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System Dynamics - the State-of-the-Art.

By

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Abstract

We have had System Dynamics available to us for 20 years. It seems to fulfil a need which is not, and cannot be met by standard planning and programming approaches, namely that of providing for the concept of controllability when the unforeseen happens. Despite this it is an unseen technique.

The explanation seems to lie in the areas of previous applications of the method, both good and bad, and the extent to which the need it satisfies was actually felt. A review of applications helps to characterise the System Dynamics method in various circumstances and leads to ideas for its improved application and further development.

Aim of the Paper

The modelling approach called 'system dynamics', and described by Forrester (1) and Coyle (2), is now practically of legal age, being about 21 years old. In its short, but colourful, life it has attracted much attention, some aclaim, and a fair amount of criticism. Most management scientists have heard of it, hardly any have used it, and it is taught far less widely than, say, linear programming. There have been favourable reviews of it from Drucker (3); and Meadows (4). 'The Limits to Growth' is probably one of the most widely read books of recent years. On the other hand the leading journals, such as Management Science, Operations Research, ORQ, and EJOR rarely publish anything on System Dynamics.

This is a confusing and intriguing situation. If so many people feel that System Dynamics has potential, why are they not using it? If, as is claimed, 2000 copies of the DYNAMO simulation language have been installed on the world's computers, why is it so hard to find someone who can write models in the language?

This paper starts from the premise or axiom that the central problems of management in the 1980's, whether it be in the business firm, the public institution, or of the nation as a whole, are those of bringing about desirable changes and inhibiting unsought variations. How, for example, can we bring about economic growth? How can we prevent a national educational system from being overwhelmed by numbers of pupils moving through the various stages? What can be done to protect a mining company from being put out of business, or from growing out of all sense and reason, by the variations in world metal prices?

The simplistic answer is 'planning'. This suggests that all we need to do is to forecast, say, the level of copper prices over the next five years and plan accordingly. The sheer breathtaking audacity of the assumption that we actually know how to do these desirable tricks is surpassed only by the charming naiveté of this view of the world. Briefly it suffers from three weaknesses.

Firstly, and already alluded to, we lack an effective planning technology for 'optimising' such complex decisions. Linear programming will, indeed, handle large numbers of variables and constraints and will compute 'optimal' solutions. We do however have to be brave enough to assume that we do know the coefficients and that they won't change, that the system is actually linear, and that the objective function actually means something.

Secondly, what we may call Murphy's Law of Forecasting guarantees, absolutely without exception, that all forecasts are always wrong. This can be so for three reasons.

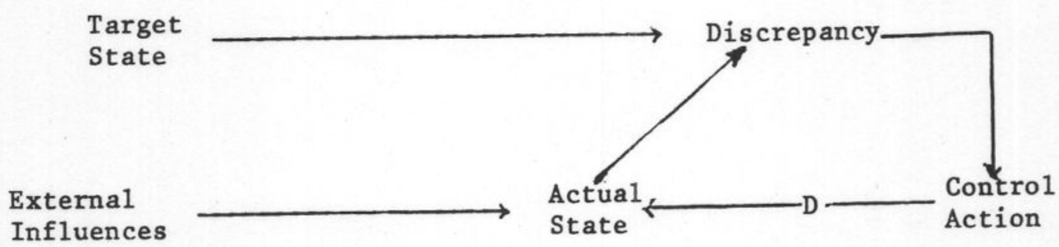
a) We are not actually very good at making forecasts (e.g. meteorology which, as Coyle (5) has argued, is one of the few cases where it is correct even to use the word 'forecasting'), or are forecasting the variables we think we are good at predicting rather than those most useful for the system. A simple example of this is the distinction between predicting the amount of rain next week and forecasting whether next week would be a good time to start the harvest - the difference being between the forecast as such, and what the 'system' does with the information in the forecast.

b) Forecasts are also wrong because they can be upset by events which those who did'nt foresee them call 'unforeseeable'. The 1973 Middle-East War and the subsequent events have filled the waste paper baskets of Western Europe with every kind of forecast ever since.

c) Finally, forecasts are wrong because we make them so. We predict that unemployment will rise, so Lord Keynes bids us spend on public goods to prevent it. We overspend, get inflation, and unemployment rises even further.

Thirdly, naive planning doesn't work well because the world changes. We plan a steel plant but the demand is for plastics. We open a copper mine, and there is a boom in aluminium. We build up a jute industry and some genius (or idiot?) invents nylon.

We are therefore left in the position of saying that, if what I have called naive planning does not work, then what do we need? The answer, I would suggest, is that we require to complement (NOT replace) planning by the concept of control. In making plans we are aiming for targets. The world, or our own mistakes, means that the targets are not achieved and the actual state, present or predicted, differs from the target and we therefore have to take corrective, or control, action



POLICY

In this diagram a POLICY is a rule for responding to discrepancies by taking action in the hope of achieving the target. The essential idea is that of error-correcting feedback as exemplified by the closed chain of cause-and-effect in the diagram, in which the delay, D, will be important.

The premise with which I started now says that, if the foregoing analysis is correct and that what is needed in management in the 1980's is planning plus a theory of control action, then system dynamics should be the very thing. It is claimed by its proponents that system dynamics provides precisely a theory of loop behaviour, and in particular the ability to handle the manifold loops of real-world systems. This theory can be employed to explain why systems behave as they do, what will happen when things go wrong, and, most importantly, to provide a method of policy design which will enable us to be far more sure that our managed systems will do far more of what we want them to do. Were that not enough, the simulation technique employed (Coyle 2, Pugh 6, Ratnatunga 7) allows the analyst to handle non-linear aspects, to build his models quickly, cheaply and easily, and even have them understood by managers and civil servants.

Not even its highest priests claim that System Dynamics is more fun than some more traditional two-person, non-zero sum games, but they hardly need to. If it can do what is claimed for it, and can meet the need for a modelling method at the interface of planning and control, it should clearly be the most popular analytical method ever. The fact is, however, that System Dynamics is not widely known and used. That is the central conundrum of this paper. In order to try to resolve it we may address ourselves to three related questions:

Where are we now?
Where do we hope to get to?
How are we to get there?

It will be taken for granted that the claims made by the writers on System Dynamics are substantially true, in the sense that the claims that feedback loops are contributory factors in producing dynamic behaviour, that dynamic systems can be represented by sets of differential or difference equations, and that the special simulation languages are merely convenient tools for those who have access to them, are all technically correct. This is, however, a matter of opinion and the detailed arguments are advanced in Forrester (1) and Coyle (2

We shall address the problem of where System Dynamics is now by two stages. Firstly, a rather cursory review of the state of the art as reflected in some of the literature, and secondly by a more detailed comment on two contrasting case studies.

The State of the Art and the Literature

The early applications of System Dynamics were very firmly in the business area. Forrester's first book (1) is actually called 'Industrial Dynamics' and several chapters in it are devoted explicitly to business problems such as production, stock control, labour recruitment and so forth.

Since those early days the subject has broadened its scope of application rather remarkably. Forrester (8) has addressed the problem of the rise and decline of cities and Forrester and Meadows (4) have applied System Dynamics to the so-called 'world problematique'. In these works we see the extension of application of the method to new areas, at a higher level of aggregation and with no clearly identifiable decision maker.

On the other hand, there have now been several applications of the method directly to the specific problems of business and industry. Coyle (2) describes three such applications and Sharp (9) provides an excellent study of many more. As the title of Sharp's paper (System Dynamics Applications to Industrial and other systems') suggests, there is a third area of historical development, which does not fall easily into the two categories, and of which the best example is certainly the work of Ratnatunga, discussed at more length later in this paper.

In the sense, then, of the use of the system dynamics method, by which we mean something recognisably similar to the ideas described by Forrester and Coyle, though by no means necessarily using the DYNAMO or DYSMAP simulation languages, we can now distinguish and appraise the present state of the art in terms of five categories of work covering: business models, socio-economic systems, national economies, and project appraisal. The fifth category is for anything not falling into the other four.

It would be tedious to list references to each of these catefories and we shall, in any case ignore the fifth area mainly because of the variety it contains. We therefore, in this paper, first attempt an appraisal of each of the first four groups, citing only one or two leading references in each case. We shall then examine two specific cases in more detail before attempting an overall assessment of the scope and future development of System Dynamics.

Our four-fold cateforisation will be manifestly unfair as it excludes a large body of application in health care, horse racing, research and development, technological forecasting, library management, and the study of boom towns. It has, however, been chosen to cover the application areas which the author believes either to be best known or to be those most capable of widespread usage in, say, the next 5 - 10 years.

<u>Business Models</u>

This is an area which received the initial attention of the early System Dynamics workers, seemed almost to languish for some years, but has undergone a major resurgence of interest during the last 6 or 7 years. Work has been done in practically every area of the business firm or other productive institution, ranging from the simple production/marketing problem in Chapter 10 of Coyle (2) to the total corporate model described below. In between there have been major efforts in finance and accounting, production plant acquisition and corporate forecasting. Many of the references are given by Sharp (9) but new cases continually appear and are reported, particularly in DYNAMICA and System Dynamics Newsletter, published, respectively, by the System Dynamics Groups at Bradford and M.I.T.

The range of industries has been at least as wide as the functional problems analysed. Consumer goods, oil, coal, metal mining, paper, fibres, chemicals, and electrical generation have all been studied.

In this category we must also include work on industries as a whole, such as that of Sharp (10) on the chemical plant construction industry, and of Price (11) on the U.K. paper industry. A natural interface between these two sub-categories is illustrated by the work of Coyle and Montaldo (12) on management of operating mines, of Coyle (13) on the relationships between an international mining company and its local operating companies, and of Wolstenholme (14) on the dynamics of a whole mining industry.

Returning, however, to the modelling of specific business firms and of functions within those firms, it is clear that this has been, and will be, a fruitful source of successful applications. In this context success can be taken to mean any of: the implementation of specific recommendations, changed managerial attitudes and improved insights, or the setting up by the company of its own System Dynamics team, often including the installation of a package such as DYSMAP on their own computer. This last has happened on several occasions, most recently in an East European country, where substantial changes are to be made in central planning, by the State, of an industry, on the basis of adding a System Dynamics capability to their existing planning methods.

It would be foolish to pretend that System Dynamics always works and always solves problems. Coyle and Sharp (15) describe at some length the problems of successful analysis and implementation. Nonetheless, the 'batting average' of System Dynamics remains far higher than that of Management Science in general.

Business projects seem to be characterised by:-

- careful and agreed identification of the problem
- a well-defined decision-maker
- exogeneous driving forces
- heavy involvement of managers leading both to a 'good' model and the development of new insight and understanding by the managers (there is no doubt that the clarity of the influence diagram and the transparency of the DYSMAP equation formulation are major factors in this)

- short duration studies (Ph.D. research is an exception but truly applied projects are hard to arrange)
- lack of data from the firm
- a high rate of "success"

The reasons for the success seem very much to be in the simplicity and economy of the technique, but also in a great increase in awareness in business of the problem of getting back on course after an upset. This is, of course, precisely what control theory/System Dynamics are about, and the author is quite convinced that the economic blizzard of the past few years has been very good for the development of System Dynamics.

Socio-economic Systems

The two best-known examples here are Forrester (8) and the enormously influential world model, originally formulated by Forrester but refined and described by Meadows (4). An undeservedly little-known book by Hamilton (16) on the socio-economic development of the Susquehanna River Basin describes some truly interdisciplinary work of great interest, which seems to have received little or no further development.

The world model has had great exposure and led to large spin-offs in other world models and many national socio-economic models. At the risk of oversimplifying a very complex issue it seems that the world modelling effort (which has tied up a very large amount of skilled modelling effort) can be characterised by:

- careful statement of the problem by the modeller but with little agreement from other thinkers in the field
- few or no exogeneous inputs so that all dynamics are model-generated
- no identified decision-maker other than 'public opinion'
- little or no involvement of analysts not identified with the modelling group
- often of long duration
- large amounts of data available, with the inevitable, though perhaps unjustified, criticism that data had been treated in rather too selective a fashion
- a large amount of criticism, covering the whole spectrum from constructive comment to hysterical condemnation

It is certainly true that thinking about global issues of conservation and resource management has vastly changed over the past decade. How much of this has been due to non-modellers such as Barbara Ward, modellers such as Forrester, and oil price rises, and the complex interconnections between these and other thought groups, is more than the present author would care to judge. It is, however, certainly a tribute, both to Professor Forrester's commanding intellect and the power and clarity of the methods he first propounded, that he was able to create the first framework of his world model during a Transatlantic flight. Subsequent man-years of effort under Meadows did not materially alter the conclusions which Forrester drew.

In passing, it must be remarked that one of the attractive features of System Dynamics modelling is that one can build a model within literally a few days of work. The model can be used, learned from, and then discarded for a more useful version, without having invested so much time, effort, and intellectual prestige that one feels forced to defend a model which may indeed rest on poor foundations. This aspect of an analyst's psychological need to defend his offspring mars a good deal of management science, and it is an attractive aspect of System Dynamics that it helps to ameliorate the consequences, providing that one guards against the inherent dangers of instant modelling. The approach can be phrased in what should be an old saying in analytical circles - 'the model should guide its own evolution'. In System Dynamics, properly done, it can.

Opinion about the value and effectiveness of the socio-economic models, whose nature I have tried to define by taking too few examples from a wide field, naturally varies. My own view, since that is what one is asked to give in a 'state-of-the-art' review, is that the work was premature and over-publicised. Both in terms of the viable evolution of System Dynamics and, far more importantly, of making a useful contribution to a vital area of decision-making it would have been better to wait a few years, partly for better techniques, and partly for 'them', the scientific community, to ask 'us', the modellers, for help. As it has turned out, I suspect that much of the furore has come from intellectual defence mechanisms.

National Economic Models

The distinction between these and the previous group is a loose, but useful, one. In socio-economic models, authors seem to have taken the approach of focussing on social variables such as 'quality of life' and studying how economic and physical factors interact with them. It could crudely be said that they envisaged their client as being a statesman, or one who is concerned with the next generation. Perhaps the reason for the lack of success has been the marked shortage of statesmen.

The national economic model concentrates rather on economic aspects, though many social variables will also be there. Such a model could be said to be aimed more at politicians, who are people interested in winning the next election (or defeating the next coup d'etat). The distinction is, in my view, more a matter of intent than of content.

There are few reported national economic models, but those of Forrester and Ratnatunga deserve mention.

Little has been reported of Forrester's current work on the U.S. National Model. It is certainly large, though capable of being decoupled into segments. It demonstrates, apparently, very clear dynamic components of the business cycle, the 7 year Kuznets cycle, and a 50 year Kondratieff cycle, under the influence of its own internal structure. Forrester has given a very convincing verbal demonstration that the classical economic explanations of the 4 year and 7 year cycles are exactly reversed so that the 'explanation' given to the 4 year cycle accounts for that of 7 years, and conversely. He connects the Kondratieff cycle to technological revolutions.

If his continuing work confirms what, to be fair, he presented as initial conclusions, this will be work of great importance. It is earnestly to be hoped that, in such a case, it is more sensibly received than some of his earlier insights.

Ratnatunga deals with more specific problems of investment in Sri Lanka and pays, properly, more attention to exogeneous factors than Forrester seems to do, Sri Lanka being clearly more vulnerable than the U.S.A. This work is, however, treated more fully below.

It is too soon to characterise national modelling very clearly but it appears to have attributes of :-

- being relevant to economic theory by offering a tractable dynamic feedback framework for something which has been treated far too statically for far too long.
- being open to the use of econometric and control theory estimation procedures for the large masses of available data, though there are also very serious objections to too great a reliance on data
- having potential for being linked to specific control actions by identifiable decision makers operating within plausible (to them) time scales on classically recognisable and established variables such as GNP.

In summary we may expect to see a great deal more of such models and, in terms of the earlier analysis of the mutual importance of planning <u>and</u> control it would seem that they have much to offer. Great care will have to be taken in that building large, economically respectable, econometrically estimated, but operationally useless models must be avoided. We shall have to start by putting utility at the head of the list, bringing in the three other attributes only to the extent that they contribute to the attainment of the first.

<u>Project Appraisal</u>

The main application to date, is what should be a viable System Dynamics field, is the work of Jacobsen (17) on the exploitation of the coal deposits of the Powder River Basin of Wyoming. Jacobsen discusses the limitations of the standard Environmental Impact Analysis and argues that a System Dynamics model can be used to evaluate many different exploitation scenarios to test their effect on housing, social capital, investment, tax revenue, water supply and land usage.

In a sense this is not a 'classical' System Dynamics application as the model contains very little feedback. In fact it is more a case of using the DYNAMO language as a very convenient way of doing what was earlier referred to as naive planning. Such a model is very easy to formulate, the graph plotting routines give very clear indications of system performance and it is an extremely simple matter to test alternatives.

One can, however, readily see how Jacobsen's model could be extended to include the explicit feedback controls by which regulation could be effected when, as will inevitably happen, things go wrong. This suggests the development of models which will:-

a) appraise several alternatives and select that which, on present information, seems to be most attractive - a model for naive planning
b) at the same time, and in the same model, design a control system which is suitable for the selected alternative and which would give a pre-designed regulatory mechanism for getting out of trouble when trouble occurs.

In practice one should do both a) and b) for each alternative so that the choice is made, not simply between alternative plans, but between the combinations of 'plan plus control policy' for each case. The control policy which most effectively overcomes problems will not, in general, be the same for each alternative because, as each alternative plan represents different actions, strategies, or investment projects, then clearly there can be different things to go wrong. An alternative which is superb only if nothing untoward happens would be a ludicrously unrealistic project choice.

This line of approach is very near indeed to the plan-<u>and</u>-control approach which was argued for at the start of this paper. Jacobsen's work was a particular example, but one's knowledge of the technology of System Dynamics modelling clearly implies that project appraisal models of the two-phase type mentioned above are feasible. They would be characterised by:-

- being closely related to some particular project such as a mining, industrial, or agricultural venture, where there are several or many alternative development paths over some years, and rather less so to a civil engineering venture such as a bridge or dam. (They would however be applicable to the irrigation spin-off from a dam)
- capable of being built very quickly and easily within, maybe, a few man-weeks at most
- able to test and evaluate a large number of scenarios very quickly
- having the potential for assessing the controllability of a project.

After that general survey of applications of System Dynamics we now consider two cases in a little more detail.

An Industrial Application

In this example, the author assisted in the construction of a System Dynamics model of corporate planning in a large industrial firm. The study has not yet been reported in the literature, but it seems to be probably the most powerful application of System Dynamics in this writer's experience.

The firm engages each year in capital projects - new plants and facilities of all kinds. New projects are started each year and previously started projects are continued, calling for further expenditure. The total volume of spending to start new projects and to continue with previous commitments is the total Capital Expenditure, CX, in £ terms, and is, of course, a standard feature of every industrial firm whether private enterprise o state regulated. The problem which arises is that CX varies from year to year by more than could be expected from the variation of, say, the business cycle. If we devide the percentage variation in CX by the percentage variation of the business cycle, we obtain a Capital Expenditure Amplification Ratio (CXAR), which measures the extent to which the firm's planning and decision-making amplify the exogenous factors, and hence quantifies the extent to which the firm is, as it were, making life worse than it needs to be. It could be shown, in this case, that the theoretical minimum for CXAR was 1.0.

The firm is a large user of certain raw materials, mainly rubber and copper, but also chemicals derived from petroleum and, of course, fuel for smelting. In the past real raw material prices could be regarded as essentially constant, but the firm now foresaw the possibility of an era of steadily rising real raw material costs. In this context there was a need to answer two questions in relation to the very efficient and sophisticated corporate planning procedures the company had evolved.

1. Is there any reason to suppose that our planning procedures actually contribute to the instability of CX and, if so, what can be done about it?
2. Even if our planning works even reasonably well in an era of constant real raw material prices will this continue to be the case when the corporate system receives further shocks from real raw material price rises?

The planning system consists of two parts. In the first phase, the operating divisions produce detailed engineering proposals for new projects based on agreed, company-wide, forecasts of demand for the next few years. Such proposals have to meet criteria of cost, profitability, and consonance with other corporate activities. There may be hundreds of such proposals and, from them and from existing projects in the pipeline, one can calculate proposed capital expenditure in detail for the next year and in outline for ensuing years.

The second part of the planning consists of using the capital expenditure proposals, together with revenue forecasts, to calculate what the financial position of the firm will be if all the proposals are sanctioned. This, of course includes allowances for the repayment of loans and for planned new borrowing.

Planning must, as we argued earlier, be linked to decision-making and, in this example, the decision process works roughly on the following lines. At the start of the year the Board review the capital proposals and the forecasts of financial position. If the latter look good the proposals would probably all be approved. To the extent, however, that the financial position seems to be unsatisfactory, capital proposals would be cut back to some degree. The final result is the project programme for the coming year. The programme is reviewed at intervals during the year and sanctioned projects may be frozen, or expanded, as the outlook gets worse or better.

There is no great problem in modelling any of this and the whole project was over in a few months.

When the model was run with constant real raw material prices, CXAR was about 3.0. It was easily shown that this was not due to errors in the forecast, so the planning and/or the decision making was making matters worse than they needed to be. When the model was run with increasing real material proces, however, the system went into explosive oscillation, with CXAR reaching 11 and getting larger all the time. This proved that the system, which had been fairly effective in the 'old days', simply could not cope with the new world and badly needed to be overhauled.

Redesign of the system involved testing various theories held by corporate planners about alternative corporate policies, and a careful examination of the model's feedback loops to see how they regulated the dynamic behaviour.

The first approach showed that the system could be brought back under control. Even with rising real raw material prices CXAR could be brought back to about 2.5, rather better than the value of 3 achieved with constant real prices. In each case the planners' theory accorded with the loop analysis.

However, the loop analysis also suggested changes which did not involve only an alteration to planning and financial procedures, but could be expressed at the interface of planning <u>and</u> decision-making. The joint effect of this more fundamental approach, and the improved procedures already tested, was to bring CXAR further down from about 2.5 to 1.05, i.e. practically the theoretical minimum.

This seems to be a successful System Dynamics project in industry, which doubtless has many applications both in capitalist and centrally-planned economies. It is certainly not easy to see how the result could have been achieved by any other modelling method with which the author is familiar.

<u>An Economic Application</u>

Ratnatunga (18) has also applied advanced methods of control engineering to some economic problems in Sri Lanka. In a sense his work is project appraisal on the national scale. Ratnatunga argues that 'most developing countries will have to accept the uncertain world environment as a fact of life and learn to adjust internal investment and pricing policies in such a manner as to minimise the detrimental effects of a noisy environment'. He applies this concept to the Sri Lankan economy as an example of a plantation agricultural system struggling to survive.

Over a 30 year period his model traces the consequences of policy as indicated by: population dynamics, educational service demand, consumer demand, production in industry and agriculture, and demand for imported raw materials.

As an example we may consider the demographic sector. This is modelled as a feedback process in which population size affects birth and death rates which in turn affect population. External factors affect fertility and mortality and the co-efficients are estimated from census data. When simulated on the computer this approach produces graphs of population against time, or three-dimensional projections of age-specific population showing waves and troughs of population.

Simulation of population produces estimates of demand for education, food subsidy, and so forth.

One of the major controls in the model is the change of consumer demand with changes in incomes and relative prices. This is modelled using established consumer behaviour theory. The main value of the model is that it shows very clearly the adjustment made by the economy, and how long that adjustment takes, to a policy variable such as an increase in the subsidised food price. Although, to be fair, Ratnatunga does not do so, it is interesting to speculate whether the model could be used to assess whether or not the fluctuations resulting from some such change would be large enough to trigger civil unrest.

The whole value of Ratnatunga's work is that it is specifically related to an actual country, and includes the salient features of that particular system as it is, and not as economics says it should be. It shows clearly how the model reacts to stimuli such as world market prices, internal change in, say, fertility, and internal regulation of prices, taxes, investment and social services provision. It is estimated from data and employs accepted economic and behavioural theory as well as the details of the Sri Lankan economic structure.

It can be used to test the effects of purely internal policy changes or to attempt to evaluate the kind of policy actions which would defend the system from exogeneous shocks.

The State of the Art Assessed

Having, in this rather discursive way, ranged over the field of past applications of System Dynamics though without, by any means, doing full justice to it, we now attempt the daunting task of appraising the state of the art. Hence, we shall attempt to identify those areas where application is most fruitful and where methodological developments could prove most beneficial.

Although the approach has been tried in nearly every field from stock control to inter-personal dynamics it is very clear that, like all management science methods, it has proved most successful when applied to problems which were unambiguously identified, where there were fairly recognisable decision makers, and where the project could be brought to a reasonably definite conclusion within a moderate span of time. By and large, it could be said that management science has become acceptable by sticking fairly firmly to this prescription and System Dynamics has been seen as unacceptable and controversial where it has strayed too far from it.

The situation has undoubtedly been aggrevated by a lack of basic textbooks describing what the technique is and how one uses it, though Coyle (2) is an attempt to fill that gap, and a surfeit of books and papers 'applying' an apparently unstated method. Had some of the critics, who have confused the application and the technique, taken the trouble actually to read Forrester's masterly "Industrial Dynamics', their criticism might have been abated, but intellectual activity does not always follow such paths.

Although with hindsight one could argue that one should walk before one runs, one should applaud the early workers, not only in America, who saw the potential in the method and applied it so widely. Had they not done so, System Dynamics could have become yet another method used only for lower-level tactical problems and never even been seen as the only approach satisfying the criterion of operating at the junction of planning <u>and</u> control, as argued earlier.

The current state of the art has to be assessed in terms of what 'we' appear to be good at doing. The collective pronoun has to be employed because what matters is the combination of: our human abilities of skill and imagination in problem recognition and solution, the technical quality and limitations of the modelling technology, and the background of case experience against which the first two must operate, and to which they contribute. It is this trio of aspects which are collectively identified as 'we'.

At present it seems that 'we' are in the position that:-

a) Production/distribution/inventory/finance, (i.e. functional models within the firm) are well within our capability. This does not mean they are easy, but we can now tackle them with confidence.

b) Corporate strategic models, such as that described above, proved to be unexpectedly amenable to analysis and capable of yielding remarkable results at the very heart of managerial strategy. (The work described above was only a small part of the project).

c) Models of industries as a whole turn out to be harder, not so much to build as to use, mainly because it is far from easy to see exactly which policy issues should be addressed. Since the purpose of a model is, or should be, a determinant of its structure and that, in turn, will affect the perceptions of people outside the modelling team, it is clear that a purpose which is not seen as important by such a group is more likely to lead to an unproductive situation.

d) The same arguments apply to the national and socio-economic model categories discussed earlier and the distinction can be seen very clearly by comparing the Ratnatunga Sri Lanka model with, say, the Forrester World Model. They are not comparable technically but the difference in purpose and client identification is noticeable and relevant.

Development Needs

So far we have said little about the modelling techniques and have only defined it roughly in relation to the contents of two books. In fact the techniques used in the corporate planning example differed from those of Forrester twenty years ago in three important aspects. Firstly, model formulation is far more sophisticated. Great care was taken to make sure that the equations represented the system precisely rather than employing simple proportional control equations. Secondly, methods of modelling forecasting processes are now far better. Some of the problems have been more thoroughly treated and some original methods of formulation have been developed. Thirdly, the loop analysis technique has been more finely developed, though much improvement can be foreseen.

Despite these qualifications the model is not recognisably different from earlier work and this is a strength. Simple methods can be applied quickly and powerfully.

Ratnatunga's model differs in its use of modern control theory and state space estimation techniques. This arises from the need to model at a macro level a system which is rich in data but opaque in structure. Most industrial problems have the contrary attributes.

These contrasts, and the arguments put forward in the course of this paper suggest the following development needs.

1. A considerable elaboration of case material and teaching texts. Coyle (2) goes some way towards this and more cases and theses are continually being added to the literature. An archive of computer models cross referenced to written sources in being developed at Bradford and it should be possible to make available a computer tape of, perhaps, 100 or more models for teaching purposes.
2. The methods of loop analysis, seem, on the basis of practical experience to be very powerful despite their inherent simplicity (or, perhaps, because of it). Rules of thumb have been developed for their application and these are being incorporated in the DYSMAP compiler. At present DYSMAP can find all the loops in a model. The next phase is to make it find the important ones.
3. System Dynamics is often criticised on the grounds that it does not 'optimise'. There are arguments against attempting to do so but they are not universally applicable. There is, therefore, a need to be able to interface a System Dynamics model with a hill-climbing package to design optimal control policies for certain cases. This can be done at present but it calls for fairly advanced knowledge. We need to be able to do it routinely, with suitable foolproofing.
4. We need to be able to draw on the more sophisticated state-space estimation, sensitivity testing, and model structure analysis methods which have become available in recent years, as a complement and extension of simple loop analysis for more advanced cases.

It is, however, to be stressed that, in this author's view, developments under 2,3 and 4 need to rest very definitely on 1. This means that we should, for the time being, aim to develop methods the need for which can clearly be seen in the case material. It is inevitable that the greater bulk of technique improvement will be done in Universities and it is to be hoped that we can avoid the trap of developing the techniques the Universities think are interesting which may, or may not, be the ones the analysts need. There is, of course, synergy in the matter and one would expect, in due course, that technique improvements would lead to more and better cases in new areas. For the next decade I would, however, prefer to see the boot on the case study foot.

Conclusion

How, then, shall we finally appraise the state of the art? In a few words I would say that System Dynamics is a method which narrowly avoided missing the boat. Only the power and originality of Forrester's original conception enabled it to avoid being sunk in a sea of controversy. By going back to its roots in industry and specific corporate and institutional decision-making on a strategic level it has been shown to have powers for handling real world problems. Its limitations have also been more clearly understood, and some criteria, Coyle (2), have been defined for testing when it is not likely to prove helpful.

With all this in mind we now turn back to the argument with which we commenced. If, as was argued there, the need in the 1980's is for planning plus control then System Dynamics will indeed be a technique whose time is at hand.

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