Systems Research and Behavioral Science
Syst. Res. **17**, 3–22 (2000)

■ *Research Paper*

Should System Dynamics be Described as a 'Hard' or 'Deterministic' Systems Approach?

David C. Lane*

Operational Research Department, London School of Economics and Political Science, University of London, London, UK

This paper explores the criticism that system dynamics is a 'hard' or 'deterministic' systems approach. This criticism is seen to have four interpretations and each is addressed from the perspectives of social theory and systems science. Firstly, system dynamics is shown to offer not prophecies but Popperian predictions. Secondly, it is shown to involve the view that system structure only partially, not fully, determines human behaviour. Thirdly, the field's assumptions are shown not to constitute a grand content theory — though its structural theory and its attachment to the notion of causality in social systems are acknowledged. Finally, system dynamics is shown to be significantly different from systems engineering. The paper concludes that such confusions have arisen partially because of limited communication at the theoretical level from within the system dynamics community but also because of imperfect command of the available literature on the part of external commentators. Improved communication on theoretical issues is encouraged, though it is observed that system dynamics will continue to justify its assumptions primarily from the point of view of practical problem solving. The answer to the question in the paper's title is therefore: on balance, no. Copyright © 2000 John Wiley & Sons, Ltd.

Keywords systems theory; systems thinking; information feedback; systems engineering; social theory; philosophy

INTRODUCTION

In this section the motivation and form of the paper are introduced. First, the main ideas of system dynamics are presented (readers familiar with the approach may wish to skip this subsection). The range of accusations that system dynamics is a 'hard' or 'deterministic' systems approach is then introduced. This provides the motivation for the remainder of the paper, the main sections of which are then outlined.

The Nature of System Dynamics

System dynamics is a system approach based on servo-mechanism theory (Richardson, 1991). It was created by Jay W. Forrester at MIT in the late 1950s and involves the modelling of social

* Correspondence to: David C. Lane, Operational Research Department, London School of Economics and Political Science, University of London, Houghton Street, London WC2A 2AE, UK.

CCC 1092–7026/2000/010003–20 $17.50
Copyright © 2000 John Wiley & Sons, Ltd.
Received 28 September 1998
Accepted 23 June 1999

systems using computer simulation, with practitioners working closely with problem owners to structure debate about long-term policy. The history of the field is discussed elsewhere (Forrester, 1990; Lane, 1998) and its main ideas may be found in a range of publications (Forrester, 1958, 1961, 1968b, 1975; Randers, 1980a; Richardson and Pugh, 1981). In the account that follows, the field is presented in terms of three aspects: the ideas behind the practical modelling approach; the theoretical assumptions of the field; and finally its institutional features, its contribution to systems thinking and its literature.

As a modelling approach, system dynamics has three characteristics. First is the concept of information feedback loops. These involve the collection of information about the state of the system, followed by some influencing action which changes the state of the system. These closed loops of causal links involve delays and non-linearities as well as processes of accumulation and draining. The second characteristic is computer simulation. Although humans can conceptualize such loops, they lack the cognitive capability to deduce the consequent dynamic behaviour without assistance (Sterman, 1989, 1994). Computer simulation is therefore used rigorously to deduce the behavioural consequences over time of the hypothesized causal network. The shifting interplay of loops means that different parts of a system become dominant at different times. Such behaviour is counter-intuitive, and may be explored using simulation models. The third and last characteristic of system dynamics is the need to engage with mental models. The most important information about social situations is only held as 'mental models', not written down. These mental models are complex and subtle, involving hard, quantitative information and more subjective, or judgmental aspects of a given situation (Doyle and Ford, 1998; Lane, 1999a). Such models are the basis for organizational decision making. Hence, eliciting, debating and facilitating change in the mental models of decision makers can result in improved ways of managing a system. Modelling work must therefore be done in close proximity to problem owners, who are then able to see that their mental models are reflected in a computer model.

This means by which these ideas are implemented are shown in Figure 1. A situation is conceptualized in terms of loops and decision points. A system dynamics study is focused around a 'dynamic hypothesis' — the idea that a certain causal structure explains a certain dynamic behaviour. Model building tests this hypothesis using rigorous formulation and by synthesising objective and judgmental data (Randers, 1980b). Such a model is a theory for the structural source of the dynamic behaviour. When problem owners have confidence in a suitably validated model (Forrester and Senge, 1980), it can be used to test the dynamic hypothesis. It is by policy analysis and repeated experimentation with such models that organizational actors can learn together to create shared mental models. Subsequent policy making is therefore informed by an improved intuitive understanding of both the dynamic possibilities of the system and of the policy levers that might be used to steer it, and also to continue to learn about its operation.

The theoretical assumptions of the field are more difficult to establish. Although a few publications have addressed this subject (Meadows, 1980; Barlas and Carpenter, 1990; Lane, 1994; Vennix, 1996), the field has tended to take its theoretical assumptions rather for granted. This concentration on trying to understand real-world phenomena perhaps reflects the field's solidly practical engineering roots (Richardson, 1991). A recent attempt to unearth the social theoretic foundation of system dynamics therefore had to rely primarily on inference from practice (Lane, 1999b). Various conclusions were proposed in that paper. On a superficial level, system dynamics appears to be locatable within the functional sociology paradigm of social theories, its ideas seeming to be a version of social systems theory (Burrell and Morgan, 1979). However, the craft of system dynamics, and hence its theory in use, has many links with more interactionist schools of thought and even some connections with interpretivism (see Lane and Oliva, 1998). This uncertainty leads to one possible conclusion that the theoretical position

Copyright © 2000 John Wiley & Sons, Ltd.

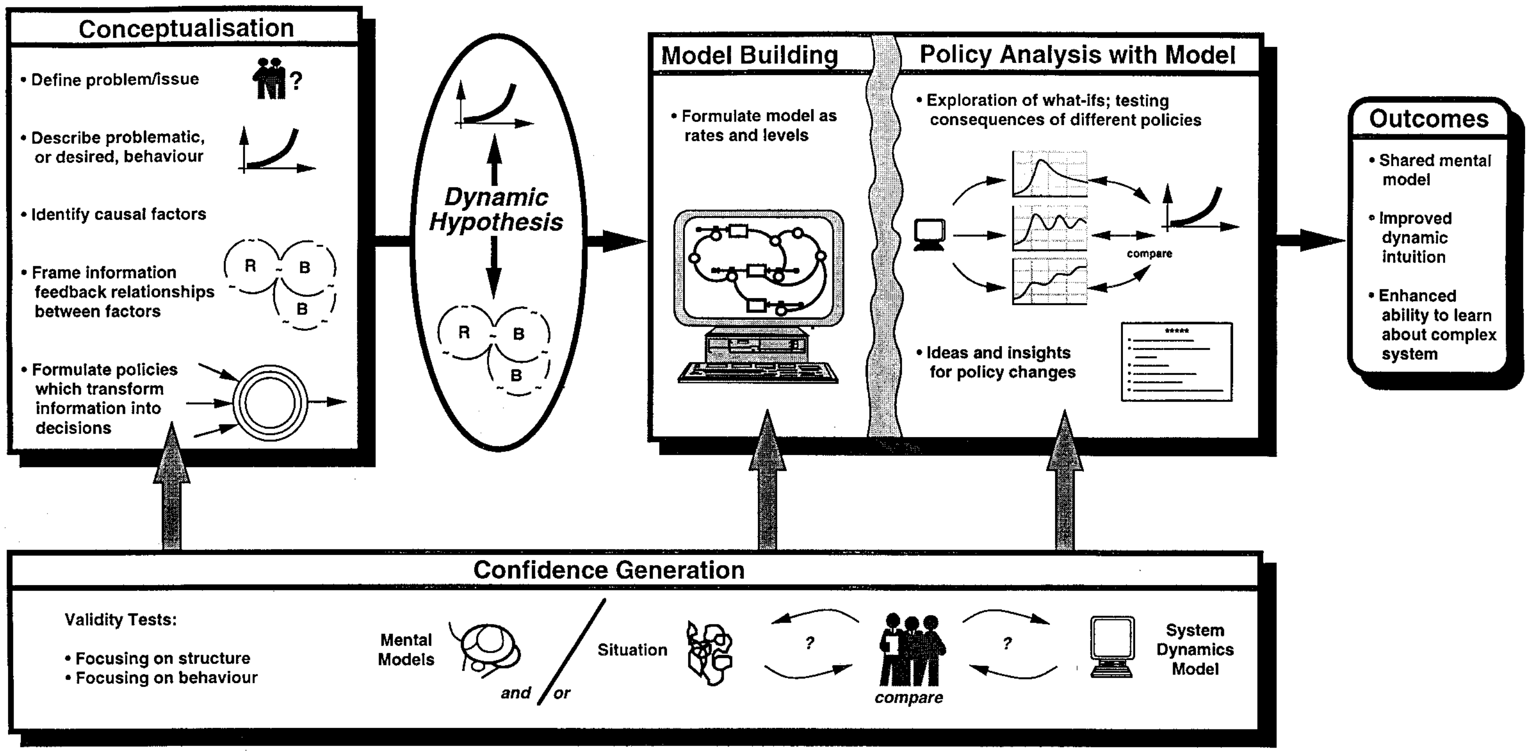

Figure 1. The main components of the system dynamics inquiry process (developed from Lane and Oliva, 1998)

Copyright © 2000 John Wiley & Sons, Ltd.

of system dynamics cannot be conveyed with reference to more traditional social theoretic assumptions but may best be seen in the light of those theories which seek to integrate the agency and structure views of the social realm (a suggestion explored elsewhere (Lane, 1999a, 1999c)).

Institutionally, system dynamics has created an International Society,[a] an annual conference and various national Chapters. There is a dedicated refereed journal, *System Dynamics Review*. The field has produced numerous publications in book and article form which record its achievements in theory building. Comprehensive lists may be found elsewhere,[b] so for the purposes of this paper it is only necessary to mention a sample. System dynamics has been applied to: the growth and stagnation of cities (Forrester, 1969), global development (Forester, 1971b; Meadows *et al*., 1972, Meadows *et al*., 1992), software development (Abdel-Hamid and Madnick, 1990), emerging economies (Saeed, 1991), health care policy (Lane *et al*., 1999), organisational learning (Senge, 1990) and the implementation of TQM initiatives (Sterman *et al*., 1997). A very useful collection of theoretical and practical articles is available in Richardson (1996).

On the 'Hard' or 'Deterministic' Criticisms of System Dynamics

Amongst the systems scientists who have offered comments on it (and the few social scientists who have come across it), system dynamics is frequently judged to be a 'hard' systems approach. This does not mean 'difficult'. Rather, it likens the approach to systems engineering and to social systems theories which conceptualize the social world as operating like a machine — both of which views modern systems science has felt a need to escape from. In fact, in the struggle to find criticisms to hurl, a barrage of terms has been employed. In addition to 'hard' (Keys, 1988; Dash, 1994), system dynamics has also been labelled as 'simple' and 'unitary' (Jackson and Keys, 1984), 'machine'-like (Flood and Jackson, 1991) and 'deterministic' (Jackson, 1991, 1994). Many of these terms overlap. For example, having asserted that system dynamics takes a deterministic view of human behaviour, Jackson (1991) proceeds to offer this as the reason why 'Forrester's modelling techniques have tended to be used in conjunction with essentially hard systems methodologies' (Jackson, 1991, p. 93).

These criticisms can be interpreted in at least four different ways (see below). For the purpose of this paper the term 'hard/deterministic' will therefore be used to describe this bundle of criticisms.

Why are these criticisms important? As already mentioned, they make a highly unwelcome linkage back to systems approaches now discredited as examples of 'hyper-rationalism' (Rosenhead, 1989; Lane, 1994). They have also led to the conclusion that the field is 'caught in an appalling paradox' (Jackson, 1993, p. 22). Further examples are given in the following sections.

This is strong stuff. Such criticism would be an important verdict for any research program. What is rather more galling is that at least two of these criticisms are, as demonstrated below, false. Yet these criticisms are widely known within the general systems science movement. For members of that movement, the above citations are possibly the most important information sources on system dynamics (notwithstanding the fact that all originate from researchers outside the system dynamics field). The systems science movement is diffusing into the social sciences via information systems, planning theory, operational research, management etc. This is creditable but it is happening with other systems approaches, system dynamics seeming to have fallen into disrepute in the eyes of some, partially because of its imputed hard/deterministic nature. For system dynamics to fail to prosper because of genuine weaknesses and inconsistencies is one thing. For such failure to occur because of incorrect readings of the field's core ideas is an entirely different matter.

To begin to counter this situation the following sections deal with the various 'hard/deterministic' criticisms that are made of system

[a] Email: SDSociety@aol.com, or sds@cnsvax.albany.edu, or System.-Dynamics@albany.edu.
[b] See Lane and Jackson (1995) and Lane (1998) for annotated lists of publications. Information (and critical comment) on the recent republication of important early system dynamics texts may be found in Lane (1997a, 1997c, 1997d).

Copyright © 2000 John Wiley & Sons, Ltd.

dynamics. These can be interpreted in four different — though not entirely distinct — ways. These are outlined below and illustrated in Figure 2:

- The first accuses system dynamics of philosophical *naïveté* in assuming that future events can be prophesied.
- The second accuses system dynamics of dehumanizing extremism in assuming complete structural control of the decisions of human agents.
- The third accuses system dynamics of social scientific crudity in assuming that there are cause and effect laws which exist outside of human subjectivity in a form of timeless 'grand theory'.
- The fourth and last accuses system dynamics of being operationally austere and coercive in that it is essentially a 'systems engineering' approach.

For ease of exposition this paper is structured around these four interpretations of the term, although it is acknowledged that the ideas are related and somewhat overlapping. In each case the criticism is described in more detail and a response is then offered. By the close of this paper it will have been argued that a majority of the criticisms are unfounded, while the terms of debate regarding the remaining criticisms have been clarified constructively.

PROPHECY CREATION?

The first interpretation of 'hard/deterministic' is that it indicates the philosophical position that 'all things, including will, have causes' (Beishon and Peters, 1981, p. 323). In this view a clockwork universe rolls forward in time in an utterly mechanical way, with all phenomena — events, thoughts and actions — as mere inevitable consequences, rationally predictable in principle. One can then obtain a 'prophecy', a 'prediction about an event which we can do nothing to prevent' (Popper, 1957, p. 43). What is then called for is not a proactive response but a stoical acceptance of the inevitable since the recipient of such a prophecy can only 'meet it prepared' (Popper, 1957, p. 43).

This deterministic position has a long history, described in Popper's exegesis of the seductive appeal of this idea (Popper, 1945a, 1945b). It has been adopted by Spinoza, Hume, Kant (reluctantly) and Mill (Popper, 1982). Deemed 'so far the purest, the most developed and the most dangerous form' (Popper, 1945b, p. 81), it is Marxist economic determinism — or 'historicism' — that is the main object of Popper's attack (Popper, 1957) and it is consequently disparagingly referred to today as 'vulgar Marxism'. However, determinism manifests itself in various forms: technological, biological, metaphysical, religious and scientific; the last being associated with Laplace (Popper, 1982).[c]

System dynamics has been criticized for determinism as prophecy, for being appropriate only for systems 'we usually cannot do very much about; the solar system, for example' (Jackson, 1994, pp. 219–220). Describing the field elsewhere, Jackson writes, '[the] deterministic perspective in hard systems thinking ... take[s] the future to be determined by factors outside the control of organizational actors. It is the job of the systems consultant to predict the inevitable future and help managers prepare for it. Thus the opportunity to mobilize people to design their own future is missed' (Jackson, 1991, p. 80). There is some terminological ambiguity here but the sense is clear — and utterly incorrect as it relates to system dynamics.

The notion of prophecy is sharply distinct from that of 'technological/scientific prediction' (Popper, 1945a, 1945b, 1957). Based on if/then arguments, predictions are both conditional and 'constructive, intimating the steps open to us if we want to achieve certain results' (Popper, 1957, p. 43). As with the rest of operational research and systems science, system dynamics helps people to think about the logical consequences of certain assumptions. Model inputs are not prophecies but

[c] Laplace has been backhandedly 'credited' with converting the doctrine of determinism from a 'truth' of religion to a 'truth' of science (Popper, 1982). However, the subtle injustice of this attribution is widely observed (for example, Sokal and Bricmont, 1998). Writing in 1825, Laplace was using the impossibility of ever knowing enough laws and antecedent conditions as an argument for the practical rejection of determinism in favour of probabilistic approaches.

Copyright © 2000 John Wiley & Sons, Ltd.

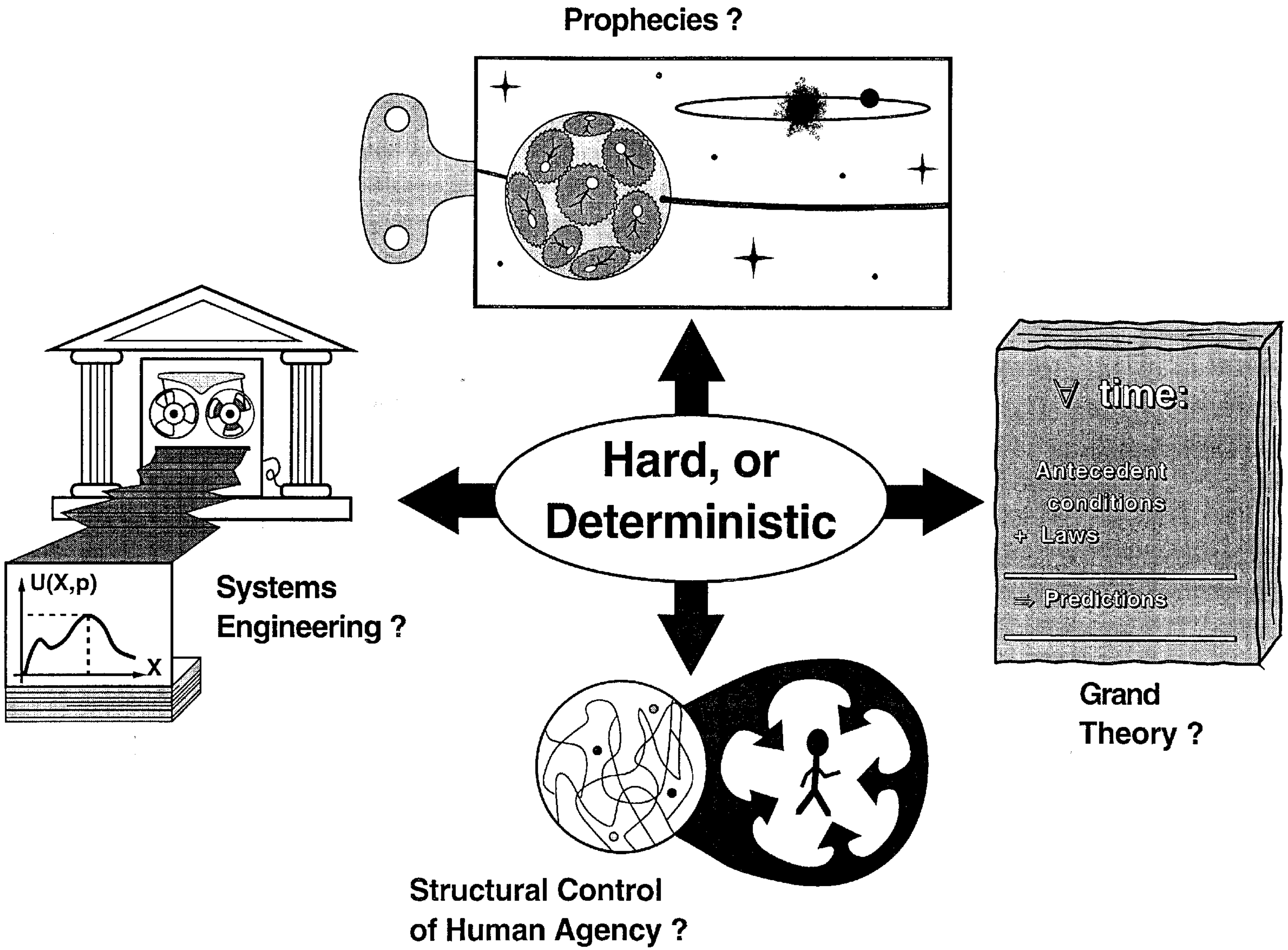

Figure 2. Four interpretations of the 'hard/deterministic' criticisms explored in this paper

Copyright © 2000 John Wiley & Sons, Ltd.

predictions and they are conditional on the assumptions. The point of an intervention is to aid in the creation of new assumptions, that is, guiding policies. This position is clear from the earliest writings of the field (Forrester, 1961) and even Forrester's most extreme remarks admit to the limits of models and therefore indicate the rejection of a deterministic aspiration (Forrester, 1980).

All-out determinism as prophecy is seldom advanced seriously today, having been comprehensively trounced as a philosophical position by Popper. Its most frequent use is as a 'straw man' against which an improved method of prediction and choice of preparation may be advantageously contrasted (see Churchman, 1970, and Ackoff, 1981, for examples). This may be the purpose of Jackson's above remarks but the result is a dangerous accusation of philosophical naïveté on the part of system dynamics. The interpretation of determinism discussed here is 'based upon a worldview which does not exist any more' (von Bertalanffy, 1962, p. 75). To be clear: this position has never been adopted by Forrester or any other system dynamicist. As an extreme illustration, consider the work on global modelling (Forrester, 1971b; Meadows *et al*., 1972, 1992). Putting aside the multiple scenarios that are presented, if the more worrying simulations in these books are indeed determined futures then system dynamicists are truly cast in the role of Cassandra; all that is being offered is the prophecy of certain disaster, the council of despair. This is not and has never been the task of the global modelling work, or any other form of system dynamics practice. The position of the field actually fits very well with Popper's conclusions on this subject: 'our universe is partly causal, partly probabilistic, and partly open [= shapeable by human will]' (Popper, 1982, p. 130).

HUMAN AGENCY SUBJECT TO COMPLETE STRUCTURAL CONTROL?

A second interpretation of the 'hard/deterministic' criticism concerns the stand taken by the field on the relationship between humans and their environment. System dynamics is said to take the view that people respond in a mechanistic way to social structure. In other words, system structure completely controls the decisions of human agents. This view relegates humans to mere cogs in a machine, passive respondents who have no autonomy. Although it may appear an extremely dehumanizing stance it nevertheless underlies the 'behaviourist' work of B. F. Skinner (see Burrell and Morgan, 1979, for an introductory discussion of the deterministic versus voluntaristic views of human nature, as represented in sociological theory).

This position is best viewed as an extreme point on a scale which might be labelled 'extent of human autonomy'. Determinism (in this sense) is then the zero point of the scale. At the other end would be the complete free-will view that 'individual decision making is unaffected by context and consequences of the system in which it takes place' (Bowen, 1994, p. 88).

Jackson believes that system dynamics takes a hard systems perspective which 'puts the system before people and their perceptions [and] extends to the ability of humans to intervene in their own destiny' (Jackson, 1991, p. 80). He also remarks that 'there is an apparent contradiction between deterministic ideas of systems governed in particular ways and voluntaristic ideas of our ability to do something about systems' (Jackson, 1994, p. 220). Again, there is some uncertainty about the exact meaning of these passages but at least part of the criticisms is that system dynamics is hard/deterministic in this sense of removing autonomy from humans and looking entirely to the social system for behavioural explanations.

Probing Forrester's Views

Does system dynamics adopt this deterministic stance? Forrester writes that 'decisions are not entirely ''free will'' but are strongly conditioned by the environment' (Forrester, 1961, p. 17) and he refers to 'man as a captive of his systems' (Forrester, 1980). A reasonable conclusion is that Forrester is simply offering a version of Skinner's behaviourism. However, a careful look at the literature shows that Forrester's views are not as deterministic as they might appear. With some

Copyright © 2000 John Wiley & Sons, Ltd.

patient delving a more subtle argument appears. In discussing the policies represented in a system dynamics model he says that 'people's reactions are a consequence of the changes of the system within which they are embedded ... relegating ... people to being cogs in a social machine is distasteful to many. Critics of [system dynamics] models lament this lack of recognition of free will, even though the mechanistic nature of a model is mitigated somewhat when randomness is introduced into decision streams' (Forrester, 1961, p. 16–17). Crucially, he then offers an extended quotation which supports the notion that the environment that controls human decision making is *itself* made by human decisions. The counter-argument is therefore twofold: that human decisions are only partly determined by system structure and that since the purpose of modelling is to make such influences explicit, the system may be recrafted advantageously.

A Clarification from Bowen

These issues have been addressed with care and subtlety by Bowen (1994) and so only a brief account of the position need be given here. Bowen rejects the notion that system dynamics is either deterministic or founded on 'the illusion of the autonomous individual' (Bowen, 1994, p. 88, echoing Skinner). Instead, the literature indicates that system structure is assumed to 'generally govern outcomes of action and to provide powerful incentives to behave in a certain manner ... [so that] individuals still retain the autonomy to decide to act as they so choose' (Bowen, 1994,p. 89). In Bowen's view, system dynamics therefore adopts a partial view of the structural control of human agency, a mid-point on the scale of human autonomy. Bowen argues that it is distinct from the ideas of Skinner because, although demonstrating experimentally that individual decisions are strongly affected by system structure, by using system dynamics 'individuals can design and affect the redesign of the social and managerial systems that impose on them ... [therefore] individuals ... retain — at least in part — the ability to make autonomous decisions that can play a role in determining their own fates' (Bowen, 1994, pp. 87–88).

Bowen (1994) observes that this partial view of human autonomy is consistent with current mainstream thinking in psychology and organizational behaviour. Indeed, the view that he offers is quite a traditional one: 'Sociology ... needs to embrace free will no more than determinism' (Durkheim, 1895, p. 141). System dynamics could be seen to sit well with this tradition. But there is an alternative.

Reframing the Question

Bowen's careful analysis is useful. However, his placement of system dynamics at a blurred mid-point of the 'extent of human autonomy' scale might be read as a somewhat unsatisfactory conclusion. The situation can be clarified by reframing the question. This is done by Bloomfield (1982). He first confirms the non-determinism of system dynamics by stating that the field does not conceptualize the 'idea of self' as a passive, undifferentiated element in a structured environment'. He then goes on to describe how system dynamics assumes that 'men have a degree of autonomy, they are active agents. Men have created the socio-economic system, they are not the victims of forces from without; but rather they are the victims of their own policies' (Bloomfield, 1982, p. 9).

This account indicates that neither the deterministic nor the free-will extremes express the position of system dynamics. There is something like a feedback process at work that links changes in the system structure to the factors influencing the decisions of human agent. Perhaps some different way is needed if the stance of the field is to be expressed? Such a way may be found in contemporary social theory. For example; 'human agency is bounded. Human beings produce society, but they do so as historically located actors, and not under conditions of their own choosing' (Giddens, 1976, pp. 168–169). It is for this reason that the question explored in this section has been reframed to suggest that system dynamics fits well with social theories which integrate agency and structure by giving an account of the processes which mutually shape them both (Lane, 1999a, 1999c).

Copyright © 2000 John Wiley & Sons, Ltd.

Position Clarified

Whichever of the two conclusions described above is seen to be correct, it is clear that system dynamics is not deterministic in the 'extent of human autonomy' sense described in this section. The fact that the field has been seen as taking a more extreme view certainly has something to do with the rhetorical tone of some of the literature and the lack of a clearer theoretic statement. On this point it could therefore be argued that some of the confusion is of the field's own making (M. G. Bowen, personal communication, 1994). However, such confusion still has more to do with the limited knowledge of some commentators than with the actual assumptions of the field.

TIMELESS GRAND THEORY?

The word 'determinism' is also used to describe the position that cause and effect are related by laws which exist outside of human subjectivity and which together form a timeless grand theory (Morrow and Brown, 1994). Relevant in this context is the 'principle of determinism', that 'The same causes will always produce the same effect' (Maxwell, 1876) and that this is so because the laws underlying the principle describe the operation of invariant relations. This therefore constitutes the third version of the 'hard/deterministic' criticism.

The pursuit of grand theory via causal laws is based on the Humean tradition that science implies explanation and that explanation involves relating phenomena to be explained to other phenomena via such causal laws (Frankfort-Nachmias and Nachmias, 1992). The value of the approach is that a set of antecedent conditions may be combined with relevant laws to make a prediction about an event (Franfort-Nachmias and Nachmias, 1992). Even in natural science the logical status of grand theory is not a closed issue, since the exact formulation of causal laws is complex and the philosophical weaknesses in the different formulations of causality would apply to any field seeking to employ the concept (Ryan, 1970).[d] However, a point made very clearly by Popper is that determinism via the principle of causality is quite different from determinism as prophecy, the former being alive and healthy as a central concept in natural science (Popper, 1982).

This third form of the hard/deterministic criticism is therefore that system dynamics posits a timeless grand theory about the existence of objective causal laws in social systems. It has been asserted that an assumption of the field is that 'well-defined laws govern behaviour' (Flood and Jackson, 1991, p. 33) and that 'Forrester talks about fundamental laws of nature and the social sciences' (Bloomfield, 1982, p. 13).

System dynamics has a range of 'theories' which appear hard/deterministic in this sense. For example, models are said to be causal theories and Forrester writes of a 'general systems theory' (Forrester, 1968a, p. 135) and lays out *Principles of Systems* (Forrester, 1968b). There is also the grandiose claim that underlying models are 'a set of principles ... incomplete as they may be, that I believe do represent the actual nature of physical and social reality' (Forrester, 1994, p. 250). Like Ashby's 'law of requisite variety' (Ashby, 1956) and Beer's laws on the viability of systems (Beer, 1979, 1981), it would indeed appear that the theories of system dynamics propose universal laws.[e] This issue is both complex and profound. Considering the deep philosophical issues that it raises it would be perilous to aim to answer it definitively here. Instead, the following is an attempt to begin the process of clarifying the claims that system dynamics makes in the context of social theoretic disputes over these issues and hence to advance the debate on the nature and plausibility of those claims. The discussion deals with two issues: the range of theories that are proposed and the treatment of causality.

The Nature of the 'Theories' in Use

One view on grand theory is that 'laws in natural and social science are logically identical' (Gid-

[d] See, for example, the respective statements and critiques of causality defined as: Humean, deductive-monological, essentialist, manipulability, counterfactual and probabilistic in Lincoln and Guba (1985, pp. 133–140).

[e] The author is grateful to Robert Flood for this comparison.

Copyright © 2000 John Wiley & Sons, Ltd.

dens, 1982, p. 15) and, as a result, positivists in social science 'attempt to frame their causal explanations in terms of universal statements ... universal propositions' (Denzin, 1978, p. 130). This thinking underlies traditional structural functionalism and social systems theory, these approaches 'hav[ing] been motivated by the belief that there is a single theory or at least a set of conceptual categories that could be used ... to analyze all societies throughout history' (Ritzer, 1996, p. 257). Arising from the work of Spencer and Parsons, this approach was dominant in 1950s and 1960s sociology — the time when system dynamics was being crafted. There have since emerged major criticisms of this approach, including attacks on its innate conservatism and its crude understanding of the contribution of human agency (see Craib, 1992; Ritzer, 1996). However, the disfavour and decline of the approach are also partially due to the wholesale rejection of grand theory (Mills, 1959). Today, 'Many critics regard ... grand theory as an illusion, believing that the best sociology can hope for is more historically specific, ''middle range'' ... theories' (Ritzer, 1996, p. 258).

System dynamics offers 'theories' at four different levels. At the highest level is the claim that the time evolutionary behaviour of social systems is explainable in terms of feedback loops and state variables. This very crude statement would need to be elaborated to establish the plausibility of the claim but what is important is the nature of this claim.[f] This is not a grand content theory. There are no specific variables or conceptual categories. For example, it is not suggested that 'socialization' and 'class stratification' are meaningful concepts which are necessary to explain the evolution of all societies (*pace* Parsons). In contrast, this grand claim of system dynamics is a structural theory — it makes a grand methodological claim about how certain types of phenomena might be explained.

Moving down to the next theory, we find the principle of how the concepts of feedback loop and state variables should be used to construct models (Forrester, 1968b). This is not a grand theory. This is a representation theory, or scheme, proposing a way of implementing the above grand methodological theory.

A more specific theory is that, unassisted, humans cannot infer the behaviour of systems represented in the above fashion in a way which is logically consistent; computers are needed to deduce the behaviour. This is an empirical claim. As such it is well supported by data (Sterman, 1994). Models therefore allow the application of logic to reveal essentially tautological but, in practical terms, hidden results (Simon, 1969).

Finally, we come to the idea that each model is a theory. These are clearly minor content theories, albeit valuable ones. A model is a concatenation of causal laws offering a plausible representation and hence explanation for a behaviour mode.

Taking these different 'theories' one by one and briefly clarifying their status makes it clear that none of them propose an invariant causal law and that therefore there is no crude grand (content) theory. The only universal law/theory on offer is a grand methodological, or structural theory, associated with a representation scheme. System dynamics offers a new structure for thinking about causality but it does not specify the content of that structure. In terms of Figure 2, the 'laws' are structural, or representational — they have no specific content. This position can still be criticized but it does not attract the hard/deterministic-related criticisms attached to grand theory in the sense of Parsons and Mills.

[f] A more elaborate statement of the claims of system dynamics would be: 'Social systems frequently behave in ways which are counter to the intuition of actors implementing policies aimed at influencing their behaviour. Because actors who are part of social systems collect information about their environment and, in light of that information, take action to influence aspects of the state of the system, the aggregate behaviour over time of such systems can usefully be explained using the concepts of feedback loops and stocks. The feedback loops are a plausible representation of the collect/influence/collect cycle of activities and the stocks are a plausible representation of the system state variables. Models based on these concepts offer a representation of causal links between variables and so allow the rigorous deduction of the consequences of those links. Such models are therefore theories of the structural source of particular aggregate behaviours and can be used to make deductions about the mode of behaviour that will flow from implementing a given influencing policy.'

The Idea of Causality

Moving down from the grand level to that of individual models raises the question of whether the causal links in system dynamics models are an adequate tool for treating human behaviour. Behind the criticisms from Flood and Jackson

Copyright © 2000 John Wiley & Sons, Ltd.

quoted earlier is the question of whether actions are governed by such (micro) laws of causality. This is the issue being referred to when Giddens defines ''Determinism'', in the social sciences ... [as] any theoretical scheme which reduces human action solely to ''event causality'' ' (Giddens, 1976, pp. 91–92). His sense is pejorative.

Social theorists differ widely in their view of causality in social systems. It is generally accepted that the practical establishment of laws and theories is much more difficult in social science (Bailey, 1987). Nevertheless, the philosophical aspiration widely remains and in its strongest form leads to the grand theoretic stances described above.[g] However, some theorists, accepting that 'the theoretical explanation of how and why people act has an entirely different structure and a different notion of cause' (Craib, 1992, p. 23), have attempted to amend and reframe the theory of causality whilst retaining the core idea.[h] Others have gone further, arguing that the concept is inappropriate and should be extirpated from social inquiry (Giddens, 1976, 1984; Lincoln and Guba, 1985; Phillips, 1987). For example, Phillips states baldly that human actions are simply not causally determined, that 'people act because they are swayed by reasons, or because they decide to follow rules, *not* because their actions are causally determined by forces' (Phillips, 1987, p. 105). He concludes that the causal laws of natural science are not to be found in social science and that if explaining human actions is the aim then an understanding of individuals may require hermeneutical interpretation.

In fact, the debate may be loosely characterized as an argument over the respective importance of these two forms of 'explanation': *Erklären* and *Verstehen* (Morrow and Brown, 1994; Ritzer, 1996). Natural scientific explanation is *Erklären* — the objective establishment of invariant, nomothetic laws of causal explanation. The tradition of German Idealism gives rise to *Verstehen* — the hermeneutical process of understanding and interpreting the subjective meaning that humans attach to their actions. Positivists can be seen to be in pursuit of *Erklären* as the only true form of science, while Critical Theorists — and others — are profoundly suspicious of this form of determinism, believing that 'social life [does] not lend itself to such causal explanation' (Morrow and Brown, 1994, p. 94). At a middle position, Weber believed that both forms of explanation are relevant to social science and this is reflected in much modern social theory.

Where do the causal models of system dynamics fit in with this range of views? There is some acknowledgement that causal laws in social science are not straightforward (Richardson, 1991, p. 7–8). Some have attempted to think in more detail about what causality means in the field (Roberts *et al.*, 1983, p. 11–15). The view to be advanced in this paper is that the issue of the appropriateness of using causal laws must be seen in the context of the aggregation of system dynamics models (Forrester, 1961).

System dynamics is concerned with aggregate social phenomena, not individual meaningful actions. The balance of appropriate explanation in social sciences (*Erklären* versus *Verstehen*) is widely seen to vary with the detail of the phenomena studied. For example, having asserted that the understanding of individuals requires hermeneutic interpretation, Phillips observes that, with groups, enduring patterns may be observable and limited prediction possible (Phillips, 1987). He uses Schelling's example of students filling up a lecture theatre. The individual choice of seat would be unpredictable, though hermeneutic interpretation might allow a researcher to understand the reasons why a particular student chose his/her seat. However, for a large number of

[g] This combined attitude is captured neatly by Scott: 'causal mechanisms both reinforce and undermine one another, they operate alongside other (as yet) unknown mechanisms, and the combination of mechanisms differs from situation to situation. As a result, actual events are never simple consequences of a particular mechanism: they are always ''overdetermined''. The task of [social] science is to comprehend this overdetermination by extending the scope of its knowledge of the causal mechanisms operating in the world' (Scott, 1995, pp. 173–174).

[h] For example, Craib argues that 'some notion of teleological [goal seeking] causality [is] necessary to understand human action: it involves notions such as intention and project' (Craib, 1992, p. 182). Similarly the concepts of 'reciprocal determinism' (Bandura, 1977) and 'mutual shaping' (Lincoln and Guba, 1985) are both attempts to respond to problems in the Humean definition of causality as applied to social phenomena. These rather unconvincing reframings are interesting examples of the tremendous difficulties that social scientists seem to have with the concept of feedback. The system dynamicist reading the tortured accounts of phenomena described in these works is likely simply to observe 'But it's simple, it's just a feedback effect!' The critique of 'reciprocal determinism' in Phillips (1987, pp. 71–76) is particularly effective in this respect.

Copyright © 2000 John Wiley & Sons, Ltd.

students, seat-filling appears to take place in a pattern which is invariant in many ways and which can be used to make predictions at an aggregate level with a wide range of audiences (Phillips, 1987, pp. 111–112).

Similarly, from system science, von Bertalanffy contrasts 'molecular' and 'molar' approaches, so that 'for mass behaviour, systems laws would apply' (von Bertalanffy, 1962, p. 76).

It is clear that there is a significant difference between causality in system dynamics (which treats causes as pressures which produce aggregate patterns of behaviour), and causality in the cybernetics of Beer (which treats events, actions and individual stimuli and decisions) (Richardson, 1991, pp. 337–338). Forrester is very clear that while the perspective to adopt when constructing a model 'is not so far away as to be unaware of the decision point and its place in the system', it is nevertheless, 'not close enough to be concerned with the mechanism of human thought', because 'We are not the psychologist delving into the nature and sources of human motivation' (Forrester, 1961, p. 96).

Having somewhat clarified the nature of the question, it becomes less clear that system dynamics involves the view that individual human decisions are completely explainable by causal laws, that subjective explanations of the *Verstehen* type are irrelevant. The field is not operating at a sufficiently low level of detail for this accusation to stick.

Currency of the Debate Established

It is worth commenting that the above pair of discussions has avoided some of the more stridently realistic views expressed within the field of system dynamics. These include Forrester's suggestion (quoted above) that the field's principles capture the nature of social reality and the generally held position that people have 'flawed cognitive maps of causal relations' (Sterman, 1994, p. 307); i.e., mental models are not 'correct'. From a philosophical position it is rather hard to imagine what these views could possibly mean since they mix the external world with intellectual constructs or representations. However, what an instrumentalist sees as naive realism can look to a pragmatic realist like cowardly relativism. This is not the place for a debate on this point, it merely being necessary to note that the issue does touch on the interpretation of hard/deterministic treated here and that the area deserves further attention.

Putting this issue to one side, we concentrate instead on the two main arguments that have been made in this section: firstly, system dynamics should not be criticized as propounding a crude grand (content) theory because what it advances is a (grand) structural theory; secondly, that the modelling of causal laws which transcend human subjectivity is a reasonable position because of the level of aggregation of models. Whether these arguments are sufficient to defend system dynamics from this hard/deterministic accusation remains to be seen. The suspicion of this author is that the subjectivist hardliners in both systems science and social theory will not have been assuaged. Subjectivism has been a powerful and insightful development in systems science but it has its limitations. For example, Giddens pronounces unacceptable 'the hermeneutical notion that causal laws have no place in social sciences at all' (Giddens, 1982, p. 15). His 'structuration theory' posits an alternative notion of 'agent causality' in which causal relations are an element of the rationalizations and maxims that agents use (Giddens, 1984).

This section leaves open many questions for system dynamics. Some further thought on the nature of the field's various claims or theories would be useful. Linkage with social theory is possible here too: it has been suggested previously that archetypes are examples of Weberian 'ideal types' (Lane and Smart, 1996) but if a single model is a micro content theory then are generic structures Mertonian middle range content theories? What are the implications of this? How do the causal links in a model relate to the idea of 'agent causality' and the notion that causal laws exist only in that they lead agents to expect certain consequences? These hard questions must be addressed, although some relief may be found in the observation that 'Generalizations about human social conduct ... may directly reflect maxims of action which are knowingly applied

Copyright © 2000 John Wiley & Sons, Ltd.

by agents . . . just how far this is the case in any specific set of circumstances has to be one of the main tasks of social research to investigate' (Giddens, 1984, p. 347).

It will indeed be a main task for the field to establish the status of causal reasoning and of its various 'theories'. However, system dynamics need not be apologetic about its attachment to causal models. As suggested by Lane (1999c), while acknowledging and responding to the contribution of subjectivism, system dynamics cannot move too far in this direction without loosing most of what is distinctive and — more to the point — effective about the approach. Indeed, if the placation of subjectivists involves the denial of the relevance of causal laws, causal explanations and the grand structural claim of system dynamics then the field should stop placating and start declaiming. While it is useful to clarify exactly what the system dynamics position is, there comes a point where criticisms must be turned on their head and worn as badges of pride.

A FORM OF HARD SYSTEMS THINKING, OR SYSTEMS ENGINEERING?

In this last section a variety of criticisms is briefly considered. Collectively these can be seen to be an assertion that system dynamics is essentially a hard systems approach, akin to systems engineering (this is referred to below as 'hard/SE'). For example, Jackson (1991) offers a broad criticism of this nature when he groups the field with hard systems thinking. He characterizes this as an approach in which 'People are treated as components to be engineered just like other mechanical parts of the system. The fact that human beings possess understanding and are only motivated to support change and perform well if they attach favourable meanings to the situation in which they find themselves is ignored' (Jackson, 1991, p. 80).

The tone of this final hard/deterministic accusation is that, in operation, system dynamics has an austere view of what should be in a model and a coercive view of how users should respond to such a model. The features of hard systems approaches described by Checkland (1981, pp. 189–191) are used below to respond to this accusation in detail. In each case the specific point is briefly stated and the position of system dynamics in respect to it described.

Model Purpose Known?

The hard/SE approach deals with well-defined problems which are taken as clear and known by all (Checkland, 1981).

The system dynamics literature certainly states that a study must be focused around a specific purpose (Forrester, 1961; Randers, 1980b). However, this does not imply the austere view that the purpose will be objectively clear to all participants. Rather, it is done to ensure that modelling centres on the treatment of a particular issue rather than flounders in trying to model some notion of a whole 'system'. Since the purpose of a model is to manifest a world-view — or mental model — relating to important issues, it is entirely possible for there to be a plurality of opinions on that purpose and for the modelling process to treat a range of these.

Having made this point it must be said that system dynamics lacks any structured way of eliciting and handling such diversity (Lane and Oliva, 1998). However, it has been suggested that the problem-structuring methods of 'soft' OR might be able to contribute in this regard (Lane, 1992, 1994). This has been greeted encouragingly (Forrester, 1994) and some progress made (Vennix, 1996).

Model Objectives Clear?

In the hard/SE approach it is assumed that decision makers already share a clear view on the objectives of the modelling.

There is no requirement in system dynamics that there be agreement of what constitutes the best outcome from a model. Forrester is clear that the usefulness of models would only be appropriately judged in a personal way: 'the evaluation of improved managerial effectiveness will almost certainly rest on a *subjective* judgement rendered by managers in regard to the help they

Copyright © 2000 John Wiley & Sons, Ltd.

have received [from engaging with a model]' (Forrester, 1961, p. 115, emphasis added).

The question of what constitutes an improved policy, or a better model run, is drawn from the model owners (Gardiner and Ford, 1980; Reagan-Cirincione *et al.*, 1991). When doing so, all system dynamicists should be asking the questions, 'Whose objectives? ...How should conflicting goals and the differing agendas of special interest groups be balanced?' (Sterman, 1988, p.39). It is clear from experience that system dynamics offers the most benefit when it generates support and commitment amongst the group whose views are modelled (Roberts, 1972; Senge, 1990; Kofman and Senge, 1993).

Scientific Imperialism?

At an extreme end of the hard/SE approach lies the implicit notion that a black-box model, created by a technical high priesthood, offers judgements which decision makers are required simply to obey.

In system dynamics the limitations of such 'expert' modelling are clear (Lane, 1992). The field has traditionally emphasized the importance of drawing participants into a 'process' of modelling, contrasting this stance with an over-attachment to finalized, black-box models which are all too frequently cast in the role of obeisance-demanding oracles and ignored (Forrester, 1961, 1971a). In system dynamics the relationship of a group to a model is not 'coercive' but 'negotiative' (Eden and Sims, 1979) and, in contrast to Jackson's remarks at the start of this section, it is accepted that users' motivation to take action will, 'depend ... on the degree to which the model communicates, helps to generate insights, enhances *understanding*, and in general reaches and influences its audiences' (Richardson and Pugh, 1981, pp. 312–313, emphasis added).

There is a regrettable trend in the field to withdraw into a 'policy engineering' approach (see below) and different types of practice do tend to emphasize to different degrees the importance of user participation in modelling. Nevertheless, the core assumptions of the field call for high levels of participation and, hence, a rejection of an 'imperialist' approach.

Impoverished Representation of Human Agents?

Frequently implicit in the hard/SE view is a highly reductionist view of humans which treats them as passive objects. The same has been said of traditional operational research practice (Rosenhead, 1989). This issue is at the centre of the criticism that system dynamics 'does not deal with the innate subjectivity of human beings' (Flood and Jackson, 1991, p. 79).

As discussed in the section on causality, system dynamics models do not purport to capture in their structure the full richness and subjectivity of human decision making. Instead, they offer a framework in which such issues can be addressed in a structured way which operates at an aggregated level away from individual decisions. System dynamics models should not stand alone but are contingent, related intimately to a specific problem and to the group that is attempting to address that problem. The factors excluded from an actual model are nevertheless partially addressed in the modelling process taken as a whole. Although not always apparent, this is a core idea of the field (Forrester, 1961, 1971a).

This approach is particularly noticeable in 'Interactive System Dynamics', where the significance that participants attach to the modelling and their commitment to agreed actions are important aspects of agreeing changes (Lane, 1999b). What is visible in such practice is an acceptance of the importance of *Verstehen* alongside *Erklären*. In the light of these remarks it can be suggested that observers objecting to the apparent austerity of the *Erklären* aspect of models have insufficiently considered the importance of the *Verstehen* taken up in the modelling process. This may be due partly to the dearth of accounts of processes but this situation is now changing (see Lane, 1993, 1997b; Vennix, 1996).

Optimal Solution Sought?

An optimal, or best system design is the usual aim for the hard/SE method.

Early in the history of the field Forrester offered a list of 'obvious truths' in modelling which he in fact believed to be false (Forrester,

Copyright © 2000 John Wiley & Sons, Ltd.

1960). One of these is the idea that model output should be optimized to find a 'best' policy. It is therefore one of the bedrock assumptions of system dynamics that optimization is not appropriate for social systems.

The only dissent from this stance emanates from the minority form of 'Policy Engineering' practice which involves 'the application of system dynamics modelling as traditional simulation modelling by expert consultants as part ... of a top-down corporate planning process' (Lane, 1999b, p. 515). Applications are varied and a few do employ optimization but this is therefore only occurring in a minority of practice.

This case aside, the field has kept to Forrester's rejection of 'optimization', concentrating instead on 'improvement'. As explored elsewhere (Lane, 1994), the reasons for this view have much in common with later discussions of the undesirability or logical impossibility of optimization in social systems (Ackoff, 1979; Rosenhead, 1989). The case rests on the impossibility of modelling completely any situation involving human decision makers. In system dynamics the view is that since '[t]he real problem will always have aspects that are not captured by a model ... [t]he best we can do is to seek policies that tend to be more robust ... than others' (Richardson and Pugh, 1981, p. 351). This aspiration is as shrewd as it is modest. It also links to the point below.

'Designed System' Implemented?

The aim of hard/SE approaches is to design and implement an improved system. This is contrasted with the SSM aim of implementing agreed changes (Checkland, 1981).

As indicated in the above treatment of optimisation, specific policy directions and new 'rules' for control are not the aim of system dynamics. It is the case that a mathematical model is created, and that the results of changing policies are experimented with using that model. But the model is never seen as the system then to be implemented. Instead, the purpose is to promote individual and organizational experiential learning in order to impart to those involved in the modelling 'a better intuitive feel [which] improves ... judgement about the factors influencing ... success' (Forrester, 1961, p. 45). It may seem paradoxical but the results of a quantitative system dynamics study are qualitative insights. Individual policy changes that are seen to be beneficial are taken back into the real world and used as the basis for further experimentation.

Again, there is an appropriate and pragmatic degree of modesty behind this aspiration. Just as the 'system' cannot be trapped and so optimized, it can never be grasped and remodelled in all its detail. A system dynamics study aims to improve the mental models of decision makers. Their improved understanding of dynamic complexity then serves as a platform for a never-ending process of learning about complex systems while operating as an actor within them (cf. the title of Sterman, 1994).

Again, Position Clarified

There is no pretence that bringing together the range of issues described in this section reveals system dynamics to be a 'soft' method in the style of SSM. However, it is clear that mathematical techniques used in the approach are surrounded by a complex set of craft skills that make the method much more than the application of ordinary differential equations to social systems. System dynamics is very different from systems engineering.

CONCLUSIONS

In this section the four separate conclusions are first drawn together. Comment is then offered on the lessons that may be derived for improving communication between the field of system dynamics and the broader systems movement. Some closing remarks are then presented.

Reviewing the Accusations

From the main sections of this paper, four conclusions may be drawn. Firstly, the idea that system dynamics offers prophecies is absolutely false; it may be difficult to believe that this accusation could ever have been made with any

Copyright © 2000 John Wiley & Sons, Ltd.

seriousness but its refutation is worthwhile and necessary. Secondly, the position of system dynamics on the structural influence on agents is not behaviourist; such influence is not total but is taken to be partial, or involving a feedback model of the relationship between agency and structure. The third question, whether system dynamics is a grand theory, is more complex; it does not propose any specific content but does advance a structural theory and a representation scheme to go with it. Further debate on the coherence and benefit of this position may prove necessary but the currency of that debate should now be more clear. Finally, the identification of system dynamics with system engineering is too crude a piece of pigeon-holing; the field has a range of properties that indicate a much more participative and contingent relationship between a model and those working with it.

What are the reasons for such confusion and misinterpretation? Some relate to the system dynamics field, while others concern the systems science movement generally. These are treated in turn below.

Lessons for System Dynamicists

The poor communication between system dynamicists and other system practitioners is partly a result of the atheoretical style of the system dynamics field. The field seeks to offer plausible and compelling explanations for a range of phenomena rather than dwelling on philosophical and theoretical issues. Since systems science is sometimes considered to be too abstract (Troncale, 1988), this undoubted success regarding practical applications should be welcomed by all. But the dearth of theoretical debates is something of a hindrance.

For example, the relationship between system dynamics and subjectivist ideas has been a particular source of uncertainty. This is considered further below from the point of view of those outside the field. However, the challenge for system dynamics is to build on subjectivist ideas that have been part of the approach from its creation, to advance them using more theoretically aware discourses, and then to communicate its position clearly.

The widespread avoidance of theoretical concerns can also lead to a certain crudity of presentation. This paper cites various descriptions of the field that seem extreme, naive or simply confusing to system (and social) scientists. Many of the hard/deterministic criticisms would not have arisen if the field had been a little more judicious in its language. Some sensitivity towards the concerns of other systems thinkers and a better command of the terminology involved would be an aid. That is a lesson for system dynamics that should be drawn from this paper.

Lessons for External Commentators

The blame for the confusion about the nature of system dynamics addressed in this paper does not all lie with the field itself. Some of the confusion results from a less than perfect grasp of the core ideas of the field on the part of external commentators. Although there is some uncertainty and crudity of presentation in system dynamics, many of the ideas deployed in this paper do not require detailed textural exegeris, merely familiarity with the literature of the field. It is a superficial reading of *Industrial Dynamics* (Forrester, 1961) which leads some to see system dynamics as being merely about inventory control. A sound grasp of this text leads to a very different view of the aspirations of the field. Similarly, much has been published which shows the range of problems that have been tackled and the elaborations of the approach that have appeared. The opening section of this paper supplies a wide range of such references.

System dynamics is still in the process of engaging with the subjectivist strand of systems thinking. Nevertheless, it really should be clear that the field is not as austerely objective as it is sometimes portrayed. As described in this paper, system dynamics already involves some acknowledgement of the power of subjectivist ideas. Therefore, what is called for is not rejection of a 'straw man' hyper-objective system dynamics; a sound understanding of the field's literature makes it very clear that such an approach does not exist.

So, while system dynamicists can improve their own methods and style of communication,

Copyright © 2000 John Wiley & Sons, Ltd.

it also behoves those offering comment to have a sound grasp of the nature of that field as presented in its publications.

Closing Comments

This paper is an attempt by a system dynamicist to engage with the broad systems science movement in a style that deals with some of their theoretical concerns. It also creates an entrance to the literature of the field so that more can be discovered — and perhaps debated or criticized. However, one thing is clear about system dynamics; it remains a very practical approach and attracts people of this inclination. Highly theoretical papers will probably continue to be a rarity. This leads to the closing points of this paper.

Firstly, the grand structure theory of system dynamics, along with the theories of logical deduction and representation, do not stand or fall as separate elements to be justified by the sort of theoretical arguments presented here. Rather, they must be judged as a coherent research programme (Lakatos, 1974). System dynamics should therefore be considered in terms of the plausibility and coherence of its grand structural claim, the reasonableness of its representative scheme and — primarily — by its empirical success in providing explanations for a range of novel phenomena. Viewed in these Lakatosian terms, the various aspects of the approach that are debated in this paper form the 'hard core' of the field. The healthy flow of diverse applications of the approach indicates that the research programme is a progressive one. While some of the issues raised here are still open and the clarified position will be criticized by some, system dynamicists are happy to justify their position less in terms of theoretical debates — though more of this should be encouraged — and more in terms of the field's ability successfully to illuminate real-world phenomena. It is on those terms that the theories, the laws, indeed, all of the ideas of system dynamics, should be judged.

The second and final point concerns the response to the question in this paper's title — should system dynamics be described as a 'hard' or 'deterministic' systems approach? The answer can be found if the rare theoretical publications are considered with sufficient seriousness. However, the answer is even more clear if we accept the fact that practical applications of system dynamics are the main source of information. As this paper seeks to demonstrate, using both sources of information, the answer to the question is — on balance, no.

REFERENCES

Abdel-Hamid, T. K., and Madnick, S. (1990). *Software Project Dynamics: An Integrated Approach*, Prentice-Hall, Englewood Cliffs, NJ.

Ackoff, R. L. (1979). The future of operational research is past. *Journal of Operational Research Society* **30**, 93–104.

Ackoff, R. L. (1981). *Creating the Corporate Future: Plan or be Planned For*, Wiley, New York.

Ashby, W. R. (1956). *An Introduction to Cybernetics*, Chapman & Hall, London.

Bailey, K. D. (1987). *Methods of Social Research* (3rd edn), Free Press, London.

Bandura, A. (1977). *Social Learning Theory*, Prentice-Hall, Englewood Cliffs, NJ.

Barlas, Y., and Carpenter, S. (1990). Philosophical roots of model validation: two paradigms. *System Dynamics Review* **6**, 148–166.

Beer, S. (1979). *The Heart of the Enterprise*, Wiley, Chichester.

Beer, S. (1981). *The Brain of the Firm*, Wiley, Chichester.

Beishon, J., and Peters, G. (1981). *Systems Behaviour* (3rd edn), Paul Chapman, London.

Bloomfield, B. (1982). Cosmology, knowledge and social structure: the case of Forrester and system dynamics. *Journal of Applied Systems Analysis* **9**, 3–15.

Bowen, M. G. (1994). System dynamics, determinism and choice: toward a reconsideration of the image of 'system man'. *System Dynamics Review* **10**, 87–90.

Burrell, G., and Morgan, G. (1979). *Sociological Paradigms and Organisational Analysis: Elements of the Sociology of Corporate Life* (1985 edn), Gower, Aldershot, UK.

Checkland, P. B. (1981). *Systems Thinking, Systems Practice*, Wiley, Chichester.

Churchman, C. W. (1970). Operational research as a profession. In Flood, R. L., and Jackson, M. C. (eds), *Critical Systems Thinking: Directed Readings* (1991 collection), Wiley, Chichester, pp. 19–40.

Craib, I. (1992). *Modern Social Theory: From Parsons to Habermas* (2nd edn), Harvester, London.

Dash, D. P. (1994). System dynamics: changing perspectives. *Systems Practice* **7**, 87–98.

Denzin, N. K. (1978). *Sociological Method: A sourcebook* (2nd edn), McGraw-Hill, London.

Copyright © 2000 John Wiley & Sons, Ltd.

Doyle, J. K., and Ford, D. N. (1998). Mental models concepts for system dynamics research. *System Dynamics Review* **14**, 3–29.

Durkheim, E. (1895). *The Rules of Sociological Method* (1966 edn), Free Press, New York.

Eden, C., and Sims, D. (1979). On the nature of problems in consulting practice. *Omega* **7**, 119–127.

Flood, R. L., and Jackson, M. C. (1991). *Creative Problem Solving: Total Systems Intervention*, Wiley, Chichester.

Forrester, J. W. (1958). Industrial dynamics: a major breakthrough for decision makers. *Harvard Business Review* **36**, 37–66.

Forrester, J. W. (1960). The impact of feedback control concepts on the management sciences. In *Collected Papers of Jay W. Forrester* (1975 collection), Wright-Allen Press, Cambridge, MA, pp. 45–60.

Forrester, J. W. (1961). *Industrial Dynamics*, MIT Press, Cambridge, MA.

Forrester, J. W. (1968a). Industrial dynamics: after the first decade. In *Collected Papers of Jay W. Forrester* (1975 collection), Wright-Allen Press, Cambridge, MA, pp. 133–150.

Forrester, J. W. (1968b). *Principles of Systems*, MIT Press, Cambridge, MA.

Forrester, J. W. (1969). *Urban Dynamics*, MIT Press, Cambridge, MA.

Forrester, J. W. (1971a). 'The' model versus a modelling 'process' (republished 1985). *System Dynamics Review* **1**, 133–134.

Forrester, J. W. (1971b). *World Dynamics*, Wright-Allen Press, Cambridge, MA.

Forrester, J. W. (1975). *Collected Papers of Jay W. Forrester*, Wright-Allen Press, Cambridge, MA.

Forrester, J. W. (1980). System dynamics: future opportunities. In Legasto, A. A., Forester, J. W., and Lyneis, J. M. (eds), *System Dynamics: future opportunities* (Vol. 14), North-Holland, Oxford, pp. 7–21.

Forrester, J. W. (1990). *The Beginnings of System Dynamics*, International System Dynamics Society, Boston, MA.

Forrester, J. W. (1994). System dynamics, systems thinking, and soft OR. *System Dynamics Review* **10**, 245–256.

Forrester, J. W., and Senge, P. M. (1980). Tests for building confidence in system dynamics models. In Lagasto, A. A., Forrester, J. W., and Lyneis, J. M. (eds), *System Dynamics: TIMS Studies in the Management Sciences*, North-Holland, Oxford, pp. 209–228.

Frankfort-Nachmias, C., and Nachmias, D. (1992). *Research Methods in the Social Sciences* (4th edn), Edward Arnold, London.

Gardiner, P. C., and Ford, A. (1980). Which policy run is best, and who says so? In Legasto, A. A., Forrester, J. W., and Lyneis, J. M. (eds), *System Dynamics: TIMS Studies in the Management Sciences* (Vol. 14), North-Holland, Oxford, pp. 241–257.

Giddens, A. (1976). *New Rules of Sociological Method: A positive Critique of Interpretive Sociologies* (2nd edn, 1993), Polity Press, Cambridge, UK.

Giddens, A. (1982). *Profiles and Critiques in Social Theory*, Macmillan, London.

Giddens, A. (1984). *The Constitution of Society*, Polity Press, Cambridge, UK.

Jackson, M. C. (1991). *Systems Methodology for the Management Sciences*, Plenum, New York.

Jackson, M. C. (1993). Beyond the fads: systems thinking for managers. *University of Hull Centre for Systems Studies Working Paper* **3**, 1–34.

Jackson, M. C. (1994). Critical systems thinking: beyond the fragments. *System Dynamics Review* **10**, 213–229.

Jackson, M. C., and Keys, P. (1984). Towards a system of system methodologies. *Journal of the Operational Research Society* **35**, 473–486.

Keys, P. (1988). System dynamics: a methodological perspective. *Transactions of the Institute of Measurement and Control* **10**, 218–224.

Kofman, F., and Senge, P. M. (1993). Communities of commitment: the heart of learning organizations. *Organizational Dynamics* Autumn, 5–23.

Lakatos, I. (1974). Falsification and the methodology of scientific research programs. In Lakatos, I., and Musgrave, A. (eds), *Criticism and the Growth of Knowledge*, Cambridge University Press, Cambridge, UK, pp. 91–196.

Lane, D. C. (1992). Modelling as learning: a consultancy methodology for enhancing learning in management teams. *European Journal of Operational Research* **59**, 64–84.

Lane, D. C. (1993). The road not taken: observing a process of issue selection and model conceptualization. *System Dynamics Review* **9**, 239–264.

Lane, D. C. (1994). With a little help from our friends: how system dynamics and 'soft' OR can learn from each other. *System Dynamics Review* **10**, 101–134.

Lane, D. C. (1997a). Four invited book reviews. *Journal of the Operational Research Society* **48**, 1144–1148.

Lane, D. C. (1997b). From discussion to dialogue: a case study using an interactive system dynamics modelling approach [De la discussion au dialogue: une étude de cas d'utilisation interactive de la dynamique des systèmes]. *Revue des Systèmes de Décision* **6**, 251–281.

Lane, D. C. (1997c). Invited review and reappraisal: 'Industrial dynamics' by Jay W. Forrester. *Journal of the Operational Research Society* **48**, 1037–1042.

Lane, D. C. (1997d). Invited reviews on system dynamics. *Journal of the Operational Research Society* **48**, 1254–1257.

Lane, D. C. (1998). Jay Wright Forrester (1918–). In Warner, M. (ed.), *The IEBM Handbook of Management Thinking*, International Thomson Business Press, London, pp. 215–219.

Copyright © 2000 John Wiley & Sons, Ltd.

Lane, D. C. (1999a). Friendly amendment: a commentary on Doyle and Ford's proposed re-definition of 'mental model'. *System Dynamics Review* **15**, 185–194.

Lane, D. C. (1999b). Social theory and system dynamics practice. *European Journal of Operational Research* **113**, 501–527.

Lane, D. C. (1999c). *Rerum cognoscere causas:* social theory, determinism and the agency/structure debate. *System Dynamics Review*, (in press).

Lane, D. C., and Jackson, M. C. (1995). Only connect! An annotated bibliography reflecting the breadth and diversity of systems thinking. *Systems Research* **12**, 217–228.

Lane, D. C., and Oliva, R. (1998). The greater whole: towards a synthesis of system dynamics and soft systems methodology. *European Journal of Operational Research* **107**, 214–235.

Lane, D. C., and Smart, C. (1996). Reinterpreting 'generic structure': evolution, application and limitations of a concept. *System Dynamics Review* **12**, 87–120.

Lane, D. C., Monefeldt, C., and Rosenhead, J. V. (1999). Looking in the wrong place for healthcare improvements: a system dynamics study of an accident and emergency department. *Journal of the Operational Research Society*, (in press).

Lincoln, Y. S., and Guba, E. G. (1985). *Naturalistic Inquiry*, Sage, London.

Maxwell, J. C. (1876). *Matter and Motion* (1952 edn), Dover, New York.

Meadows, D. H. (1980). The unavoidable a priori. In Randers, J. (ed.), *Elements of the System Dynamics Method*, MIT Press, Cambridge, MA, pp. 23–57.

Meadows, D. H., Meadows, D. L., Randers, J., and Behrens, W. W. (1972). *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*, Earth Island, London.

Meadows, D. H., Meadows, D. L., and Randers, J. (1992). *Beyond the Limits*, Earthscan, London.

Mills, C. W. (1959). *The Sociological Imagination*, Oxford University Press, Oxford.

Morrow, R. A., and Brown, D. D. (1994). *Critical Theory and Methodology*, Sage, London.

Phillips, D. C. (1987). *Philosophy, Science and Social Inquiry: Contemporary Methodological Controversies in Social Science and Related Applied Fields of Research*, Pergamon, Oxford.

Popper, K. R. (1945a). *The Open Society and Its Enemies. Vol. I: The Spell of Plato* (1952 edn), Routledge & Kegan Paul, London.

Popper, K. R. (1945b). *The Open Society and Its Enemies, Vol. II: The High Tide of Prophecy: Hegel, Marx, and the aftermath* (1952 edn), Routledge & Kegan Paul, London.

Popper, K. R. (1957). *The Poverty of Historicism*, Routledge & Kegan Paul, London.

Popper, K. R. (1982). *The Open Universe: An Argument for Indeterminism (From the Postscript to 'The Logic of Scientific Discovery')*, Rowman & Littlefeld, Totowa, NJ.

Randers, J. (ed.) (1980a). *Elements of the System Dynamics Method*, MIT Press, Cambridge, MA.

Randers, J. (1980b). Guidelines for model conceptualisation. In Randers, J. (ed.), *Elements of the System Dynamics Method*, MIT Press, Cambridge, MA, pp. 117–139.

Reagan-Cirincione, P., Schuman, S., Richardson, G. P., and Dorf, S. A. (1991). Decision modelling: tools for strategic thinking. *Interfaces* **21**, 52–65.

Richardson, G. P. (1991). *Feedback Thought in Social Science and Systems Theory*, University of Pennsylvania, Philadelphia.

Richardson, G. P. (ed.) (1996). *Modelling for Management*, Dartmouth, Aldershot, UK.

Richardson, G. P., and Pugh, A. L. (1981). *Introduction to System Dynamics Modelling with DYNAMO* (republished edn), Productivity, Cambridge, MA.

Ritzer, G. (1996). *Sociological Theory* (4th edn), McGraw-Hill, London.

Roberts, E. D. (1972). Strategies for effective implementation of complex corporate models (1978 collection). In Roberts, E. B. (ed.), *Managerial Applications of System Dynamics*, Productivity Press, Cambridge, MA, pp. 77–85.

Roberts, N., Andersen, D. F., Deal, R., Garet, M., and Shaffer, W. (1983). *Introduction to Computer Simulation: A System Dynamics Approach*, Addison-Wesley, Reading, MA.

Rosenhead, J. (1989). Introduction: old and new paradigms of analysis. In Rosenhead, J. (ed.), *Rational Analysis for a Problematic World: Problem Structuring Methods for Complexity, Uncertainty and Conflict*, Wiley, Chichester, pp. 1–20.

Ryan, A. (1970). *The Philosophy of the Social Sciences*, Macmillan, London.

Saeed, K. (1991). *Towards Sustainable Development: Essays on Systems Analysis of National Policy*, Progressive Publishers, Lahore.

Scott, J. (1995). *Sociological Theory: Contemporary Debates*, Edward Elgar, Aldershot, UK.

Senge, P. M. (1990). *The Fifth Discipline: The Art and Practice of the Learning Organization*, Doubleday/Currency, New York.

Simon, H. A. (1969). Understanding the natural and the artificial worlds. In *The Sciences of the Artificial*, MIT Press, London, pp. 3–29.

Sokal, A., and Bricmont, J. (1998). *Intellectual Impostures: Postmodern Philosophers' Abuse of Science*, Profile Books, London.

Sterman, J. D. (1988). A skeptic's guide to computer models. In Grant, L. (ed.), *Foresight and National Decisions*, University Press of America, Lanham, MD, pp. 133–169.

Copyright © 2000 John Wiley & Sons, Ltd.

Sterman, J. D. (1989). Modelling managerial behaviour: misperceptions of feedback in a dynamic decision making experiment. *Management Science* **35**, 321–339.
Sterman, J. D. (1994). Learning in and about complex systems. *System Dynamics Reviews* **10**, 291–330.
Sterman, J. D., Repenning, N., and Kofman, F. (1997). Unanticipated side effects of successful quality improvement programs: exploring a paradox of organizational improvement. *Management Science* **43**, 503–521.
Troncale, L. (1988). The systems sciences: what are they? Are they one, or many? *European Journal of Operational Research* **37**, 8–33.
Vennix, J. A. M. (1996). *Group Model-Building: Facilitating Team Learning Using System Dynamics*, Wiley, Chichester.
von Bertalanffy, L. (1962). General system theory: a critical review. In Beishon, J., and Peters, G. (eds), *System Behaviour* (1981 collection), Paul Chapman, London, pp. 59–79.

Copyright © 2000 John Wiley & Sons, Ltd.