the gain of the self interaction $|a_{12}|\ |a_{21}| > |a_{11}||a_{22}|$ (Rule 4, figure 15). The first and third conditions are related to the existence of complex eigenvalues in the linearized system. The second one, ($a_{11} + a_{22} = 0$) is related to the Poincare-Bendixon theorem about oscillations.

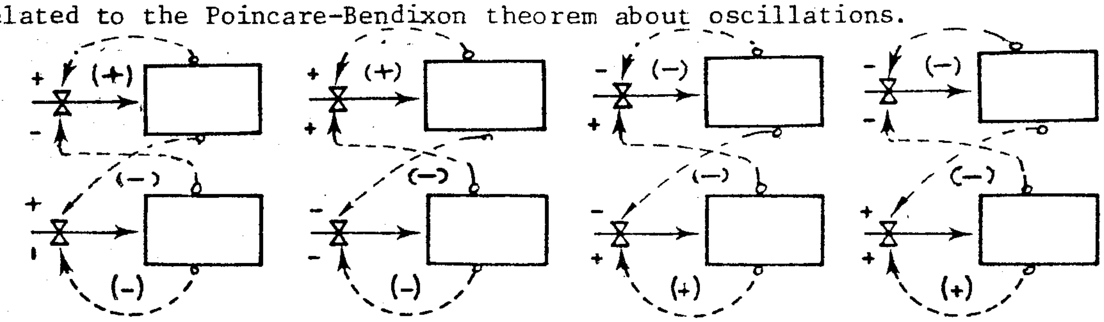


Figure 15. Oscillating two levels structures. Opposite sign in cross interactions (negative Loop). Null or opposite sign self interactions. Cross interactions stronger than self interactions. (Rule 4).

Departures from any of the three conditions established in rule 4 constitute ways for controlling oscillations. In synthesis, there must be a negative Loop between the two levels, and the self interactions of opposite sign favors oscillations. Naturally, 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.

The complex eigenvalues of the linearized system come in pairs, usually related to two levels interacting in the pattern presented in rule 4. However, the repertoire of possible behaviors is considerably increased when more levels are added to the model. Therefore, even though Rule 4 is certainly very useful in n-levels systems, additional guides are needed for structural intervention. Next, some results will be presented which extend the scope of the rules to some multiple level systems. The rule 5 is an adaptation of the results presented by Othmer (1976) and confirmed by Graham (1977, p.97,234,186) and it reads as follow: In a system of several levels and rates, initially in equilibrium, the response to an external disturbance may be smoother if the strength of any of its positive loops is increased. On the other hand, if the strength of a negative loop,with less than 5 levels is increased, then the system will tend to oscillate. If the negative loops contain five or more levels, nothing can be said about their impact on the overall behavior if their gain is increased. (Note that adding a loop is a particular case of increasing its strength, form zero to something).

5. THE DESIGN OF MANAGEMENT INTERVENTION

Given the goals, supplied by the needs of people, management intervention is oriented toward making the system plus control stable (tracking the trajectory determined by the goals). But, this intervention incorporates mostly changes in the structure rather than in the parameters, because SD model are not very sensitive to changes in the parameters. The rules presented in the previous section constitute a basic reference for counterintuitive behavior of the decision makers. The managers observe (directly) the levels, they compare those observations with the desired outputs, and based on the results of that evaluation, take actions upon the controllable rates. These action are guided by a set of principles or policies; policies that often describe structures to be added.

Therefore, in the process of designing a management or control system the sets of variables to be measured, the set of variables to be forecasted and the set of rates to be manipulated must be specified. The concepts of controllability and observability are essential in making such decisions. A level is controllable when it can be driven toward a specified future value in a finite interval DT by the manipulation of some rates connected to it. A level is observable when it is measurable (mapped to an ordered value set).

5.1 Controllability.

A level x is controllable when its value can be changed by the manipulation of some rate. Therefore, there must be a direct or indirect trajectory from a manipulable rate to the input or to the output rate of that level. Besides, those trajectories should convey positive as well as negative influences. The other influences that affect the level x but cannot be manipulated (out of the control management) should be observable. The mathematical details of these principles can be found in Franco (1979,p.91-100).

5.2 Observability.

The issue of observability poses a whole area of interest in System

Dynamic. Not every level in a system is observable directly. To build indirect observations of levels is certainly a problem which deserves further research. For instance, Richmond (1979) presented a brilliant description of the structure of American Government, but the levels that represent the functioning of the government are not necessarily as easily measurable or observable as the accumulation of goods in a factory. Besides, there may be legal, economic or social constraints in many aspects in the observation of some levels (typical in Health Systems, Hirsch, 1977). Indirect measures algebraically related to the levels of the system may be necessary.

When the process of observing does have a significant Dynamics, namely $Y(t+Dt) = f(X(t))$, for instance when the observed variable is dynamically affected by the level then the variable Y has to be forecasted in order to know X(t), then a level X is observable when it can be directly or indirectly measurable or any level dynamically affected by X can be forecasted. Naturally, if a rate is measured or perceived, then the delay involved in this process will make this rate a level. The controllability and observability may be extended to include any number of levels, even all of them. In the latter case, the system is controllable and observable as a whole.

6. QUANTITATIVE PROPERTIES OF THE CAUSAL LOOPS

The interest of this section is to express simulation languages like KSIM, developed by J.Kane (1972), using the DYNAMO Compiler. In my opinion, there is no special advantage in doing this, however, I have found a lot of people interested in these quantitative formulations. Simulating the level-to-level structure has no advantage over System Dynamic, even thougt it is easy to simulate the level-to-level interactions by using SMOOTH functions relating the changes in the correspondig levels. The delay correspond to the inverse of the interactions. Franco (1979) presents examples of this kind of calculations. Of a little more interest is the transformation suggested by J. Kane (1972), to simulate the interactions is the Causal Loop Diagram. When level-to-rates interactions are specified.

Acording to Kane:

$$X(t+Dt) = X(t)^{\frac{1+DT(f^-)}{1+DT(f^+)}} = X(t)^{\frac{1+NX}{1+PX}}$$

Or X.K= CAUSE(X.J, PX.J,NX.J) L

Where: NX = DT*(f^-) negative influences on X

PX = DT*(f^+) positive influences on X

f is a function of the effects of the individual causes.

The most simple expression for f is to assume that it is linear and the individual strengths are unitary. DT is the simulation time interval which may be also set at the value of 1. In this case NX is the sum of the minuses and PX is the sum of the pluses.

In DYNAMO the function CAUSE has three parameters. Therefore, it requires the instruction:

```
FNCTN CAUSE (3)
```

The FORTRAN instructions for the function CAUSE are:

```
FUNCTION  CAUSE(X, A, B)
CAUSE = X**( (1 +B)/(1+ A) )
RETURN
END
```

There is also in implicit assumption in this transformation that the levels are bounded by external effects not included in the model. Franco (1979) presents singular examples of the application of this technique in many socio-economic applications.

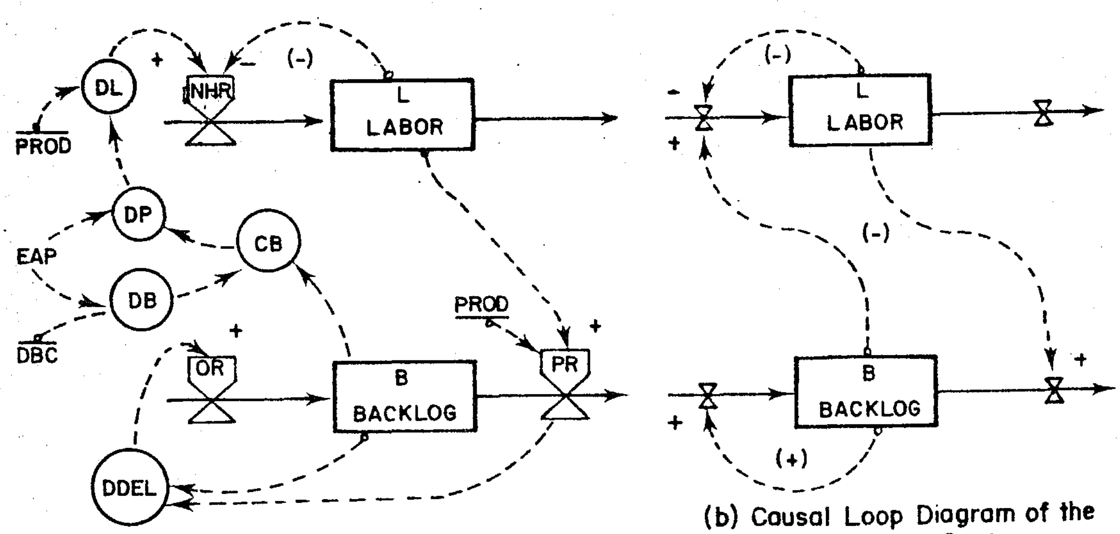
CONCLUSION

Finally, the Causal Loop Diagram, in terms of level-to-rate interaction, is a useful tool for the synthesis of the structure of socioeconomic systems. Moreover, it has many properties other than the ones traditionally attributed to it, some of these properties habe been introduced in this paper.

APPENDIX

Example of the Application of the Rules. The Labor-Backlog System.

A company receives orders for its products which accumulate in an order backlog until the company fills the order by producing the required product. If the order backlog becomes too high, the company hires more people to produce its goods more rapidly and then reduce the backlog. A DYNAMO flow diagram of the system and also a Causal Diagram are presente in Figure 16. As can be seen, the more labor that is hired, the less willing the managers are to hire more people. The more workers, the more production, and, therefore, less backlog, then the more pressure on the managers to hire more people.



(a) Labor Backlog System.
(b) Causal Loop Diagram of the Labor Backlog System.

Figure 16. Labor-Backlog System. DYNAMO and Causal Diagrams.

It is important to emphasize that in this case, oscillations can be undesirable because of the frictions that this behavior can create with the labor unions. In practice, it could be even politically unfeasible to fire people when labor exceeds the required quota according to the order backlog.

In table 1, the full model is presented simulations and results are shown, and a design of policies according to CLD properties is attempted.

Labor is a level variable altered by the net hiring rate (Instructions 10,12 in table 1).

The net hiring rate represents the management policy which corresponds to the adjustment in the labor force. This adjustment or correction is made by the average delay required to hire a person HDEL. (Instructions 14,15 in table 1)

The desired labor DL responds to production plans, as represented by the desired production DP. Thus, the desired labor is simply equal to the desired production divided by the productivity PROD. PROD corresponds to the average number of units produced by one employee in one year. (Instructions 16,17 in table 1).

The desired production is equal to the expected average production plus the correction for backlog. (Instruction 18 in table 1).

The correction for backlog is simply a term which allows adjustment of the desired production to the increases or decreases in the backlog. (Instructions 19,20 in table 1).

The desired backlog DB sets a goal of a constant backlog coverage (the desired backlog coverage DBC) based on the expected level of activity as measured by the expected average production EAP. Thus, if the company is manufacturing 1000 units/year, and the desired backlog coverage equals 0.5 years, the company wants to have $1000 \times 0.5 = 500$ orders for units in the backlog. (Instructions 21,22 in table 1).

The backlog B of orders is a level increased by the incoming order rate OR, and decreased by the company production PR. Note that it is assumed that the goods are shipped immediately and that the backlog B is thus depleted.

Naturally, the backlog is initialized at its desired level, the desired backlog . (Instructions 23,25 table 1).

For the production, a Cobb-Douglas production function will be assumed. But, the purpose of this illustration, labor will be the only factor of production that wil be considered. (Instructions 27,28 table 1).

NL has been estimated at 2080 HRS/YR. PY, the actual hours per year worked, is assumed constant and equal to 2080 hours. The system is stimulated by a step increase of 500 units over the normal or equilibrium value of the ordering rate. (NR) (Instructions 27,35 table 1).

The response of the system to the step increase in the order rate is shown in Figure 18 a.

The delivery delay or lead time depends on the backlog and the production rate. (Instruction 42, table 1).

The more lead time there is, the higher the order rate because the customers perceive a longer delay in the goods they are ordering, and thus try to order more to cover the longer delay. The delays in perception are not considered in the interest of simplicity.

Under these circumstances, Figure 18 a presents the response of this system to a step increase in the order rate. As it can be seen from the Causal Loop Diagram of this model, the cross interactions are of opposite signs and the self interactions too. Therefore, according to the principles presented previously, This system will tend to exhibit sustained oscillations. (Rule 4). This cyclical behavior may be undesirable for the firm. Having to lay off employees when the backlog is small can create frictions with labor unions that could made the firm politically unstable.

Next the Causal Loop Diagram will be used as a tool to design a policy that could made the oscillations disappear. For instance, one alternative for stopping oscillations is to eliminate the opposite sign of the self interactions

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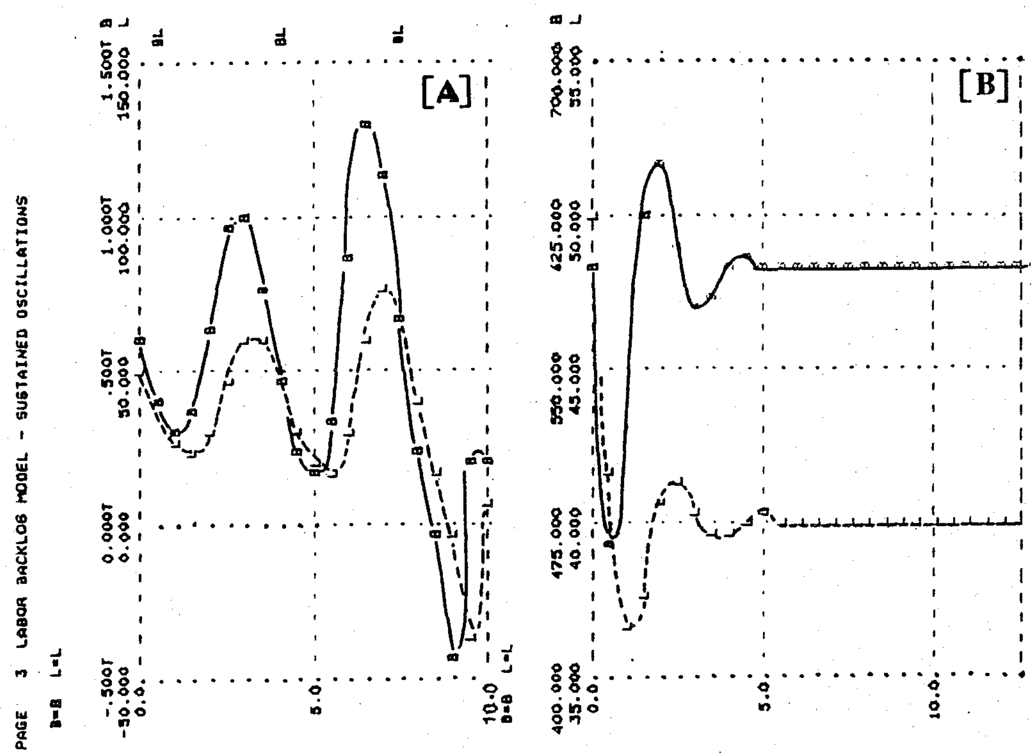
10=* LABOR BACKLOG MODEL - SUSTAINED OSCILLATIONS
11=L L.K.= L.J+(DT)(NHR.JK)                        LABOR LEVEL
12=N L= LN                                         NORMAL VALUE OF LABOR
13=C LN= 50 MEN
14=R NHR.KL=(DL.K-L.K)/HDEL  MEN/YEAR              NET HIRING RATE
15=C HDEL= 0.5 YEARS                               HIRING DELAY
16=A DL.K= DP.K/PROD MEN                           DESIRED LABOR
17=C PROD= 30 UNITS/MEN-YEAR                       PRODUCTIVITY
18=A DP.K= EAP.K+ CB.K                             DESIRED PRODUCTION
19=A CB.K= (B.K-DB.K)/DCB    UNITS/YEAR            BACKLOG CORRECTION
20=C DCB = 0.5 YEARS                               DELAY TO CORRECT BACKLOG
21=A DB.K= (EAP)(DCB) UNITS                        DESIRED BACKLOG
22=C EAP = 1200 UNITS                              EXPECTED AVERAGE PRODUCTION
23=L B.K=B.J+(DT)(OR.JK-PR.JK)                     BACKLOG(UNITS)
24=N B=BN                                          NORMAL BACKLOG
25=C BN=600 UNITS
26=NOTE COBB-DOUGLAS PRODUCTION RATE
27=R PR.KL=(PROD)(L.K)(EXP(A*LOGN(PY.K/NL)))
28=C A=0.8                                         ELASTICITY OF OVERTIME
29=C NL=2080 DAYS/YEAR
30=NOTE ORDER RATE
31=R OR.KL=(DDEL.K/NDEL)(NR+STEP(TI,HGT))
32=C NDEL=0.5 YEARS
33=C NR=1200 UNITS
34=C HGT=300 UNITS
35=C TI=0                                          INITIAL TIME
36=A PY.K=MIN(B.K/BN,1+P)*PYN*ZERO1+ZERO2*PYN
37=C P=0.3                                         OVERTIME FRACTION
38=C PYN=2080 DAYS/YEAR
39=C ZERO1=0                                       INACTIVE OVERTIME
40=C ZERO2=1                                       FIXED WORKING TIME
41=NOTE DELIVERY DELAY OR LEADTIME
42=L DDEL.K=SMOOTH(B.J/PR.JK,PBEL)
43=N DDEL=NDEL
44=C PDEL=0.2 YEARS                                PERCEPTION DELAY
45=SPEC PLTPER=0.5/DT=0.05/LENGTH=20
46=PLOT B=B/L=L
47=RUN 0
```

Table 1. Labor Backlog Model. Sustained Oscillations.



A) Before the change.
(Without over time)

B) After the change.
(With over time)

Figure **18.** Oscillatory Labor Backlog System.

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