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Synthetic Policy Design in System Dynamics Models: Some Observations

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This paper suggest a noval approach to policy design in system dynamics models. The approach is based on optimal control theory to evolve synthetic policy structures and then design realistic policies for the famous production - distribution model of Forrester. New policy sets have been presented for purchase decision rate at retail and distributor sectors and manufacturing decision rate at factory. It is shown that the suggested policy sets show a marked improvement of model behaviour over that obtained by Forrester. The approach suggested here will enhance the art of policy design.

Introduction:

The poineering work of Forrester and Meadows have demonstrated the usefulness of system dynamics as a powerful methodology of a large scale societal system. The application of system dynamics encompasses complex system such as urban and world system (Forrester 1969, 1971). This methodology for modelling the social system has poineered new area of research in social sciences. The greatest assets of this methodology is its qualitative foundation and ease of modelling. The excessive dependence on intution for model understanding and subsequent policy design is its drawback. As compared to other system modelling techniques the policy design phase of system dynamics way of modelling is still non-rigorous. Much efforts needs to be directed towards the development of better policy design procedures. Two major problems surrounds the policy design phase, (1) The complete dependence on the designer's ability to intuitively generate an exhaustive list of policy alternatives, and (2) An excessive reliance for support on the traditional parameters sensitivity test to gain model understanding.

The shortcomings of the senstivity studies and causal loop diagrams has been well established (Coyle 1977, 237; Morecraft 1982, 22; Legasto and Maciariello 1980, 40). Fortunatelly, alternative policy design tools are forthcoming. While some of these tools attempt to get over come shortcomings of the traditional design aids, the others provide entirely new approach to policy design. The use of digraph (McLean and Shephard 1976), eigenvalues analysis approach to locate the dominant feedback loops (Forrester N.B. 1983), building of a senstivity model (Vermeulen and de Jongh 1977), uses of digraph techniques to identify the critical parameters (Starr 1981), eigenvalues analysis for selection of policy parameters (Mohapatra and Sharma 1985) are some of the policy design aids which helps to overcome the traditional way of policy design by trail and error and subsequent improvements , as one gathers more insight of the model.

Many researchers have attempted to use dynamic optimization as policy design tools (Burns and Malone 1974) were possibly first to use optimal control theory where optimization analysis are shown to contribute model utility and policy formulation. (Dercksen and Rademaker 1976) have reported the use of dynamic optimization technique to the world model (Forrester 1971). In these studies the original policy structures have been kept intacked and only the contents defining the rate variable have been optimized. Various problems in applying dynamic optimization techniques like defining the control variables and objective function, selecting the solution methodology and the enormous computational time have been pointed out by these authors. (Keloharju 1977a,1977b),has suggested a noval method in which policy equation are developed by first defining artificial decision parameters which link the policy variables with other model variables, and then finding out the values of these parameters which are optimal with respect to a predetermined objective criterion. This helps in revealing new information sources and the weight to be attached to this in designing new policy.(Mohapatra 1976,1979),has used modal control theory , a branch of control theory to design synthetic policies in multi - stage production inventory system.(Talvage 198Ø), has developed a computer program called MODEMAP which provide great assistance in using modal control theory to policy design in system dynamics model. (Appiah and Coyle 1983),have reported formulation and solution of policy design problems as a model in an adoptive control frame work. (Keloharju and Wolstenwholme 1989) have recently used DYSMOD (Keloharju 1983) to design parameters,table functions and structures for project model of (Richardson 1981).

Review of Optimal Control Theory:

In optimal control problem the objective function is expressed in the form of an integral over a time period, and the evolution of the state variable is governed by a system of first-order differential equation. A linear dynamical system is characterized by

$$\dot{\mathbf{x}} = A\,\mathbf{x}(t) + B\,\mathbf{u}(t) \qquad \ldots (1)$$
$$\mathbf{x}(0) = \mathbf{x}_0$$

where $\mathbf{x}$ is an n-th order state vector and $\mathbf{u}$ is an m-th order control vector. A and B are (n x n) and (m x m) matrices respectively. The quardratic performance criterion is defined as following :

$$J = \int_{t_0}^{t_f} [\mathbf{x}(t)^T Q\,\mathbf{x}(t) + \mathbf{u}(t)^T R\,\mathbf{u}(t)\,dt\,] \qquad \ldots (2)$$

Q,R,and S are real symmetric weighting matrices, and the final time period is considered here as infinity (Shultz and Melsa 1963, Luenberger 1979). In addition, Q and S are assumed to be positive - semidefinite, whereas R is assumed a positive - definite.

It is possible to evaluate the elements of an (m x n) matrix F by solving a matrix - Riccati equation such that

$$\mathbf{u}(t) = -F\mathbf{x}(t) \qquad \ldots (3)$$

which minimizes the quadratic cost criterion defined earlier. The Riccati equation is actually a set kof interconnected differential equations whose terminal conditions are specified and the solution of this equation requires backward integration over time. (Melsa and Jones 1973), give a computer program necessary to carry out this integration.

General Approach to Synthetic Design Procedure:

The paper uses the matrix-Riccati equation to evaluate the closed-loop feedback coefficient of F matrix inorder to synthetically design the control policies in a system dynamics model. On the basis of magnitude and direction (signs) of these coefficients, new realistic policy structurs have been designed. It is shown that new policy structures give results comparable to those given by intutively designed policy set. The synthetically designed policy are ideal in nature and cannot be implemented in the form given by Eqn. (3). A close examination of Eqn.(3) will reveal that the magnitude of f_{ij} indicate the strength of the impact of state variable x_j on the control variable u_i, and the sign of f_{ij} indicate the direction and the strength of the impact. each direction of causation must be supported by observed facts and /or logic ; otherwise, the design procedure and computational are definitely at suspect. If, however, an element f_{kl} = Ø, that particular state variable x_l has no influence on control variable u_k.The presence of a non-zero f_{ij} implies that x_j should be used as information source for design of policy variable u_i . (Sharma 1985), discusses various ways of generating realistic policy structure on the basis of close feedback matrix F. This method of synthesizing policy structure does not assume a priori assumption about the policy structure .

Reduced Production-Distribution Model of Forrester:

The production - distribution model of Forrester which contains six pure level variables, three smoothed level variables and eight third-order exponential delay is available in the celeberated book entitled 'Industrial Dynamics' by Forrester (1961). The original formulated DYNAMO policy equation for purchase decision rate at retail PDR,purchase decision rate at distributer PDD, manufacturing decision rate at factory MDF are given below :

```
R     PDR.KL = RRR.JK + (1/DIR) [ (IDR.K-IAR.K) + (LDR.K -LAR.K)
                      + (UOR.K - UNR.K)]                 ... ... (4)

R     PDD.KL = RRD.JK + (1/DID) [ (IDD.K-IAD.K) + (LDD.K-LAD.K)
                      + (UOD.K-UND.K)]                   ... ... (5)

R     MDF.K  = RRF.JK + (1/DIF) [ (IDF.K-IAF.K) + (LDF.K - LAF.K)
                      + (UOF.K-UNF.K)]                   ... ... (6)
```

where,

PDR,PDD	: purchasing rate decision at retail and distributer sectors,respectively (units/week)
RRR,RRD,RRF	: requisition received at retail, distributer, and factory sectors respectively (units/week)
DIR,DID,DIF	: delay in inventory adjustments at retail, distributer,and factory sectors, respectively (weeks)
IAR,IAD,IAF	: inventory actual at retail, distributer, and factory sectors, respectively (units)
LDR,LDD,LDF	: pipeline orders desired in transit at retail, distributer,and factory sectors, respectively (units)

UOR,UOD,UOF : unfilled orders at retail, distributer, and factory sectors, respectively (units)

MDF : manufacturing decisions at factory sector(units/week)

This model has been restructured and reduced as shown in figure 1. This has been done to obtained two desirable factors, the first is that this modified model should be linear to enable one to use the powerful techniques of linear control theory,the other is that it should be of low order to be able to handle the designed computation with ease. Here the basic structure of the physical flows of orders and material are retained and the information flow structure necessary to define the policy variables PDR,PDD,MDF, have been eliminated. Following simplification have been introduced to restructure and reduce the model (Sharma 1986; Sharma and Mohapatra 1988):

(a)The retail and distributor are stucturally equivalent, hence distributer sector has been eliminated for sake of simplicity.

(b)The purchase decision rate at retail PDR, the manufacturing decision rate at factory MDF,are treated as control variable, Hence there is no needs to have links from auxilarly variables.

(c) Because shipment sent from retail SSR and factory SSF are assumed to depend on order backlogs ,these are treated as outflows of first-order delay.

(d) Some of the cascaded third-order delays are combined and all the delays are assumed to be of first-order.

(e) The variable have been defined as discrepancy from their desired values.

It is easy to write the following vector-matrix differential equation for the reduced model depicted in figure 1.

$$\dot{\mathbf{x}}(t) = A\,\mathbf{x}(t) + B\,\mathbf{u}(t) + \mathbf{C}z(t) \quad \ldots \quad \ldots \quad (7)$$

where,

$$\mathbf{X} = \begin{bmatrix} UOR \\ IAR \\ CPMPR \\ MTR \\ UOF \\ IAF \\ CPF \\ OPF \end{bmatrix}; \quad \mathbf{u} = \begin{bmatrix} PDR \\ MDF \end{bmatrix}; \quad z = \begin{bmatrix} RRR \end{bmatrix}$$

$$A = \begin{bmatrix} -1/DNFR & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset \\ 1/DNRF & \emptyset & \emptyset & 1/DTR & \emptyset & \emptyset & \emptyset & \emptyset \\ \emptyset & \emptyset & -1/DCMR & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset \\ \emptyset & \emptyset & \emptyset & -1/DTR & \emptyset & \emptyset & \emptyset & \emptyset \\ \emptyset & \emptyset & 1/DCMR & \emptyset & -1/DNFF & \emptyset & \emptyset & \emptyset \\ \emptyset & \emptyset & \emptyset & \emptyset & -/DNFF & \emptyset & \emptyset & 1/DPF \\ \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & -1/DCF & \emptyset \\ \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & 1/DCF & -1/DPF \end{bmatrix};$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} ; \quad c = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The various terms used above are defined as under :

CPMPR : clerical in process and mail orders at retail (units)
MTR : material in transit to retail (units)
CPF : clerical in process manufacturing order at factory(units)
OPF : order in production at factory (units)
DNFR : delay normal in filling orders at retail (weeks)
DNFF : delay normal in filling orders at factory (weeks)
DTR : delay in transportion of goods to retail (weeks)
DCMR : delay in processing clerical and mail orders at retail(wk)
DPF : delay in production lead time at factory (weeks)
DCF : delay in clerical processing of orders at factory (weeks)

Eqn.(7) is also acceptable if the variables are defined as discrepancies from their desired values with the exception of exogenous requisition received at retail RRR which has been defined as the discrepancy from its initial value. Thus the stste vector x, the control vector, and exogenous variable z are defined as :

$$x = \begin{bmatrix} UOR - UNR \\ IAR - IDR \\ CPMPR - CPMPDR \\ MTR - MTDR \\ UOF - UNF \\ IAF - IDF \\ CPF - CPDF \\ OPF - OPDF \end{bmatrix} ; \quad u = \begin{bmatrix} PDR - RSR \\ MDF - RSF \end{bmatrix} ; \quad z = \begin{bmatrix} RRR - RRI \end{bmatrix}$$

RRI is initial value of requisition received at retail. Most of the variable have been defined earlier. The new variables in x are the desired values of the level variables. The value of the constants appearing in equation (7) are the following:
DNFR = 1.4 (weeks), DTR = 1.0 (weeks), DMOR = 3.5 (weeks)
DNFF = 2.0 (weeks), DPF = 8.0 (weeks), DCF = 1.0 (weeks)
The main purpose of policy design in the Forrester's production-distribution model is to achieve a stable inventory behaviour at factory sector. The performance index to be minimized for this particular problem can be assumed to be a quadratic function of the states and control as given by Eqn. (2). The optimal control problem is then to designed the control vector u as a feedback of the state vector x for a system whose dynamics is governedby the Eqn. (7) so that the performance index is minimized .

Synthetic Policy Equation:

The weighting matrices Q and R are taken as unit matrices of dimension(8 x 8) and (2 x 2) respectively. Solving the matric-Riccati equation for evaluating the study state feedback gain F (Melsa and Jones 1973) for this case has been obtained as :

$$F = \begin{bmatrix} 0 & 0 & +0.9533 & 0 & +0.8161 & -0.7914 & -0.1124 & 0 \\ 0 & 0 & -0.1124 & 0 & -0.4832 & +0.6112 & +0.9379 & +0.8442 \end{bmatrix} \quad \ldots(8)$$

using the Eqn. (8) the control law (eqn. 3) is obtained as :

$$\begin{aligned} PDR(t) = RSR(t) &- 0.9533 [CPMPR(t) - CPMPDR(t)] \\ &- 0.8161 [UOF(t) - UNF(t)] \\ &+ 0.7914 [IAF(t) - IDF(t)] \end{aligned} \quad \ldots (9)$$

$$\begin{aligned} MDF(t) = RSF(t) &+ 0.4832 [UOF(t) - UNF(t)] \\ &- 0.6112 [IAF(t) - IDF(t)] \\ &- 0.9379 [CPF(t) - CPDF(t)] \\ &- 0.8442 [OPF(t) - OPDF(t)] \end{aligned} \quad \ldots (10)$$

These are the ideal policy equations.
In Eqn. (9) the negative dependence of PDR on clerical-in-process and purchase order in mail delay at retail CPMPR and unfilled order backlog at next higher sector (i.e. factory sector in the present two sector model) UOF, have been considered by Forrester, who treats them as pipelines order and inventories. The positive dependence of PDR on the inventory and the pipeline inventory at the factory sector are new facet of this ideal policy. This implies that retail should take advantage of comfortable inventory position at the higher sector by placing more orders and conversely should refrain from placing high orders at the time of low inventory. However, at a first-glance,one will be surprise to notice the absence of the retail inventory and backlog terms in influencing PDR, since any practitioner will use these terms to decide his replenishment order rates . In fact, Forrester has also considered these terms while designing PDR.
Eqn. (10) indicates the influence of some of the level variables on the MDF. Most of the level variables present were introduced by the Forrester. The only other level variables which qalifies to be present in Eqn. (10) is CPMPR. The corresponding entry in the matrix F is -0.1124.So the coefficient of CPMPR, when used and included in eqn.(10) will be +0.1124.Though the positive sign is quite justified from causal consideration, the weightage is considered very small, and the term has not been included.

Design of Realistic Policy Decision:

Sharma (1985), has discussed the problems and method to overcome them while designing the realistic policies from the synthetic policies. In designing the realistic policies in the light of Eqn. (9) and (10) four considerations are made:

(i) It is recalled that the original Forrester's model has a distributer sector which was identical to the retail sector and was neglected while reducing the model (Fig. 1). This sector has to be included now while designing the testing realistic policies.

(ii) The ideal policies often need modifications to make it meaningful to practioner. Thus the inventory and backlog terms must be included while designing the realistic purchase decision policies.

(iii) The influence of many of the terms which appears in the ideal policies but do not appear in the Forrester's original policies, will be represented as multipliers defined through table functions or defined as discrepencies from their desired values.

(iv) The terms having small coefficient values compared to the highest term in each row of the F-matrix are neglected as they indicate less dominant influences.

Policy Set-I:

Considering the above argument, the policy equation for three sectors are given by

```
R       PDR.KL = [ RSR.K + (1/DIR) ( (IDR.K - IAR.K)
                        + (LDR.K - LAR.K) + (UOR.K - UNR.K) ) ]
                        + (PRMUOD.K)* (PRMID.K)              ... (11)

A         PRMUOD.K = TABHL(TPRMUOD,RUOUND.K,Ø,2,Ø.5)
T         TPRMUOD  = 1.Ø/1.Ø/1.Ø/Ø.85/Ø.5
A         RUOUND.K = UOD.K/UND.K
A         PRMID.K  = TABHL (TRRMID,RIADD.K,Ø,2,Ø.5)
T         TPRMID   = Ø.5/Ø.75/1.Ø/1.Ø/1.Ø
A         RIADD.K  = IAD.K/IDD.K
```

PRMUOD : purchase decision rate multiplier at retail from unfilled order backlog at distributer (dimensionless)

PRMID : purchase decision rate multiplier from inventory at distributer (dimensionless)

It may be noted here that in Eqn. (9), there is no need to seperately consider multiplier from CPMPR as it is already included in the original equation of PDR (Eqn. 4). The above multipliers are shown in figures 2 and 3. as table functions whose slopes are approximately equal to coefficient associated with the variable they represent in Eqn.(9).The purchase decision rate at distributor is similarly defined as:

```
R       PDD.KL = [ RSD.K + (1/DID) ( ( IDD.K - IAD.K)
                       + (LDD.K - LAD.K) + (UOD.K - UND.K) ) ]
                       * (PDMUOF.K) * (PDMIF.K)              ... (12)

A         PDMUOF.K = TABHL (TPDMUOF,RUOUNF.K,Ø,2,Ø.5)
T         TPDMUOF  = 1.Ø/1.Ø/1.Ø/Ø.85/Ø.5
A         RUOUNF.K = UOF.K/UNF.K
A         PDMIF.K  = TABHL ( TPDMIF,RIADF.K,Ø,2,Ø.5)
T         TPDMIF   = Ø.5/Ø.85/1.Ø/1.Ø/1.Ø
A         RIADF    = IAF.K/IDF.K.
```

where, PDMUOF and PDMIF are the multipliers and are shown as table functions in the figures 4 and 5.It can be noticed that eqn. 11 and 12 retains the original equations with new information sources acting as multipliers.

The MDF is modelled by retaining the original equation (6) and modifying the time constants of this equation in the light of Eqn. (1Ø),

```
R         MDF.KL  = RRF.K + (IDF.K - IAF.K) /DIAF
                        + (LDF.K - LAF.K)/DLAF
                        + (UOF.K - UNF.K)/DUOF               ... (13)
```

The values of above mentioned parameters are taken as DIAF = 1.75 (weeks),DLAF=1.Ø (week), DUOF = 2.Ø (weeks).

Policy Set -II :

Further refinement in the policy set I is possible by modelling the new information sources as discrepancies from their desired values. The new policy equation for PDR is written as :

```
R       PDR.KL = [ RSR.K + (1/DIR) ( (IDR.K - IAR.K)
                   + (UOR.K-UNR.K) ) + (LDR.K - LAR.K)/DLAR
                   + (UND.K - UOD.K)/DUOR
                   + (IAD.K - IDD.K)/DIAR          ...  (14)
```

The values of the parameters DLAR,DUOR,DIAR have been chosen as 1.Ø, 1.Ø, and 1.5 weeks respectively. Eqn. (14) has the usual terms and parameter values except the parameter value of DLAR, the associated coefficient for this variable from Eqn. (9) is - Ø.9533.This implies that the values of DLAR should be selected as 1/Ø.9533 which is approximately equal to one week instead of 4 weeks in the original Eqn. (4). Apart from this it also models the two new information sources namely the order backlog at distributor and inventory actual at distributor as additional features of policy equation. Similarly the equation for PDD is expressed as :

```
R       PDD.KL = [ RSD.K + (1/DID) ( (IDD.K - IAD.K) +
                   + (UOD.K - UND.K) )+(UOD.K - UND.K))
                   + (LDD.K - LAD.K)/DLAD
                   + (UNF.K - UOF.K)/DUOD
                   + (IAF.K - IDF.K)/DIAD ]        ...(15)
```

The values of DLAD, DUOD, and DIAD are 1.Ø,1.Ø, and 1.5 weeks respectively.

Experiments :

The original production-distribution model was simulated with the suggested policy sets. These results are then compared with the behaviour of the model with original policies. The exogenous input RRR is subjected to a 1Ø% increase over the steady state value of 1ØØØ units per week in the fourth week. The variations of SRF,IAF, are shown in figures 6 and 7. It is evident from the figure 6 that the requisition received at different sectors are growing progressively but have far less pronounced peaks as compared to those obtained by Forrester. The policy set II gives better results than policy set I.The peak values for factory output SRF for policy set I and II are 27% at 21st week and 15% at 12th week as compared 45% at 21st week in the original policy set. As with the ordering policy and production rates the inventory fluctuations are also greatly attenuated as shown in Fig.8 . The inventory at factory sector for policy set I has a peak of 19% at 53rd week and for policy set II a peak of 16.5% in 17Øth week above the initial value without any overshoot as compared to 32% at 32nd weein the original policy set. From figures 8 and 9, similar observation can be made for SRF and inventory at factory for periodic variation in retail sales which rise and fall gradually over a one year interval.

Fig. 1Ø and 11 shows the comparision of SRF and IAF for suggested policy sets with initial policy set respectively, for random fluctuations in retail sales.

Conclusions:
This paper presents the usefulness of optimal control theory to assists in the policy design phase in system dynamics modelling. The time behaviour obtained with various policy sets have given improved results. The time behaviour of inventory at three sectors in general is slugish but free from fluctuations. In this study of production-distribution system Forrester has identified the delays in the inventory adjustments as the most critical parameters and for larger values of delays the system shows improvement. It is observed clearly that the proposed policies yield more atteniuted response with low values of inventory adjustment delays. However, it is very difficult to say which policy give better result when overall results for three sectors are taken. The fact that most of the causal loops developed synthetically were considered by Forrester points out to the robustness of Forrester's policy.
The proposed policy sets, however, suffer from the difficulty that it is possible to implement these policies whend complete intersector information is available. Also the dapproach lined out is restricted to linear quadratic problem and at present suited for problems of low order. The paper demonstrates the use of optimal control theory and stresses on the Inter-disiplenary transfer of ideas to enrich the paradigm of system dynamics.

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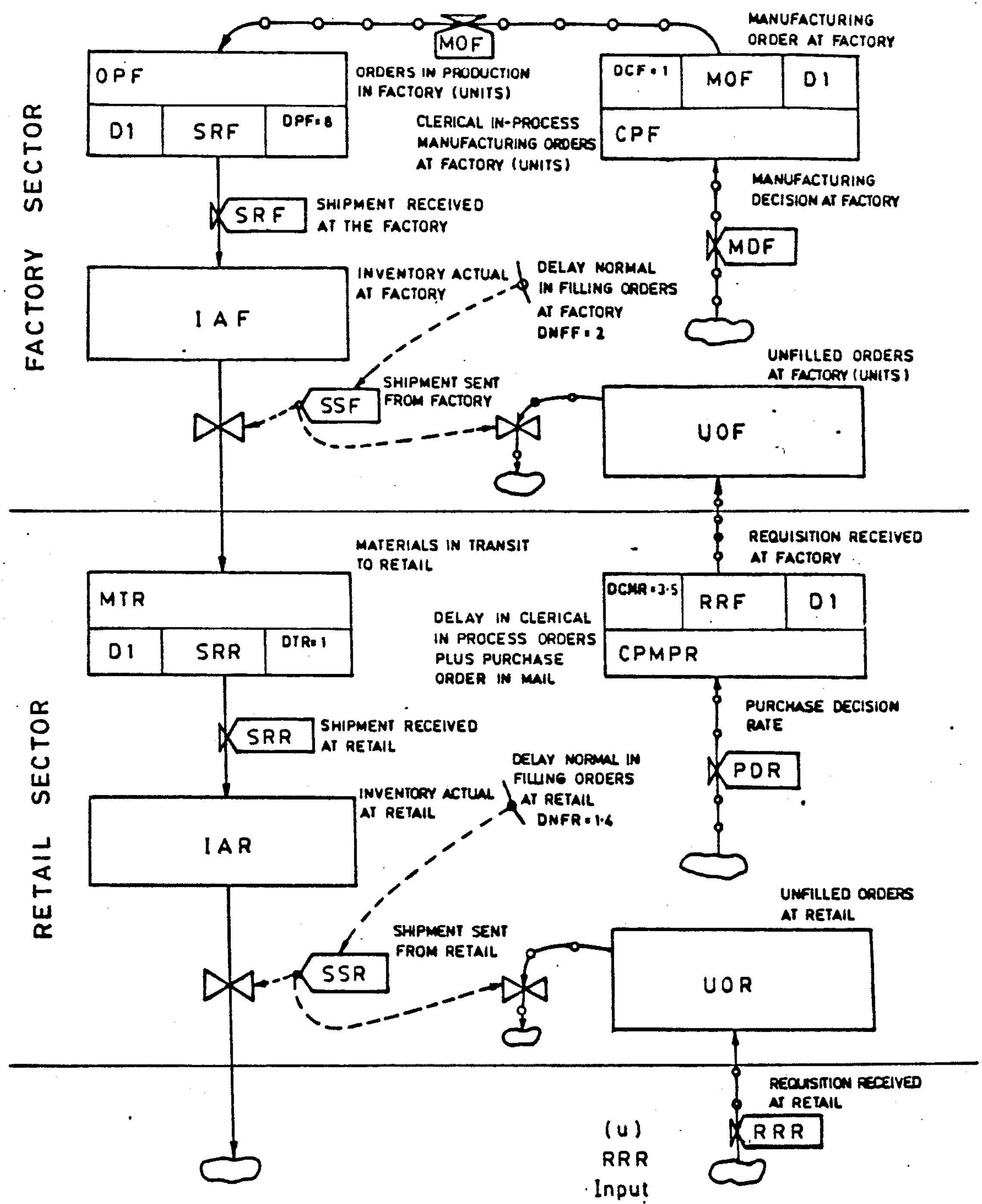

Fig.1: The reduced production distribution model

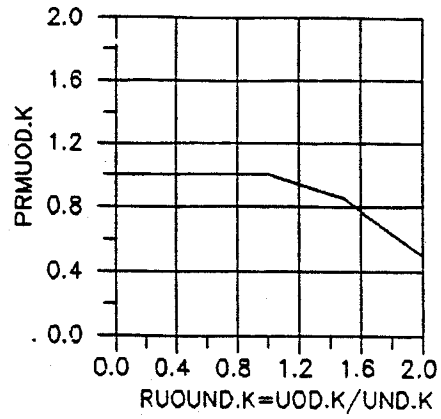

Fig. 2
Purchase decision rate multiplier from order backlog at distributor

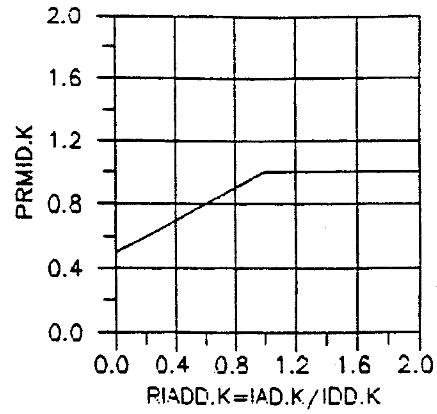

Fig.3
Purchase decision rate multiplier from inventory at distributer

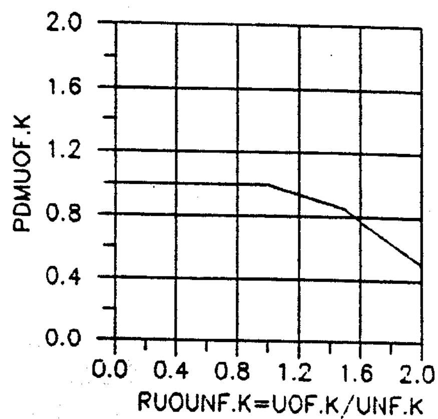

Fig.4
Purchase decision rate multiplier from order backlog at factory

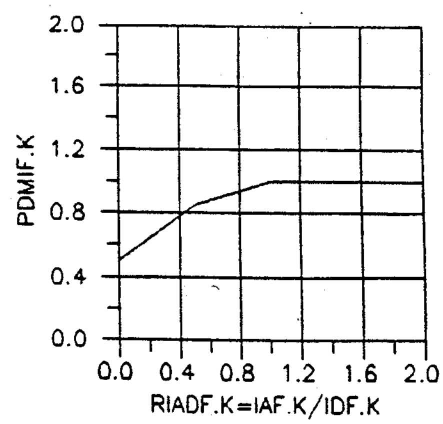

Fig. 5
Purchase decision rate multiplier from inventory at factory

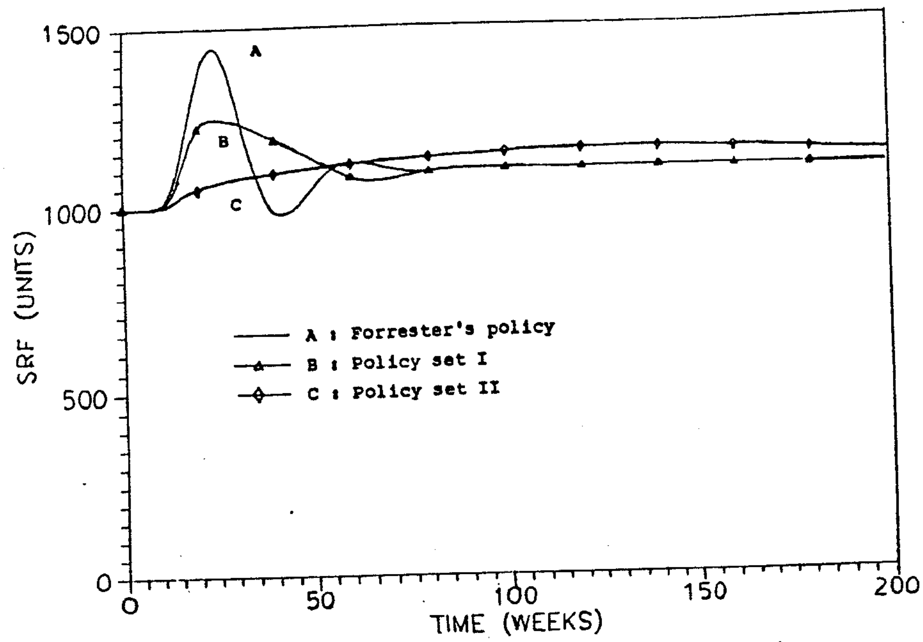

Fig. 6: comparision of shipment received at factories SRF for varicus policies for step input.

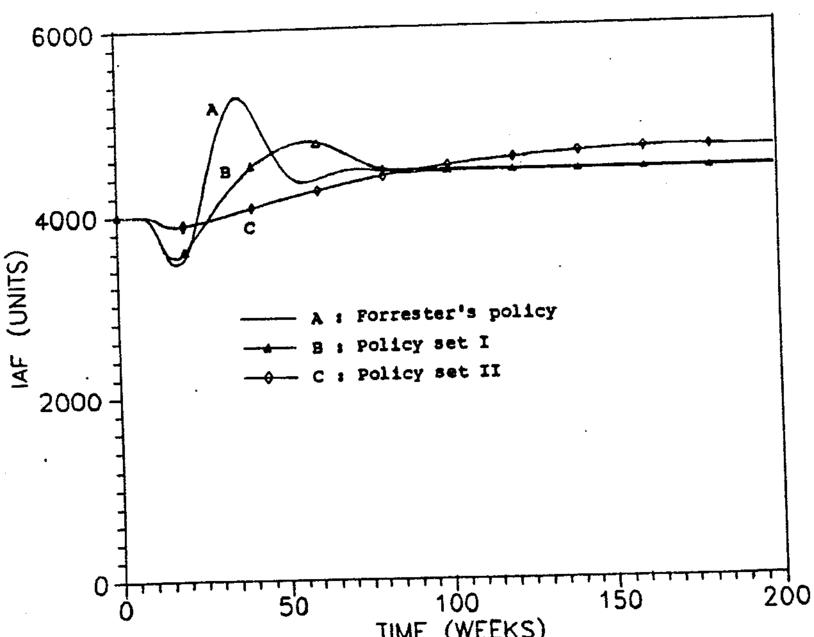

Fig. 7: comparision of inventories at factory IAF for various policies with step input.

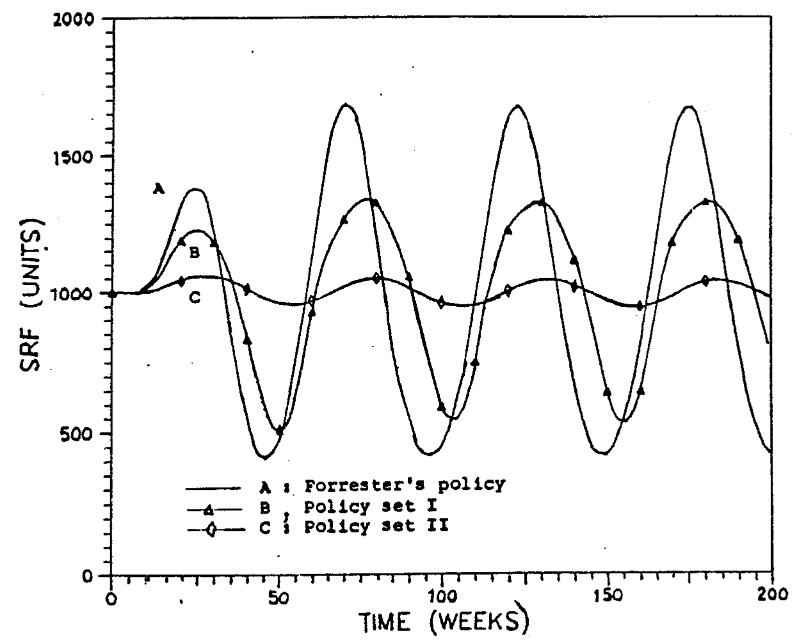

Fig. 8: Comparision of Shipment received at factories SRF for various policies for sinusoidal input.

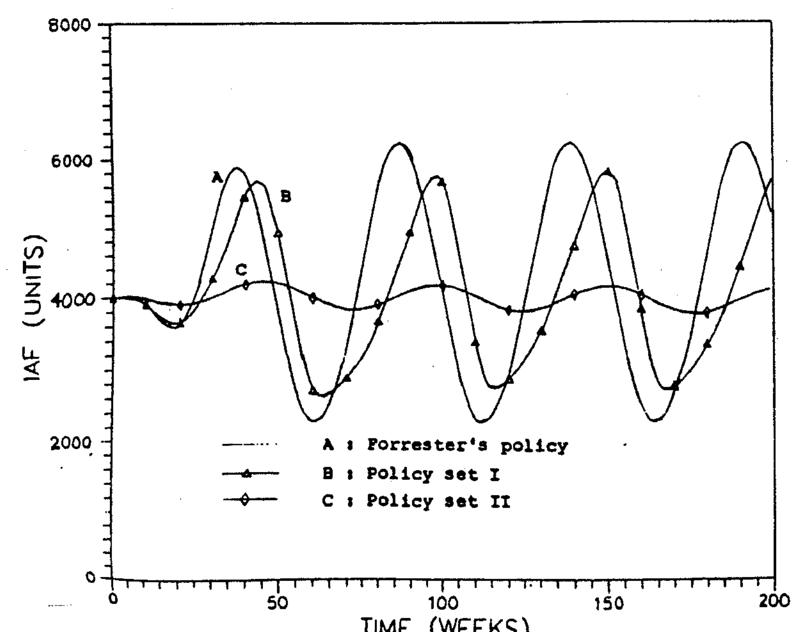

Fig. 9: Comparision of inventories at factory IFA for various policies with sinusoidal input.

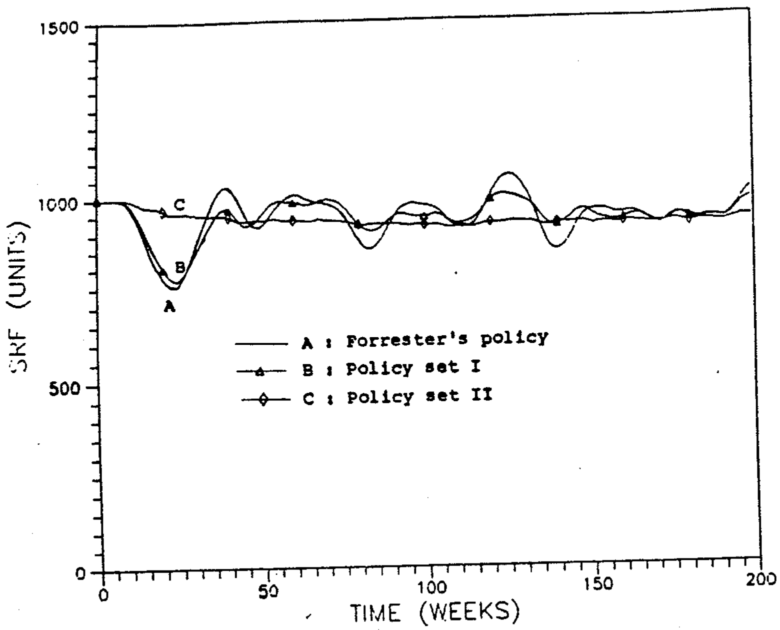

Fig.10 Comparision of Shipment received at factories SRF for various policies for random fluctuation.

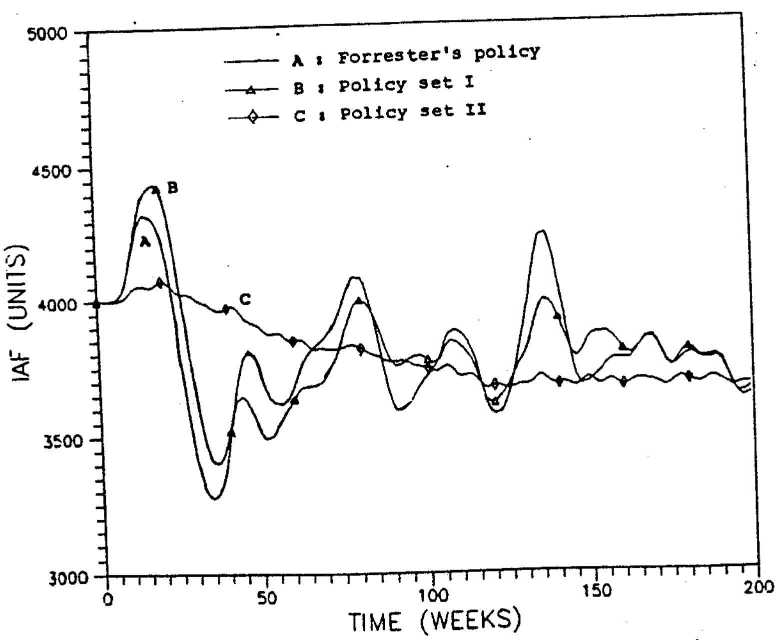

Fig.11: Comparision of inventories at factory IAF for various policies with random fluctuation.