SYSTEM DYNAMICS: A SYSTEM METHODOLOGY OR A SYSTEM MODELLING TECHNIQUE

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ABSTRACT

The purpose of this paper is to highlight and enhance recent development in system dynamics by presenting the subject as currently perceived by the System Dynamics Research Group at Bradford Management Centre. Emphasis is placed on the role of System Dynamics in system description, problem identification and qualitative analysis. It is concluded that the subject satisfies many of the requirements of a general methodology, as currently sought within the system field, as well as being a sophisticated dynamic modelling technique.

1. INTRODUCTION

The conception and development of system dynamics took place during the late 1950's at The Massachusetts Institute of Technology under Forrester, and although early work was in the management field,[1] the subject became primarily known during the late 1960's for its application at the macro level in urban and global modelling by Forrester[2,3] and Meadows.[4] Although macro applications are still in evidence,[5] the scale of individual applications has significantly reduced and diversified during the 1970's. During this period the subject has also developed its armoury of sub-techniques and its overall philosophy[6,43,44] and moved some way in defining its relationships with other enquiry methods.[7,8]

The purpose of this paper is to enhance this development trend by presenting a revised perception of the subject, which it is felt can both complement its traditional use and also make it a more useful tool for general analysts in a wide range of fields of enquiry. Earlier definitions of the subject[1,9,10] have been combined and re-orientated to produce a new subject summary, which is presented in Figure 1. Here a very clear split is made between the system description/qualitative analysis mode of system dynamics and the quantitative analysis mode using continuous simulation techniques. This split was not inherent in the original approach but is introduced here since it has been found useful in its own right and is an aid to compatibility with other methods of system enquiry. This summary will be expanded in the next section as a prerequisite to later discussions on the requirements of system enquiry methods and the merits of this approach. The summary may be stated in definition terms as:

> *"A rigorous method of system description, which facilitates feedback analysis, usually via a continuous simulation model, of the effects of alternative system structure and control policies on system behaviour".*

2. SYSTEM DYNAMICS AS A METHOD OF SYSTEM DESCRIPTION AND QUALITATIVE ANALYSIS

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

System Description, Qualitative Analysis	Quantified Analysis Using Continuous Simulation Techniques		
	Stage I	Stage II	Stage III
1. Of existing/proposed systems. 2. In terms of system flows (using levels and rates) and objectives. 3. Using physical, cash and information flows. 4. To examine feedback loop structure	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 structures and control policies based on: (i) intuitive ideas; (ii) control theory analogies; (iii) control theory algorithms; in terms of non-optimising robust policy design.	To optimise system parameters
To provide: (i) a perspective on the observed problem or symptom; (ii) a qualitative analysis on which to base recommendations for change	To provide a quantified assessment of alternative ways of improving system performance		

Figure 1: System dynamics – a subject summary

theory, and the literature abounds with examples of methods of system representation. Such diagrams are often referred to themselves as system models. A good selection of the simpler description methods (Venn diagrams, input/output diagrams, flow block diagrams, material flow diagrams, algorithms) are presented by the Open University.[11] Some of these have limited use, whilst others, such as algorithms or flow charts, have a well accepted and clearly defined role in computer systems analysis. A further excellent review of systems modelling techniques (here referred to as structural modelling) is presented by Linstone *et al.*[12] Some of which overlap considerably into the system dynamics field.

System dynamics utilises a specific method of system description based on rates and levels, which will be very briefly described here to emphasise the characteristic content of the left hand box in Figure 1. Levels are the state variables of measurable quantities of a system, whereas rates are the systems action or policy variables that effect changes in the levels and utilise information from the levels.[10] Forrester's original convention was to use sources and sinks for each type of flow, and to depict rate variables by values, since these were a direct physical analogy of the control function of such variables. Today, however, system dynamics diagrams are almost entirely based on the digraph principles of control engineering. These are more commonly known as influence diagrams,[10] casual loop diagrams[13] or signed digraphs.[12] Morecroft[13] summarises the history and development of such diagrams.

The convention of these diagrams is that the links between stated variables are indicated by arrows, depicting both the direction and sign of influence. Thus, for example, in Figure 2 an increase in recruitment rate increase the level of the workfoce (a positive effect) and an increase in leaving rate decreases the level of the workforce (a negative effect).

Although many sophistications to these procedures are possible, this brief description encapsulates the underlying simplicity and elegance of the approach. Chains of relationships are hence constructed, built up of physical flows (cash, materials and manpower etc.) and information flows. The inclusion of the latter is of fundamental importance and results in the creation of information feedback loops which determine system behaviour in the light of which information is used and in what way. It is perhaps this ability of the method to represent natural processes of adaptation which brings it closer to reality than most other approaches. Simple examples of two negative feedback loops (A and B) are shown in Figure 2, where it is inferred that both recruitment rate and leaving rate will themselves depend on the sixe of the workforce. An extension of this could easily be to define a target

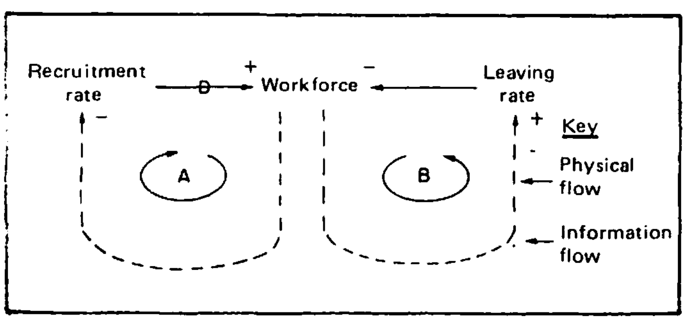

Figure 2:

or objective size for the workforce (which itself could be adaptive). Policies could then be defined as the rules by which the rates could be regulated in the hope of achieving this target. Sub-system objectives and control policies, together with delays (e.g. in training, as shown by the letter 'D' in Figure 2) are very important facets of the description process.

The overall sign of the feedback loops are determined by the product of the signs on their constituent links, and it is this factor along with other more detailed characteristics of the loops (for example the existence of delays and the number of levels), which can be used to explain system behaviour and guide thinking for structural and policy improvement. It is important to note that the qualitative analysis facilitated by this description phase of applying system dynamics is often sufficient in itself to generate problem understanding and ideas for change. This theme will be developed after a brief description of the system simulation phase of system dynamics.

3. SYSTEM DYNAMICS SIMULATION

Having obtained a system dynamics diagram of a particular system, this is sufficiently rigorous to be directly translated into a set of mathematical equations capable of being handled by a computer. The medium for this is the use of different equations to approximate the process of integrating rates into levels, using a standardised notation. Originally developed by Pugh[14] and incorporated in a set of programmes known as DYNAMO. These have been considerably enhanced since their original introduction and joined by other similar packages. Such as DYSMAP (Dynamic System Modelling and Analysis Package), developed by the Systems Dynamic Group at Bradford Management Centre.[15] These programmes allow equations to be written direct from the influence diagram (each equation representing an individual link of the diagram) and facilitate easy revision of the model.

The simulation method incorporated into all the above system dynamics packages is essentially a time slicing simulation applied to continuous variables and incorporating continuously adaptive information feedback facilities. This contrasts strongly with the more conventional and essentially open system approach of stochastic simulation, involving discrete entities. Any natural phenomena is, of course, a mixture of discrete and continuous relationships, and the format of packages such as DYSMAP are designed to give considerable flexibility to incorporate discontinuities and random processes, as demonstrated for example by Wolstenholme and Coyle.[16] Although system dynamics computer packages have a variety of functions to assist the formulation of a simulation model, only two basic 'types' of equation are necessary. These are level and rate equations. The former are generally of a fixed format associated with either conservation or average of flows, and the latter are associated with policy definition.

It will be seen from Figure 1 that three states are identified with the simulation phase of the subject. The elements listed in each stage will be familiar to those conversant with traditional full scale applications of the subject. A full description of this phase is beyond the scope of this paper but brief reference will be made to recent development. For example, in stage I model validation methods have received considerable attention.[6,17,18] in stage II many advances have taken place in the incorporation of control system theory,[19,20] control algorithms[21] and performance measures[22] in system dynamics models; and in stage III techniques of parameter estimation and the optimisation of composite objective functions have been developed.[23,24,25]

It is therefore possible to achieve a very full and deep, quantified analysis from this phase of the subject, if this is justified.

4. SYSTEM ENQUIRY METHODS

Having described the major individual elements which constitute the subject of system dynamics, the purpose of this section of the paper is to examine the relevance of other approaches to system enquiry. The words system enquiry have been carefully chosen in this context to cover what is an enormous field of investigation, which, although very well established and documented in some areas, constitutes in total a very fragmented, overlapping and ambiguous grouping of ideas, and one where attempts to relate the groups have been very limited. The objective here, therefore, is not to provide a comprehensive guide to these groups but to present a personal overview which it is hoped will enhance general understanding and set a framework for understanding the potential contribution of the system dynamics philosophy described.

The major difficulties arise from the sheer diversity of the field studied, and the literature abounds with both the definitions and classification of systems. Three major systems characteristics are isolated here, which are considered sufficient for the purpose of contrasting the merits of alternative approaches to them. These are:

1. *Hardness:* the degree (or ease) with which systems can be precisely specified and quantified.
2. *Ownership:* the number of individual interests within a system; usually equivalent to the number of competing objectives, and hence policies, within a system.
3. *Size/complexity:* the degree of interaction of system parts and hence the ease with which factors can be isolated.

None of these characteristics is, of course, entirely independent, and many fine distinctions are possible. Naughton,[26] for example, differentiates between purposeful systems, which have objectives, and purposive ones, which only appear to have objectives. This implies that the latter are really driven by sub-objectives within purposeful sub-systems and that at higher levels the combined system simply evolves as a result. In general, systems with clear top level objectives and ownership can be defined as managed systems, although this term is often used to differentiate between systems controlled by people and the automated systems used in engineering. Any system, however, can encompass any degree of the above characteristics depending simply on where the boundaries are drawn, and this is often determined by the type of question we require to ask of the system: for example, whether a simple prescriptive answer is sought or whether advancement in understanding or redesign is the aim. The types of approach developed for system enquiry have centred on an appreciation of all these factors.

We shall for convenience define the single owner, small scale, harder end of the systems spectrum as the bottom end. This is effectively the areas where classical scientific methods have thrived and been adapted and developed for application in softer, man made systems. Operational Research is perhaps the prime example of such development and has achieved much success by the development and application of generalised techniques, particularly for short term answers in problem orientated situations. However, as the complexity, softness and multiple interest factors increase, the rigidity of these ideas has seriously limited their ability to provide similar success. The adaptive response often seen here is based on a philosophy of reductionism; that is to increase the depth and detail of individual modelling techniques to make them fit, often resulting in vase multiple hierarchical models. There are exceptions to this, but it is of interested to note that, where such techniques have made an impact at the higher levels, they have conceded the need to overcome one or more of the above system characteristics. This is usually achieved by the introduction of many more simplifying factors and associated assumptions, but is also apparent in the use of ideas to overcome the difficulties of softness. This is inherent, for example, in the use of probability theory and utility in decision theory.

The foregoing difficulties were recognised by Forrester[9] and formed the basis of one of his main arguments used for the development of the whole subject of system dynamics. Recently Linstone,[12] for example, has underlined the difficulties which arise when systems go beyond purely technological factors. According to Johnson,[27] the lack of compatibility between the techniques used and actual management thinking is one of the major problems in applying Operational Research at the strategic level. This situation is also highlighted by Coyle,[28] who points out that most teaching of theory to managers is currently based on techniques *only* relevant to prescriptive solutions in hard systems and that this is not the area in which management generally requires guidance.

Ultimately, of course, it is feasible to simplify to the extreme and consider a system as merely a conversion process, which ignores any attempt to understand the true mechanisms of

	Stage 1	Stage 2	Stage 3
Social sciences	Recognition of need for information	Collection and interpretation of data (statistical techniques)	Conclusions and implications for change
Operational research	Problem identification	Definition and application of relevant modelling techniques	Implementation of results
Computer systems analysis	Definition of objectives	Generation and evaluation of alternative systems	System selection

Figure 3: Some discipline based interpretations of the pure scientific methodology.

conversion. Such approaches are widely used and are inherent in the philosophy of both input–output analysis and econometrics.

Hence what might be described as the bottom-up approach to system enquiry is recognised to have limitations. These limitations, perhaps, can best be considered as the limitations generated by strict adherence to approaches, based on extensions to the pure science research methodology of observation, hypothesis formulation/testing and application of findings. The way the overall methodology has been adapted to suit different disciplines and areas of application is very varied, and Figure 3 presents just three examples of such adaptations. In general, these can be summarised as the stages of problem identification, analysis and implementation.

In fact, most approaches based on this methodology of enquiry do not provide any formal steps for the first and last stages but concentrate almost entirely on the analysis phase. Further, the word methodology is often applied simply to the second stage; that is, it is used to represent only the process by which particular techniques of analysis or modelling are deployed – for example, the linear programming methodology.

In a results orientated world it is difficult to escape from the philosophy of developing techniques of analysis for limited problem forms. However, the need to have a much wider and flexible approach to ill-structured, problematic situations has long veen recognised and perhaps epitomises the purpose of systems thinking. The philosophy of holism employed in such thinking represents an ancient and beautiful idea which continues to grow in popularity. The systems movement as a medium by which to apply holistic ideas is equally desirable, being seen, for example, by Drew[7] as a movement to put back together a world the generations of analytical science has taken apart. However, the derivation of meaningful concepts, for example via the general system theory (GST) of Bertalanffy,[29] has not materialised, and the systems movement is seen by both Drew[7] and Checkland[30] as nothing more than a doctrine for uniting specialists and conditioning generalists.

Hence, moving away from science based methodologies into a purely top down approach to system enquiry would appear to be unrealistic from a practical viewpoint.

Consequently there continues to be extensive research into compromise approaches, and current systems work in characterised by this search for alternative methodologies, which might be more relevant to the higher reaches of the systems spectrum. Methodology is defined here as the overall processes of investigation by which concepts, philosophies and theories can be expressed independently of the process of the investigation, and ideally, independently of the problem type.

The ideal methodology, according to Checkland,[30] "must avoid the content free methodologies derived from GST and the over precise goal orientated formulations stemming from system analysis". He further emphasises the need, simultaneously, to "be precise enough to provide guidelines but vague enough to remain problem orientated".

Within the framework of recent research, a number of compromise approaches have evolved but the main theme of work, however, still stems essentially from bottom-up ideas. In particular much use has been made of retaining the philosophy, but not the detail, of system analysis ideas arising out of the strand of computer system design and often combining these ideas with existing management science techniques.

This approach is, of course, exploited in most strategic planning methods and has been/is being extensively used in system design via the media of system engineering and system management, De Neufville and Stafford[31] have extended the concepts into the softer systems area by applying the ideas to generate and objectivity compare alternative systems. However, one of the major difficulties in such approaches is how to generate the alternatives.

The Checkland methodology is perhaps the closest approach to date to a general methodology as described above. This methodology, although evolving upwards from system analysis via the ideas of Hall[32] and Jenkins,[33] is much closer to the GST transdition.[26] The characteristic of the method is to provide guidance on the isolation of relevant problem themes from a given situation and on the definition and conceptualisation of new systems to avoid each theme. This is a very powerful approach, which clearly separates important factors such as organisational structure/process and systems/real world thinking but is essentially descriptive.

In considering the merits of any method of system enquiry, it should, of course, be recognised that all face a task which becomes more impossible as we move up the systems spectrum. This is best summarised by Linstone[34] in terms of eight paradigms particularly relevant to higher levels of the spectrum. These are:

(i) There are no solutions, and investigation merely shifts the problem to a higher level.

(ii) There are no best solutions, as only the most primitive systems optimise.

(iii) Reductionism and specialism are natural human ideals in that these generate the greater chance of fame and success, and modelling is an end to this.

(iv) Data and models are unreliable modes of enquiry.

(v) Ambiguity is often more desirable than quantification.

(vi) Objectivity is a myth.

(vii) The individual as an individual is ignored.

(viii) Time itself is a perception.

The above paradigms are undoubtedly real, and Linstone[34] uses this list to emphasise that it is *how* a situation is perceived that is important rather than what the situation is and further, that separate perspectives ecist from the points of view of technology, the organisation and the individual.

5. SYSTEM DYNAMICS: A SYSTEMS METHODOLOGY OR A SYSTEMS MODELLING TECHNIQUE

System dynamics has over many years been applied to a wide variety of situations with either an implicit belief that the approach was correct or eithout, in general, too much detailed concern by the analyst as to how the systems studied related to any general classification. The usefulness of such studies have provided their own justification for the approach. 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. These attributes will be discussed for each of the two distinct parts of the subject defined in Figure 1, relative to the needs of system enquiry methods previously outlined in the previous section of the paper.

The method of system description used within system dynamics and its ability to provide qualitative analysis is, in general, taken for granted by practitioners of the subject. Consequently it is rarely published in isolation from a full, qualified study and is therefore not widely appreciated outside the subject. Exceptions to this are available[28,35,36] as a result of the current research orientation at Bradford. The prime purpose of this paper is, in fact, to publicise the general merits of isolating this aspect of system dynamics, since it is considered to have much to offer, in its own right, to the current methodological dilemma in the field of system enquiry. The building blocks of rates and levels are of universal generality, and the method provides extreme flexibility with formal guidelines for application – for example, through the technique of list extension.[10] More rigorous and formal techniques are currently under development.[35]

The potential of this descriptive process is best considered by outlining its attributes in some of the more difficult areas of system enquiry.

The first of these concerns problem identification and isolation within complex situations. It is obviously good practice in any system investigation to have a specific problem or symptom to address, and system dynamics is no exception to this.[37] However, as previously indicated, most methods of enquiry then move straight into an analysis phase using some appropriate technique of solution without consideration, or the means to determine, whether or not the problem is correct. This is not the case in system dynamics. Here, the initial emphasis is on exploring the perceived problem context. One or two of the more obvious real world elements or variables which have a bearing on the problem are taken as the starting point, and a descriptive model systematically created around these elements. This is achieved by a progressive and logical expansion of the cause and effect chains leading from the initially defined elements.

This process facilitates both the recognition of important additional elements and the elimination of others. In other words, problem understanding and perspective is enhanced, and it is often the case that the final conceptualisation achieved and used for analysis does not emphasise, or even contain, the elements from which it originated.

It is important to note that the conceptualisation process described can be achieved across existing functional and organisational boundaries using a mixture of flow types and that, although the method is essentially one of process diagramming, it is possible to keep in mind the implications of organisational structure and areas of decision responsibility implied by the model.

The second major problem of system enquiry which is greatly assisted by this same process is that of defining the boundaries of a model for problem analysis. Model development by controlled extension and enrichment, in which each link must be individually justified, enables a sensible balance to be achieved between remaining sufficiently relevant, in all aspects of the problem area, to generate insight, and sufficiently simple to promote understanding. This is particularly important at the higher level of the systems spectrum where structural guidance is provided to help overcome the tendency to create very detailed and complex models.

Attaining a well balanced model is, of course, difficult for the analyst in isolation, and this leads to the third major problem of system enquiry: that is the need to establish and maintain involvement with system actors during both problem and model definition. One of the major attributes of the process of system description used in system dynamics is that it is sufficiently straightforward and realistic to facilitate communication. In fact, it has been argued by Senge[38] that system dynamics diagrams mirror very closely the way in which senior management has to think, and that the cause and effects 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 sufficient scope and merit in promoting such practices in those less well endowed. This theme is now being developed in the United States by the introduction of casual loop diagramming into secondary school cirricula.[39]

The process of qualitative analysis of influence diagrams will now be considered. This is a distinct operation which follows naturally from the construction of a good structurally coherent diagram.[10] It can be considered, particularly in very soft systems, as an end itself, or as a forerunner to simulation analysis. The analysis generally takes the form of tracing the effects of perturbations and policies on the system, right through the casual loop structure of the diagram. It has been shown[28] that, in addition to receiving unpreditable and adverse external shocks, systems have an outstanding propensity to shock themselves; and analysis can aid the identification of the relative parts played by external and internal influences. The important point is that such analysis provides guidance in moving from 'what is' to 'what should be' by assisting both in the generation of alternatives for improvement and in their assessment. This facilitates the formulation of groups of recommendations of both what to do and what not to do to enhance performance rather than specific answers.

Further, the process of diagram examination facilitates identification of critical factors or restrictions and leverage points where the biggest impact on performance might be achieved.[33] This can often lead to implications concerning the use of more specific and detailed modelling techniques to further understand individual links of the diagram. In other words, systematic guidance to the application of more formal system modelling techniques is facilitated.

It is further possible in multiple ownership situations to use influence diagrams to demonstrate to the owners of system sub-sectors how their respective policies interact with one another. This is particularly useful in comparing individual perceptions of systems and enhancing communication and compromise.

Together, the system dynamics process of problem/symptom explanation, qualitative analysis and recommendations for change, as described above, constitutes a general methodology for system enquiry. This is essentially a further adaptation of the pure science research methodology but with the following advantages:

1. general applicability and independance of content of enquiry;
2. an ability to provide guidelines at *every* stage;
3. sufficiently flexible to function at the higher levels of the systems spectrum.

Although the qualitative aspects of system dynamics modelling have been emphasised in the foregoing discussion, system investigations involving the approach should, wherever possible, take advantage of the ease with which this can be supplemented by quantitative analysis. Indeed, 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. There is, in fact, much evidence in the references to this paper and elsewhere to suggest that this simulation technique can itself be applied to situations well up the system spectrum. The ability of the software used to accommodate subjective relationships in fact facilitates applications in what might previously have been thought to be very soft system areas. In particular, recent studies in multiple ownership situations have demonstrated how the approach can be used to simulate overall system behaviour, resulting from the influence and relative strength of conflicting policies, within major subsystems.[40,41,42] The scope for studying the merits of introducing control of such systems by higher level intervention (for example, governmental or international) is enormous.

In general system dynamics can claim to have taken both descriptive and quantified modelling ideas into the higher reaches of the 'system spectrum whilst preserving sufficient, relevant model content to provide explanations of system behaviour.

This is not to say it should or can supersede other methods. Rather it is seen as a useful approach which can provide an initial qualitative overview, which may then be used to define the appropriateness of other more specific, problem orientated techniques, including its own simulation phase.

CONCLUSIONS

This paper has presented system dynamics as a system methodology, capable of assisting with practical problem definition, analysis and change in a wide range of systems and with a potential to provide a more significant contribution to current general system practice than presently achieved. It is felt that the major reasons why this potential has been inhibited stems from its misperception and the wide range of issues to which it has some relevance. In the extreme case, this results in its perception by soft system methodologists as a hard system modelling technique and in its perception by hard system modellers as a soft system approach. In practice it combines some of the better features of both worlds, and it is hoped that, by the revised perception of the subject defined here and the presentation in the context of system enquiry methods, understanding has been improved.

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