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PAPER: THE DEVELOPMENT OF SYSTEM DYNAMICS INTO A MORE COMPLETE METHODOLOGY FOR PRACTICAL SYSTEMIC ENQUIRY

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SYNOPSIS

The premise of this paper is that System Dynamics has, in the past, been primarily perceived, both by external observers and by most of its own practitioners, as a technique of computer simulation. Although this situation is changing, there is still little wide scale recognition of its true generality and relevance as a complete subject of systemic enquiry.

The purpose of the paper is to explore the merits of System Dynamics as a total systems methodology. Specifically the presentation will undertake to review the need for and the requirements demanded of such problem solving methodologies, to briefly explore the dilemma resulting from historic attempts to create them and to present changes to the existing Systems Dynamics method which might improve its conformity and acceptability as such a methodology. These include the formal definition of Qualitative System Dynamics and the presentation of a set of rigorous rules to provide much needed guidance in its application; firstly, Stepwise Influence Diagramming, aimed at enhancing problem exploration and model development and secondly, Qualitative Analysis, aimed at identifying critical system components and exploring the effects of change.

It is concluded that the establishment of Systems Dynamics as a general systems methodology should be a prime objective of all practitioners and that consolidation of the existing portfolio of techniques comprising the subject should be a priority over an enlargement of the paradigm to encompass further embryonic themes and concepts. It is suggested that without change at the roots System Dynamics will not realise its vast potential and will not establish itself as a leading method for generalised systematic enquiry; indeed it is suggested there is a distinct danger of other more recent paradigms gaining this much sought after position.

INTRODUCTION

In the current debate on the merits and relevance of expanding the current Systems Dynamics paradigm to include additional sophisticated themes and concepts[1], it is very easy to overlook the priority needs of word problem solving and the responsibilities of analysts to expand their abilities to address these in the most useful way. If it is the objective of Systems Dynamics practitioners to expand their numbers and achieve the latter, then, in the opinion of the author the direction of debate should be towards the roots of the subject rather than its frontiers and concerned with examining how its use can be improved. This requires that we determine how it can be simplified rather than complicated and how it can be made more comprehensible.

Systems Dynamics has been in existence for around 25 years and it is generally accepted that the growth in its use over that period has fallen short of expectations.[2,3] More recent systemic problem solving methodologies are emerging[4,5,6] and drawing attention to practicing analysts by their mode of presentation to facilitate user guidance and their emphasis towards qualitative audiences and total generality of application. There is therefore clear competition to the base concepts of Systems Dynamics which cannot be ignored.

One of the fundamental issues in the acceptance of Systems Dynamics is that it is primarily perceived, even by most of its practitioners, as solely a technique of computer system simulation applicable only to a restricted range of systems and a restricted range of performance criteria. This perception needs to be dispelled since the elements of modelling used in Systems Dynamics are of the utmost generality. It is recognised that there is a great need to examine reformulations of the basic method[7] to provide a new image which will appeal to a wider audience. It is the opinion of the author that Systems Dynamics has both the necessary and sufficient ingredients in its current portfolio to take on a much wider role in the field of system enquiry than at present and the purpose of this paper will be to examine this premise. System enquiry is used here to define the whole field of investigation concerning the understanding of and design of change in complex human activity systems. This is prefered to the term system analysis since the latter now has specific connotations with the computer field.

The sequencing of the paper will be firstly to examine the needs and requirements of system enquiry methods and to emphasise the elusive and abortive search taking place for useable holistic methods; secondly to assess the credentials and limitations of Systems Dynamics for such a general role; and thirdly to suggest further changes to the Systems Dynamics method which might improve its acceptance and credibility for the task.

THE SEARCH FOR A SYSTEMS METHODOLOGY

A belief in the need for holistic thinking has existed for a very long time and its advantages over reductionist attitudes has been well expounded[8,9,10]. However, the development of meaningful methods by which to apply holistic ideas has so far proved very difficult, certainly in any practical rather than theoretical sense, although the literature is well sprinkled with attempts. These attempts come from a wide variety of disciplines. Discounting for a moment the methods of Systems Dynamics there are those arising out of the isomorphic elements of systems theory[11,12,13], those resulting from attempts to expand and elevate mathematical problem based techniques[14], those concerned with the wider interpretations of cybermetics[5], those based on the method of computer systems analysis[6], those based on highly sophisticated structural modelling ideas[15] and those based on purely qualitative diagrammatic and verbal procedures.[4]

The difficulties in generating useful methods centre on the compromise required between the vagueness necessary to be sufficiently general and the precision needed to produce specific results. In terms of problem analysis this dilemma takes the form of a need to have a wide and flexible approach to facilitate structuring of symptoms and problem identification whilst simultaneously requiring a narrow rigid approach to facilitate the creation and testing of remedies.

Consequently, there continues to be extensive research into compromise approaches for system enquiry, based on a mixture of hard result-orientated techniques and soft subjective methods, and current systems work is characterised by the search for improved methodologies. Methodology is defined here as the overall process of investigation usually stepwise and

iterative, by which concepts philosophies and theories can be expressed independently of the subject matter of the investigation and independently of the problem type to be considered. This use of the word methodology is not be confused with its use in a specific technique sense where it simply implies a list of the steps necessary for the application of that technique for example, the linear programming methodology. The ideal methodology according to Cheekland[4] 'must avoid the content free methodologies derived from General Systems Theory and the ever precise goal orientated formulation stemming from system analysis'.

It is very apparent from an audit of the systems field that the developments towards such an ideal goal are intensifying and that efforts should be made to ensure that, simply for want of clarification, Systems Dynamics does not take a back row seat in the current debate.

THE CREDENTIALS AND LIMITATIONS OF SYSTEM DYNAMICS AS A METHODOLOGY FOR SYSTEMIC ENQUIRY

The systemic merits of Systems Dynamics are impressive. The first major group of attributes of the subject centre on the universal generality of its building blocks of rates and levels and the creation through these of an extremely flexible system diagramming method.

The need for a system description method which is simple, compact and easily understood is a prime requisite of any approach to system enquiry. A good system diagram can formalise and communicate a modeller's mental image and hence understanding of a given situation in a way that the written language cannot. However, the search for 'good' system diagrams of general acceptability has been one of the major bottlenecks in the advancement of system theory, and the literature abounds[16] with examples of methods of system representation.

The Systems Dynamics diagramming methods, particularly that of influence or casual loop diagramming, is a powerful tool in its own right and is currently being exploited as such[17] for assisting with the qualitative recognition of feedback structures. However, current methods have not fully exploited the potential of this form of diagramming for assisting with formal problem identification and system boundary definition; two of the major problem areas of system enquiry. The importance of the need for methods to assist with problem definition is widely recognised both inside[18] and outside[20] of Systems Dynamics. However, few methods exist which are capable of assisting with this task. Immediately after initial problem definition, most methods of enquiry move straight into an analysis phase using some appropriate technique of solution without considering whether or not the problem is correct. Systems Dynamics does possess the potential for such problem exploration. The work of Randers[20] and Coyle[21] in creating methods of developing models outward from key issues by controlled expansion and enrichment has pioneered this potential for uncovering relevant issues, although these were methods presented primarily to facilitate a sensible compromise between model size and relevance to a pre-defined base problem. In general, current methods tend to lack formal guidance and much is left to the imagination and initiative of the analyst.

Attaining a well balanced model is, of course, difficult for the analyst in isolation, and this leads to a further important advantage of Systems Dynamics diagrams, that is their ability to establish and maintain involvement with system actors during both problem and model definition. The process of system description used in System Dynamics essentials creates white box models which are straightforward and realistic enough to facilitate communication. In fact, it has been argued by Senge[21], that System Dynamics mirror very closely the way in which senior management has to think, and that the cause and effect chains used are very close to the sub-conscious models inherent in the style of management employed by the most effective managers. It follows that there is scope and merit in promoting such practices in those less well endowed.

The second major group of systemic attributes of Systems Dynamics understandably centres on its ability to incorporate the concept of control. By clearly separating out the controllable and uncontrollable elements in a system and examining how control operates as a unifying element in a system and determines is mode of evolution, an understanding of system behaviour is possible. Further, integrated design and testing of changes to system operations is feasible.

Systems Dynamics has been criticised in the past from a number of

technical aspects. However, the purpose of discussing criticisms here is not to look for detailed flaws in the method as a technique but to concentrate on those philosophical issues that might cause difficulties in its acceptance as a methodology.

The first of these is the fact that it is essentially a process diagramming method and as such is not capable of application to problems associated with organisational structure. A related issue to this is that it is not relevant to multiple ownership systems where there is dissension between system actors within the organisational structure.

The interactions of organisational structure and process (sometimes referred to as the climate[4]) are seen by some systems practitioners as a key concern and certainly one that has not been fully addressed by Systems Dynamics. There is a need to emphasise how Systems Dynamics relates to this, for indeed it does. Organisational structure is undoubtably a determinant of system behaviour. However, the mechanism of this is through the actions of individuals to control the processes of the system and the fundamental contribution of influence diagramming is to facilitate the recognition of such control. It is of interest to note this recognition is in itself an important step in Systems Dynamics which is undervalued simply because it is considered trivial and simply a forerunner to the much more interesting issue of designing <u>how</u> to control the variable. It is suggested here that much more care is needed in Systems Dynamics to determine who controls which rate variables and to what extend control of each variable depends on the status and power of the controller. Further, by extending this to a comparison of organisational responsibilities for each rate variable within a given resource flow it is possible to formally identify and analyse conflict. Although the effects of conflict have been tackled in the full scale quantitative Systems Dynamics models[22, 23, 24], the detailed procedure by which the subject relates to the issues has not been well communicated or stressed outside the field.

A further fundamental criticism of System Dynamics is that by assuming a feedback perspective it restricts itself only to the analysis of problems associated with system behaviour (that is the dynamics of systems) and established practitioners of Systems Dynamics have tended to reinforce that this is a limitation which in fact defines the paradigm. Perhaps it is worth exploring just how guarded a stance this is.

If we accept that the need for a systems view is created by the natural integration of elements inherent in the real world and that the integrating links are primarily regulatory ones, then feedback is a relevant component of all systems and why should Systems Dynamics not relate to all systemic problems. Even if we cannot claim feedback to be as all embracing as this it is of interest to ask whether or not the rigour of the diagramming methods of System Dynamics have a role and relevance outside the concepts of feedback. Many people do not even think in terms of processes and such diagrams have a part to play in open loop modelling to provide a systemic view of the multitude of functions, responsibilities and delays through which resources often pass. This is particularly true of flows of people through, for example, the criminal justice and social welfare systems; where policies of rerouting create commitments lasting many, many years.

Any examination of the total field of systems enquiry leads very quickly to the conclusion that it is quite strongly split into two camps; these are the soft systems area where quantification is considered impossible and improper either through philosophical stance or practitioner inability and the hard system area where quantification is considered mandatory. In the opinion of the author it is perhaps that it does not clearly fall into either camp that it receives more than its fair share of criticism.

As a result of its close association with computer simulation software Systems Dynamics is generally perceived by the soft systems methodologists as a hard system modelling technique, incapable of adequately dealing with subjective issues and generally far too sophisticated for real life use. Given that most system design today is centred on capacity size rather than capacity control perhaps the latter has some truth and that the concept of control is still ahead of its time. On the other hand where subjective elements are incorporated into Systems Dynamics models there is criticism by hard system methodologists that Systems Dynamics generates invalid models which lack rigour and scientific method.

Systems Dynamics over many years has been applied to a wide variety of situations with either an implicit belief that the approach was correct or without, in general, too much detailed concern by the analyst as to how the systems studied related to any general classification. On the other hand, the development of the subject in this way has enhanced its insularity as a specific systems modelling technique, and there is a genuine need to relate its general attributes within the broader systems field.

The need for change has been increasingly recognised over the past few years and change has occurred. This is particularly so in the development of

specific guidelines for sub techniques and in the general willingness of practitioners to justify their stance in comparison to alternative paradigms. However, further change on a more comprehensive basis is seen here as essential to improve the subject image and encourage the recognition of its attributes and the use which its potential deserves.

Firstly, it is felt by this author that there is a need to exploit and develop further the valuable qualitative aspects of the method so as to provide a more useful tool for general analysts in a wider range of fields of enquiry. Secondly, there is a need to develop more rigorous stepwise procedures by which to guide users right through the whole method. The remainder of this paper is therefore concerned with a presentation of how these needs might be achieved. Further analysis of the rationale for the changes to be presented is discussed by the author elsewhere[25,26] and further details of the method are available.[27,28.]

THE PRESENTATION OF SYSTEM DYNAMICS AS A GENERAL STEPWISE SYSTEMS METHODOLOGY

Figure 1 presents a breakdown of Systems Dynamics into two separate parts aimed at consolidating the approach into a general framework of large scale system enquiry. The first of these is referred to as Qualitative System Dynamics and encompasses the complete phases of system enquiry namely, problem identification, problem analysis (qualitative) and recommendations for change.

The second of the parts is referred to as Quantitative System Dynamics. This is seen as an extension or sub set of the first part where the qualitative model may be quantified into a traditional type of System Dynamics model with all the associated advantages facilitated by the total method. This sub-division of System Dynamics into two parts leads to a revised definition of the total subject which may be stated as:

> "A rigorous method for problem identification, system description, qualitative modelling and analysis of change in complex systems; which facilitates and can lead to quantitative modelling and dynamic analysis for the design of system structure and control."

Quantitative System Dynamics and its associated software[17,21,29,30] is of course well documented elsewhere and will not be considered further here. What will be presented in detail is a summary of recent work aimed at

QUALITATIVE SYSTEM DYNAMICS	QUANTITATIVE SYSTEM DYNAMICS		
1 To assist symptom/problem identification 2 To identify relevant system components in terms of physical resources and their states 3 To describe the system and its boundaries by controlled expansion in terms of: i) resource conversion mechanisms ii) behavioural elements iii) information and control elements 4 To facilitate a qualitative dynamic analysis on which to base recommendations for change	1 To examine the behaviour of all system variables over time 2 To examine the validity and sensitivity of the model to changes in: i) structure ii) policies iii) delays/uncertainties	To examine alternative system structures and control policies based on: i) intuitive ideas ii) control theory analogies iii) control theory algorithms in terms of non-optimising robuse policy design	To optimise system parameters

Figure 1 Definition of the Split Between Qualitative and Quantitative System Dynamics

producing a stepwise approach to Qualitative System Dynamics (Q.S.D.)

Prior to doing this, however, it is useful to outline some of the implications of this definition. Many traditional system dynamics practitioners would find it incongruous to separate the methodology into the distinctive phases suggested here and argue that influence diagrams are drawn with the relationships and dimensions of quantified analysis in mind. However, whilst this statement is true, it is important to realise that the argument only tends to reinforce the perception of system dynamics as just a technique for simulation analysis. In general system enquiry terms it is much more, and the simulation phase of system dynamics can alternatively be viewed as just in-depth expansion of the analysis phase of the methodology - that is, as a technique within the overall methodology. This perception should not, however, detract in any way from the potential and power of the simulation phase and the changes presented should be considered as no more than a logical re-emphasis.

The stepwise procedure to be outlined will be split for convenience into two phases, Part I presented in Fig. 2 concerns the creation of a model and Part II presented in Fig. 3 concerns its qualitative analysis.

In creating steps for assisting with model creation it is of

interest to recall that there are basically two ways of constructing System Dynamics models; the traditional approach involving flow diagrams and the contemporary approach using influence or casual loop diagrams. Flow diagrams are essentially algorithmic in nature and represent an exact diagrammatic form of the final quantified simulation model to be produced. They relied on a precise and detailed knowledge of the system to be investigated and provided little or no convenient basis for explaining the context and relevance of the model. Influence diagrams was basically developed to facilitate the latter. They provided a much less rigid format (for example by ignoring both the distinction between each type of flow represented and the distinction between variable types) and were seen as a prior step to flow diagramming and hence final quantitative model construction. However, it was later found necessary to develop additional techniques, such as coherence testing and variable type assignment[21], to facilitate the transformation. The diagrams are now commonly used in model construction work but there are few guidelines other than common sense and experience to guide their use. They are perhaps easiest to use where a feedback hypothesis already exists, and it is required to decide how to hand relevant meat onto this skeleton loop, or to develop a feedback hypothesis

Fig. 2 A Stepwise Methodology for System Dynamics
Part I - Problem exploration/Model creation

1. Recognise the key variables associated with the observed symptoms of concern (reference mode) and to the need for enquiry.

2. Identify some of the initial system resources associated with the key variables.

3. Identify some of the initial states (levels) of each resource to be used.

4. Construct physical flow modules associated with each state of each resource, containing the physical processes or rates which affect these. (A module must contain at least one resource state and one rate).

5. If more than one state of a resource is involved cascade flow modules together to produce a chain of resource conversion or transfer.

6. For each module a set of cascaded modules identify the intra module behavioural information and contol (policy) links by which the levels affect the rates.

7. Identify similar behavioural, informal and control links between modules of different resource types. For complex situations this should be carried out for small groups of resources at a time within a defined theme and the resultant diagrams reduced to produce the simplest representation possible, consistent with relating the key variables of the investigation.

8. Identify any new states of existing resources, or new resources, which affect the rates of the modules created or new key variables, and add these to those recognised at 1 and 2. Reiterate if necessary.

Fig. 3. A Stepwise Methodology of System Dynamics
Part II - Model Analysis

Carry out a qualitative analysis of the overal diagram to identify

1. further problems, in addition to those used in Stage I (1) associated with the system.

2. specific relationships in the system which need further analysis by specific techniques.

3. controllable variables (and the controllers in multiple ownership systems).

4. the general systemic impact of changes to controllable variables.

5. the vulnerability of the system to changes in uncontrollable variables.

6. alternative groups of compromise changes which might lead to improvements in the system.

7. The merits and definition of a quantitative analysis.

in a system with which the analyst is familiar. However, when both the hypothesis and the subject matter are poorly known severe difficulties exist and it is precisely with this type of situation that the stepwise influence diagramming method has been devised. Fig 4 is presented to highlight the different system starting conditions that an analyst might be faced with and the methods of model construction that may be most appropriate to each.

One of the major attractions of a complete methodology is to provide guidance in unfamiliar subject areas and, although some guidance should be forthcoming from the system actors, the method itself should be capable of providing detailed guidance for exploring the feedback structure relevant to the perceived cause for concern.

The steps of Fig. 2 attempt to do this by a formal process which progressively increases model complexity and then tries to simplify the diagram down to an end product which is the simplest representation possible, consistent with relating the key variables of the investigation within a feedback structure. These steps takes the analyst through a process of having to think firstly about each key variable and each resource type associated with the observed problem symptom, and secondly about each alternative state of that resource and its appropriate level of aggregation which could be included in the model. These resource states are, of course, the system levels and the method ensures the early recognition of these. Emphasis is placed on the fact that the initial choices attached to concerns,key variables, resources and status are not binding. The procedure is iterative and aimed at discarding and replacing if necessary the original choices of these elements as progress is made and understanding enhanced.

The core of the method consists of the generation of physical flow modules which identify the way in which resource states physically influence one another. The construction of these is assisted by the stress placed on rates as the means by which resources are converted from one state to another. Examples of pre-defined modules have been found useful to assist at this stage.[26,27] Each rate variable defined is considered in turn to identify how it is influenced by effects from within its own resource flow or from others. Inter module information links are thus created and for

		Condition	Method Appropriate
1.		Feedback Hypothesis Defined Knowledge of System Good	System Dynamic Flow Diagramming
2.	(a)	Feedback Hypothesis Defined Knowledge of System Poor	Influence Diagramming
	(b)	Feedback Hypothesis Unknown Knowledge of System Good	
3.		Feedback Hypothesis Unknown Knowledge of System Poor	Stepwise Influence Diagramming

Fig 4 Methods available for the construction of System Dynamics Models

convenience classified into control and behavioural types. Behavioural mechanisms are defined as the means by which systems adapt themselves in the long term if left to their own devices, whereas control mechanisms are defined to represent the actions of humans aimed at changing system performance in the short term in line with perceived objectives. The iterative process of Fig. 2 essentially combines the important issues of general systemic problem structuring and identification and the generation of a feedback hypothesis. The resultant model can be considered as a logically derived hypothesis.

Once a model in diagram form is thought to be complete it is possible to move into an analysis phase. This in turn may indicate further shortcomings but is essentially aimed at assisting understanding and policy interpretation. The steps inherent in this qualitative analysis stage, some of which represent formalised statements of the outcome of Part I are summarised in Fig. 3.

Qualitative analysis primarily consists of tracing through the links, feedback loops and delays of the diagrammatic model to determine the systemic consequences of exogeneous shocks, natural processes and internal control changes. This is often facilitated in complex diagrams by the isolation and individual treatment of each feedback loop. Of particular interest here is the identification of undesirable side effects of intuitively 'good' changes, by which the likely natural response of the system might act to counteract the effects of control; and the determination of groups of alternative, appropriate control measures, which can assist the system owners to make changes.

It is considered that such general assistance in complex systems is basically what decision makers need rather than hard answers and therefore what analysist must supply. The qualitative model broadly provides an overview picture readily accessible for interrogation as conditions change and can further be used to identify critical areas where greater information

is required. In this sense the model provides a framework by which to coordinate and control micro research studies where each analyst in a team can clearly see their role and contribution to the understanding of the whole. In particular it assists most where most other methods assist least; that is in the most difficult early stages of an enquiry where defining the real elements contributing to a problem and specifying and controlling the boundaries of a model are vitally important. Experience so far has shown that the method does help in overcoming the mystic often surrounding the derivation of System Dynamics models and that the use of the controlled expansion procedures, used to develop a model in logical and well defined steps, can be eminently useful in isolating missing elements during system description. Additionally, the transparency of the stepwise method presented further facilitates the communicative attributes of System Dynamics and the ability of the subject to identify important leverage points in a system during the analysis phase. The final stage of analysis at this point is, of course, to assess the merits of and to define the purpose and design of a quantitative simulation analysis.

CONCLUSIONS

This paper has primarily accused traditional System Dynamics of some reductionist behaviour, certainly in the sense defined by Linstone[15], relating to a tendency to maintain too specified a stance in the face of its own under-achievement and the needs of the market for systemic enquiry. It is suggested that the full breadth of potential of System Dynamics is not fully understood by its practictioners. Too many of its attributes are taken for granted and under valued in its emphasis on in-depth analysis. When its broader implications are viewed relative to other methods available for practical systems enquiry these attributes are seen to be sophisticated and highly important.

It is considered that the existing paradigm contains more than sufficient depth to achieve a more prestigious status within the field of system enquiry.

The challenge is for practitioners to examine the systemic limits achievable by the existing paradigm and to define appropriate practical re-orientations of the method to promote these rather than confuse the subject image further by the incorporation of additional theory. Changes have been presented in the paper which might help this process of promotion and it is felt that the qualitative and stepwise procedures described for model creation and analysis are appropriate to developing systemic understanding. Unless these and other attempts are made to break the subject of System Dynamics down into more understandable and widely accepted steps it will not increase its share of a rapidly expanding market.

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