SYSTEM DYNAMICS

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ABSTRACT [2]
In a companion paper published in the Simulation 77 Proceedings (Lebel 1977a), we hope to have provided the reader with an elementary background in System Dynamics.

In this paper we would like to try to put a new light on

the "raison d'être" of System Dynamics

its underlying basic assumptions

the question of uncertainty

the problem of validity

"RAISON D'ETRE" of SYSTEM DYNAMICS
Recently Professor J. W. Forrester at the banquet address of the M.I.T. seminar on Macro-Engineering (June 1980) introduced System Dynamics by remarking that an ancient Greek returning to earth would see fantastic technological changes:

Man on the moon,

Routine contacts of people thousands of miles away in less than a minute,

Flights across the Mediterranean sea in less than one or two hours.

But, alas, the same ancient Greek would notice almost no difference with respect to his knowledge in:

Forecasting economic growth,

Educating children,

Controlling inflation,

Predicting the weather,

Maintaining world peace.

I would add that Engineers have made possible those near miracles because they have been trained to deal with hardware. When they created the digital computer, they had to invent software, i.e. the rules of the game of information processing (G. S. Brown 1973).

To bring technology from concepts to the service of society one must obey the "software" of

the corporation,

the banking system,

the government,

the trade unions,

even the churches.

It is relatively easy to visit the moon because the central "software" is trivial. But it is very difficult to repair our cities because the "societal software" is vastly complex. "Societal software" is a set of:

doctrines,

codes,

procedures,

rules,

which makes up the culture of society.

Hence Engineers-Managers must be trained differently today than fifty years ago (Lebel 1980).

The gap between science and society, scientists and social-leaders has become unwisely and unproductively large because:

scientists (usually) have not considered complex society problem areas their prime responsibility,

the social imperative of these problem areas has militated against their selective, objective, systematic investigation,

the training of scientists has tended to discourage them when conflicting purposes of social values are directly apparent.

Engineers and social leaders need to speak a common language (Lebel 1977a).

Bridging the gap requires more work, more productive work on the study of complex systems. Complex systems may be viewed as the interface of science and society (M. B. Wilk 1973).

System Dynamics aims at bridging the gap by providing:

$$\left.\begin{array}{l}\text{an analysis of}\\ \text{a synthesis of}\\ \text{a language for}\end{array}\right\}\ \text{complex systems}$$

BASIC ASSUMPTIONS AND ORIGINALITY OF SYSTEM DYNAMICS
System Dynamics analyses a system in terms of state (level) and rate (flux) variables. A level represents at every instant the interaction of the fluxes having entered and left in the past that level.

System Dynamics, probably more than any other techniques, emphasizes the concept of feedback.

So, inherent to System Dynamics are

DYNAMIC since changes take time,

FEEDBACK since states determine changes of states which produce new states and so on. . . .

Dynamic without feedback is not system dynamics.

Feedback without dynamic is hardly system dynamics.

Because of the importance of feedback the behaviour of a system analysed using System Dynamics will mostly depend upon its internal structure. Exogeneous variables are defined as those upon which the system does not feedback.

In System Dynamics the structure of a model is more important than the exact values of parameters and functions. That point alone has been sufficient to discourage some scientific people from using System Dynamics (Rechenmann 1979). That also allows to use uncertain datae whose role in the overall behaviour of the system cannot be neglected. Sensitivity tests of the resulting uncertain parameters are necessary. Validation of the model will be made by its ability to reproduce behaviours known from past experience with the system.

Attempts to use fuzzy set theory together with System Dynamics (Adamo 1977) did not yield significant improvements. Also a test to probabilize the information delays in the Urban Model did not show much difference (Bourdon 1973).

System Dynamics appears as a unique tool for analysing data deficient social systems (Schroeder 1972). Data may be simply unexistant: there will never be records of the perceived value of promotion. Promotion can be measured, not its perception; but it is the perception of promotion which motivates people. One will not be able to validate perception of promotion, but only the overall behaviour of the model including it.

Due to the deep analysis required by System Dynamics, the model so built is ready at the time of synthesis (simulation) to be taken again partially apart to investigate the role of such and such sectors to generate various modes.

Clearly System Dynamics Models play a cognitive role.

UNCERTAINTY:

Uncertainty is one of the most profound and fascinating concepts in the affairs of men. Someone wrote a book whose humoristic title was "How to gamble *if you must*". But we all must gamble every day:

elections of national leaders,

technology decisions,

selection of economic policies,

choosing employment or employees.

With M. B. Wilk (1973) we distinguish four forms of uncertainty:

IGNORANCE: things we do not know but could in principle find out. Science is well adapted to testing and social sharing of knowledge: its motivation comes from both the prestige of prior publication and the stigma of published errors. System Dynamics is a cognitive process by the analysis required as the first step of its implementation

RANDOMNESS: things we do not know with exactitude until they happen (the outcome of a dice throw). Randomness is handled scientifically by defining and studying the invariants of classes of events or things. Aggregation of random events permits to define properties. Whereas the velocities of gas molecules are random, the temperature of that gas falls in the category of ignorance. System Dynamics does not deal with random events but rather aggregates of them:

Population groups rather than individuals

Trends instead of events.

SEMANTIC CONFUSION: when the words or symbols seem to make sense but no mechanism exists for determining what would constitute an answer. For instance:

Where does God live?

We shall become young again if we live long enough (from a science fiction novel).

Semantic confusion is pervasive in many system analysis of complex systems. Phrases and forms used in law were developed, in part, to minimize uncertainty due to semantic confusion. System Dynamics is helpful in reducing semantic confusion by:

defining terms accurately,

avoiding hollow questions,

substituting diagrams to verbal descriptions.

INDETERMINISM: things we cannot know (the velocity of a particle if we know its position). Before saying more about indeterminism we would like to quote from M. B. Wilk (1973) a familiar anecdote:

"A bright young statistician was hired by a firm, and shortly thereafter was asked by the President of the firm to forecast sales for the month of January. The young man went off, worked diligently in applying the best principles and methods of his training, and in due course he developed his results. In his presentation to the President, with due emphasis, of course, on errors of estimates and confidence limits, he forecast a decided decline in sales next January. After hearing this, the President called in his Sales Manager. "George," he said, "the sales forecast for January is very low, so you better get on the ball." Thereupon, George, the Sales Manager, mobilized his forces and mounted a big sales effort. Sure enough, when January sales figures came in, they showed an increase rather than the drop which had been forecasted. Though pleased with the sales results, the President was indignant with the gross error made by his young statistician. So he called him in and curtly demanded an explanation. "Well, you see Sir," the young man said, "I forecast a decline in sales and, because I did, the Sales Department mounted a special effort, as a result of which sales increased. Now, if instead I had not forecast a drop, then the Sales People would not have worked so hard and then sales would have declined." "Yes," said the President, shaking his head in bewildered frustration, "and you'd have been wrong again!"

Semantic confusion is responsible, in that anecdote for the failure of communication across the employment gap. The company *ignored* its future sales and used statistics because of *randomness* of events.

The interaction of the analysis with consequent events is a

form of *indeterminism.* By its own nature indeterminism will always remain. A very small change somewhere may drive the system one way or another. When a prediction is made it has an undetermined effect on what is predicted. Indeterminism cannot be suppressed by any method. It will always remain. It might be interesting to try to recognize other forms of indeterminism in socio-economic complex systems.

Indeterminism is not randomness. Aggregation (as in System Dynamics or otherwise) does not do any good to reduce indeterminism.

System Dynamics is NOT a predictive tool. Its purpose is to find out an answer to the question "WHAT would happen to such and such complex system IF such and such conditions were changed".

System Dynamics is deterministic. But randomness can be included in the simulation. Furthermore:

the simulated complex system can exchange matter and energy with the outside world.

feedback loops are inherent to the structure.

The work of the group of Professor I. Prigogine (P. M. Allen 1979) has shown that this is enough to allow for SELF-ORGANISATION. Fluctuations play the role of "organiser".

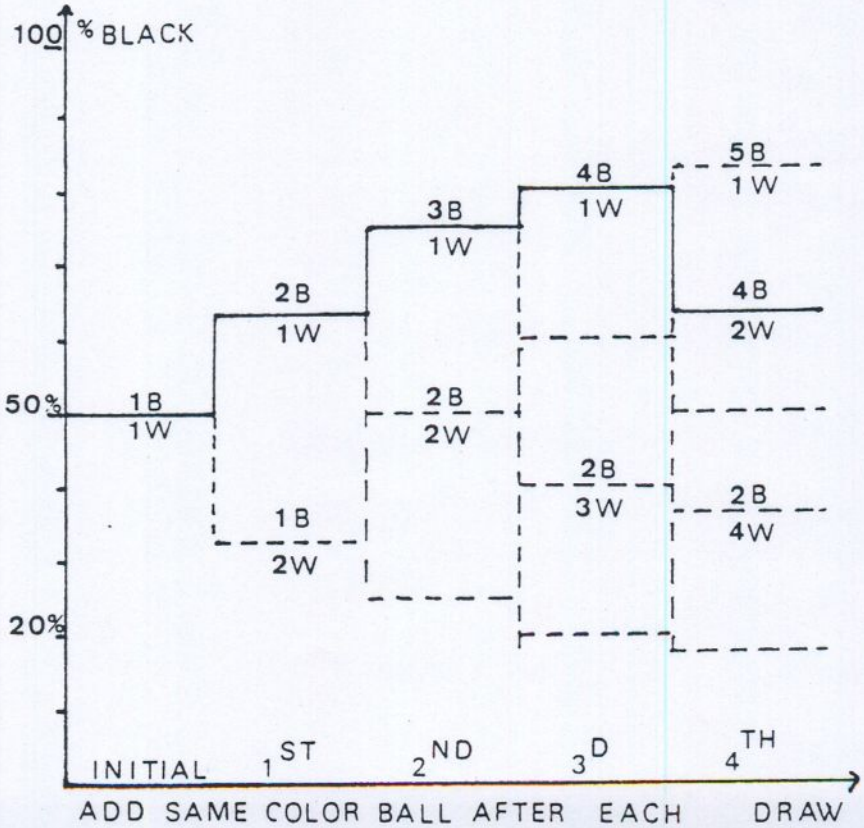
As an example we will mention an experiment with a box which contains black and white balls. Each time a ball is drawn out of the box, it is put back in the box together with an added ball of the same color. Then one will observe that the percentage of, say, black balls will remain constant in that box. Maybe at 63% for instance. One might conclude that something is "organizing" the percentage of black balls to be 63%.

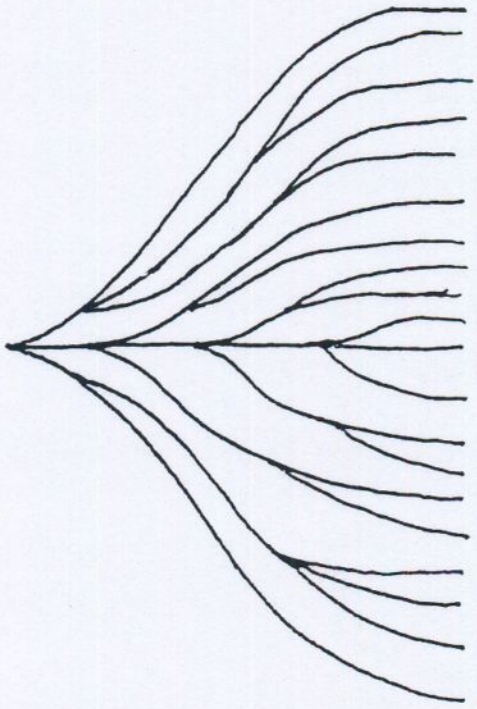
But another box will reveal another percentage. As a matter of fact I have been told that the density of probabilities to find any percentage after enough trials in various boxes is uniform on the interval 0 to 100% (but it is fixed for a given box).

Large scale complex systems may exhibit bifurcation points around which the system will follow one path or the other depending upon small random variations of a parameter (G. Nicolis 1977). Between the bifurcation points the system will restore to a more conventional behaviour.[1]

Those discoveries by I. Prigogine group strongly evoke J. Forrester (1969) statements about usual insensitivity to parameter changes together with the fact that "complex systems have high sensitivity to changes in a few parameters and to some changes in structure". And he adds "Thus the converse of parameter insensitivity is true too". We would like to risk to jokingly say that determinism plus chance equals indeterminism.

Behaviour of that type is not uncommon in System Dynamic models: for instance[2] the Urban Model will not grow if the Tax assessment is reduced to 10$/year/1000$ of assessed value. The value used in the model is 50$/y/1000$. For some value between 10 and 50 a small change in that parameter (TAN) will completely change the behaviour of the system. The size of the needed change in TAN will depend upon the state of the system at the time of the change, in line with the non linear properties of reality and model building using System Dynamics.





BIFURCATIONS

System Dynamics is time reversible. If dt becomes –dt the system will revert to its initial conditions from its final conditions. Maybe to demonstrate their bad faith, detractors of the World Model once said that they had run the model backward and that they had found a twenty feet layer of street manure in 1800.

What they really demonstrated is their ignorance . . . of aggregation (street manure would be in the aggregate of pollution).

Newtonian mechanic also is time reversible. It is interesting to remark with Prigogine (1979) that Newtonian mechanic was unchallenged until the 19th century when thermodynamics appeared. System Dynamics is a Newtonian description of systems; if one thinks that irreversibility has a fundamental role to play in socio-economic processes (to prevent organisation maybe) then it will have to try to prove it and invent another methodology.

The NON-LINEARITY of complex systems is what makes their behaviour very sensitive to a few parameter changes while the FEEDBACK renders them unsensitive to most. Those non linearities are inherent to simulations of complex systems using System Dynamics.

Parameter sensitivity analysis must be carefully made:

to discover the points where actions could be useful

to validate the model

VALIDATION

In 1969 J. Rueff looked upon an essay he had written in 1922 while he was a student at Ecole Polytechnique of Paris (Rueff 1969). The purpose of the essay was to attempt (in 1922) to extend the methods of physical sciences to what was then called "sciences morales" (socio-economy?). His conclusions in 1969 were that if for the physical theories the keystone is experiment, for the socio-economic models the keystone is datae. But for both the criterium of validity is purposedness.

System Dynamics validates socio-economic complex models:

on historical datae. One would find examples of that in the work of Schroder 1974b, or Alexandre (1975).

on past experience (see for instance Champigneux (1977).

on series of industrial datae (see almost any reference on Industrial Dynamics).

In a work done for A.F.C.E.T. (Lebel et al 1975b) the methodology used to elaborate a System Dynamics model is described by a diagram. The role played by the key variables versus the role of the structure is explicited. Validation often calls for disaggregation (see for instance Schroeder op. cit.).

To give CONFIDENCE the client must be assured that the model is adequate, regardless of whether its criteria include eye-balling historical comparison, R2 calculation or even spectral density function (Roberts 1978).

But one should always remember that USEFULNESS of a model is its PURPOSE. There lies the true validation.

Limits to Growth (Meadows 1972) undoubtedly cast doubts in people's minds about the validation of System Dynamics studies. Owing to its unusually large distribution (it was translated in more than twenty languages) and the literally hundreds, maybe thousands, of press articles referring to it, its impact was rather formidable.

But World Dynamics (Forrester 1971) published a year before, was made on request of the Club of Rome only to prove that a methodology existed to study the predicaments of the human race. Forrester told me that he had accepted to do it provided a few members of the Club would agree to come to M.I.T. to examine the behaviour of a preliminary model. They came. After the usual necessary improvements they valided the model for the purpose for which it was conceived, I repeat: To prove that a methodology existed to investigate the predicament of the human race. Nobody should doubt that it was ever validated for any other purpose.

I invite anyone thinking that System Dynamics models are unsufficiently validated to open the book Managerial Applications of System Dynamics (E. Roberts 1978) and look up the index under "validity". He will find that about five per cent of the book is devoted to validation. That may seem not much, but the chapters of the book are reprints of papers where most of the place was given to model description and its behaviour, the behaviour itself validating the model by comparison with past datae. The same test on Industrial Dynamics (Forrester 1961) gives about the same result.

We will now try to illustrate what precedes.

Work has been going on at M.I.T. for the last several years on the System Dynamics National Model (of the U.S. Economy). It was conceived "not as a vehicle for generating any particular cyclic behaviour but instead as a way to capture the structure of the real economy and the essence of those managerial policies in business and in government that control day by day decision making" (Forrester 1977). After assembling parts of the model it exhibited business cycles, Kuznets cycles and . . . Kondratieff cycles. That in itself provides a strong basis for the validation of the model. Furthermore the long wave cycles were more or less unexpected from the group. The literature is scant on the subject and nobody at the time of model assembly thought of it. But the model behaviour, as a result of interactions between sectors of the economy, exhibited the long wave.

That preliminary work presently allows the System Dynamics Group to investigate the mechanisms of inflation (Forrester 1980): "No exogeneous time series exist in this model. Realistic behaviour is internally generated". Four modes of price changes (not necessarily inflation) have been associated with the three cycles mentioned in the previous paragraph plus a stress cycle mode. "The unique structure causing each mode can be identified. Policies for altering each mode can be separately tested. Then, modes can be simultaneously activated, as they are in real life, so that one can see they can be separately identified."

After validation comes usefulness which reinforces confidence in the model. And so the loop is closed.

CONCLUSION

That paper is completed by a rather extensive bibliography:

more than seven hundred references including about sixty books. Most of which deals directly with System Dynamics; the rest is relevant to the subject. Nevertheless the only sure thing about that bibliography is that it is uncomplete.

Too many people have heard about System Dynamics without really looking into it. To them I would like to quote Confucius:

> I hear and I forget,
> I see and I remember,
> I do and I understand.

I hope it will encourage them to try their hand at one of the most fascinating methodology brought over by a genial engineer (J. W. Forrester) working at a business school (A. P. Sloan) in the surrounding of the exceptional Massachusetts Institute of Technology.

Rather than to conclude I would like to reiterate what I already said: let's hope that the System Dynamic way of thinking will spread enough to provide a common practical language for System Analysis. To those who regret its mecanist description we will quote Bergson "On ne comprend une chose qu'en s'en faisant une représentation mécanique". Or, if they prefer, Wiener "In fact the whole mechanist-vitalist controversy has been relegated to the limbs of badly posed questions".

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Notes

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(1) See also the recent book "Dynamique Chaotiqu" GUMOWSKI 1980

(2) Work done at the C.E.R.T. Onera, Toulouse.