ON ACCURACY, PRECISION AND THE REAL WORLD: SOME THOUGHTS ON SYSTEM DYNAMICS AS A POLICY TOOL

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ABSTRACT

This paper is a critique of the assumptions underlying the "World Model," a computer-based model of the global ecology, designed by Jay W. Forrester and Dennis Meadows, as delineated in World Dynamics and The Limits to Growth. The views of Forrester and Meadows as to what constitutes a valid and useful model and what role quantification plays in the generation of an accurate model are examined. Two important modifications of the World Model are described as are the criteria employed in each for the evaluation of Forrester's model as a useful policy tool. It is concluded that Forrester and Meadows generally overstate the case for the appropriateness of their model as a policy tool. A great deal more scientific inquiry is required before models of this kind can be considered to be reliable aids to policy-making.

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Introduction. In this paper I will consider several important issues concerning the methodology of modeling, using a recent, large-scale modeling study, reported in *World Dynamics*[1] and *The Limits to Growth*,[2] as the central example. The latter is the nontechnical report of the results of a computer-based modeling project, done at the Massachusetts Institute of Technology in 1971, in which an effort was made to project global ecological trends to the end of the next century. The study forecasts the collapse of the world socioeconomic system some fifty years from now. The project team, led by Dr. Dennis Meadows, a systems analyst, utilized a version of the "World Model" designed by Dr. Jay W. Forrester and described in his book, *World Dynamics*. The methods which Forrester has developed to model the behavior of systems he has called "System Dynamics."

The World Model incorporates the interactions of five basic variables: population growth, capital investment, agricultural production, nonrenewable resources and environmental pollution, which make up the global system. According to Forrester, an electrical engineer by training, all systems--not only physical, but social and ecological as well--are characterized by complex multivariable feedback loop structures. Underlying the Forrester-

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[1] Jay W. Forrester, *World Dynamics* (Cambridge, Mass.: Wright-Allen Press, 1971). Hereafter referred to as *WD*.

[2] Donella H. Meadows, Dennis L. Meadows, Jørgen Randers and William W. Behrens III, *The Limits to Growth* (New York: Universe Books, 1972).

Meadows modeling effort is "the recognition that the *structure* of any system--the many circular, interlocking, sometimes time-delayed relationships among its components--is often just as important in determining its behavior as the individual components themselves."[3] As significant as this idea is, it is not to the particular structure of the World Model that I will devote this paper, for the quantitative, structural aspects of the model have already received substantial critical attention.[4]

My interest here is with the assumptions Forrester and Meadows make about what constitutes a useful model, and what role quantification plays in the generation of an accurate model. For the purposes of this inquiry, I shall make primary reference to Forrester's work. Although Meadows improved on Forrester's model both by adding data and by modifying the structure slightly, the "new insights" arising from *The Limits to Growth* "do not alter in any substantial way the broad implications reported"[5] in *World Dynamics*. Moreover, Meadows does not differ significantly with Forrester in his published views regarding the nature of the modeling process. This paper can thus be construed as being a critique of the views delineated in both books.

Aspects of Forrester's approach to modeling are quite similar to the philosophical views advanced by the logical positivists in the 1930s. I will try to show that certain of these methodological biases lead Forrester to make unsound arguments as to the validity of his conclusions. In the

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[3] Ibid., p. 31.

[4] H. S. D. Cole, Christopher Freeman, Marie Jahoda, and K. L. R. Pavitt, eds., *Models of Doom* (New York: Universe Books, 1973). Originally published in Great Britain as *Thinking About the Future*, a volume of thirteen papers, including many of a technical nature, prepared by associates of the Science Policy Research Unit of the University of Sussex, in which the System Dynamics method of forecasting is examined and criticized.

[5] *WD*, p. viii.

course of the paper I shall rewrite one of his major assumptions in order to demonstrate that taking a less generalized, more judicious position need not damage his case, as he seems to fear, but indeed tends to strengthen it. Finally, I will examine two important critiques of the World Model along with the criteria employed in each for the evaluation of Forrester's model as a useful policy tool.

Mental Models vs. Computer Models. The first issue to be considered is Forrester's notion of the "counterintuitive behavior of social systems,"[6] which has attracted some criticism, but not as much as might be expected given the importance of the idea to his analysis. That social systems behave in "generally unexpected"[7] ways functions both as an assumption and as a conclusion for Forrester. To begin with, he assumes that "all of our decisions are taken on the basis of models."[8] In *World Dynamics*, models are defined as mental images which, it is argued, we use constantly.[9] The mental models we use are vague and fuzzy. Their basic tenets are often contradictory one with another, both within an individual's world view and, less surprisingly, between two or more people.

To demonstrate the inadequacy of mental models, Forrester writes, "within one individual, a mental model changes with time and even during the flow of a single conversation."[10] Furthermore, in conversation people do not generally have the same model in mind; in fact, they can be counted on

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[6] Jay W. Forrester, "Counterintuitive Behavior of Social Systems," *Technology Review* (January, 1971), pp. 53-68. Hereafter referred to as *Tech. Rev.*

[7] Ibid., p. 55.

[8] Ibid., p. 54.

[9] *WD*, p. 14.

[10] *Tech. Rev.*, p. 54.

to have often widely differing estimations of those aspects of reality being addressed. Forrester states that "fundamental assumptions differ but are never brought into the open. Goals differ and are left unstated."[11] It is inaccurate to say, as a statement of empirical fact, that in discussions of public policy, for example, assumptions are "never" brought into the open. Moreover, Forrester is not the first to emphasize the fundamental importance of biases in policy-making, nor does he give any evidence that he is familiar with the work of researchers who have discussed this topic.[12]

How Do Models Influence Behavior? Forrester believes, and takes it as generally accepted by others, that mental models are not as accurate as those with which computers are capable of dealing. Simply stated, a computer program is a quantified mental model, one with the ambiguities edited out. Because they are usually ambiguous, mental models are often undefined and even unnoticed by the same people whose behavior they influence. This phenomenon is commonly recognized, although ambiguity is only one of many possible reasons for it. What is not so firmly agreed upon, however, is the extent to which models, per se, influence human behavior.

There is evidence from behavioral psychology to indicate that models do not mediate between certain intentions and their corresponding, but not necessarily consequent, behavioral events. At some point in the history of an individual, a model or mental image may play a causal role in shaping or determining behavior, but there exists an epistemological difficulty in ascertaining positively that in one case a model was operative, whereas in another

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[11] Ibid.

[12] See, for example, Gunnar Myrdal, *Objectivity in Social Research* (New York: Pantheon Books, 1969).

it was not. Much of human behavior seems to occur quite spontaneously or automatically, without an accompanying calculus of decisions, including some behavior that looks like "model-based decision-making behavior" from the point of view of an observer. The influence of a model can be inferred from the evidence of an individual's behavior after the fact, as it were, but such an inference by no means confirms causality or even anteriority.

Overstatement of the Case. Forrester wants to argue that because mental models are the foundations of all decision-making, the model which best represents reality and is the least ambiguous--his World Model--should be adopted as the basis for policy as soon as possible. But there is very little need for Forrester to postulate as he does that all decisions are based on mental models, especially when there remains the likelihood that some behavioral processes happen without the benefit of models. The argument it is important for him to advance is that global planning and resource management need to be based on more explicit models than those currently being used, ones which might enable people to clarify their assumptions and to critique the logical consequences of possible policy decisions based on those models. He is not content, however, to make a limited case for himself and his model.

Assuming that a completely generalizable case is required, Forrester allows for no exceptions, and thus for no qualifications as to when his model is, and when it is not, useful in decision-making. The same is true for his claims regarding the role of models in general: for him, there are no possible instances when mental models are not operative in the complex processes of human behavior. But as John Platt has argued, "there is no point in making hypotheses that are not falsifiable, because such hypotheses

do not say anything."[13] Forrester's assumption that all decisions are based on models falls under Platt's description of "The All-Encompassing Theory Which Can Never Be Falsified," which "is not a theory at all, because it does not exclude anything and therefore it does not predict anything."[14]

Aside from the problems of overgeneralization and untestability, Forrester's notion of counterintuitiveness suffers from another difficulty. A major theoretical assumption that Forrester makes is that "the human mind is not adapted to interpreting how social systems behave."[15] But it is unclear whether he means that we are biologically not adapted or that, although capable, we simply have not yet learned to understand the feedback processes of the complex social-industrial systems in which we live. In support of the first explanation he has written, "evolutionary processes have not given us the mental skill needed to properly interpret the dynamic behavior of the systems of which we have now become a part."[16] On the other hand, in *World Dynamics* he suggests that "human experience trains the mind only poorly for estimating the dynamic consequences of how the parts of a system will interact with one another."[17]

In the one case his argument is that because explosive growth has occurred only in the last century or two, the human mind, used to dealing with simple, linear social processes over the course of evolutionary time, has not got the mental equipment required for analyzing social systems of the sort we find in contemporary advanced societies. In the other, lack

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[13] John R. Platt, "Strong Inference," *Science*, Vol. 146 (16 October 1964), p. 350.

[14] Ibid.

[15] *Tech. Rev.*, p. 53.

[16] Ibid.

[17] *WD*, p. 15.

of experience is seen as the basis for our inability to deal with the variables of social systems, in which case we could improve. In Forrester's argument for the use of the World Model, the human mental defect by virtue of nature or nurture question is not resolved, and so it can only be acknowledged as problematic. Forrester does note, however, that human beings are capable of identifying social problems and can often separate those problems into their component parts. But although we may even achieve a measure of clarity as to the operative forces, we are not able to foresee where the possible solutions to those problems will take us. What computers do that human beings are incapable of doing is to follow the interactions of the various assumptions that comprise a model to their logical conclusions. Here I tend to agree with Forrester, at least with regard to what computers do, though I am less sure that human beings are "incapable of doing" so.

A Softer Version. Forrester's assertion that the consequences of his "realistic"[18] model of the global ecology are "generally unexpected" somehow gives more credence to the model than might otherwise be the case. The implications of this argument are as follows:

1) The behavior of social systems is counterintuitive, given the present evolutionary state of the human mind, and therefore the translation of our fuzzy mental models into precise computer models is required if we are to make any headway in solving social problems.

2) The behavior of social systems can be accurately and effectively modeled using the World Model, as described in *The Limits to Growth*.

3) The computer printouts of the World Model are not what one would generally expect and therefore the model is a realistic one which ought to be used to determine policy.

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[18] *Tech. Rev.*, p. 54.

This argument could be stated in a seemingly weaker, and yet more accurate, manner; it would at the same time be more convincing. Forrester could argue that *some* social systems under *certain* circumstances behave in a counterintuitive way. After all, some phsycal systems have been found to behave in a "generally unexpected" manner. The question then is, of course, counter to *whose* intuition?

Intuition is not an entity to which a particular value can be assigned; it is not something that exists apart from its possession by individual human beings. The word intuition is defined in the *Oxford English Dictionary* as "the immediate apprehension of an object by the mind (or by the intellect or by sense) without the intervention of any reasoning process." For Forrester, intuition describes the process by which all those who do not concur with his analysis come to believe what they do about the way the various parts of the global system interact. Forrester's conclusions are certainly not counter to the intuition of the participants in the Malthusian tradition, but only of those who, for reasons of either intellection or intuition, find themselves questioning Forrester's logic or disagreeing with his premises.

Another important issue is raised by step (1) in the argument outlined above. Does the mere translation of a mental model into the quantified variables of a computer language make it more useful or give it more predictive power? A computer model is only as good as the verbal assumptions from which its structure is derived. With this Forrester would not disagree. The quantification of verbal models, especially those of social systems, might render them more precise, in that their parameters would be more sharply delineated. However, it is an open question whether such quantification would add to a model's accuracy in representing its subject. In other words,

the logical validity of a mental model is not likely to be improved simply by quantification. The predictive power of such an "improved" model might conceivably increase, but only if the whole quantitative structural assembly were empirically more accurate as well.

Forrester's bias on this issue is clearly revealed in his statement that "any concept or assumption that can be clearly described in words can be incorporated in a computer model."[19] His implication is that if a concept or an assumption cannot be translated into the formalism of a computer language then it is too vague and fuzzy to be of any real use in a model in any case, mental or otherwise. There are, of course, describable concepts whose nature is paradoxical or whose subject matter is ambiguous by definition. Concepts in ethics or law, such as the idea of "the good" have been clearly described--well enough to form an integral part of systems of moral philosophy.[20] Such concepts would undoubtedly lose their richness and, indeed, their very substance if they were "translated" into computer language.

Sweeping Applicability? Forrester's advocacy of precise quantifiable variables as the only basis for useful model building is complemented by his extensive claims for his method. He asserts that the system dynamics methods he developed for application to physical systems are "sweepingly"[21] applicable to the analysis of social systems. Moreover, he states, "the methods apply to complex systems regardless of the field in which they are

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[19] Ibid.

[20] See, for example, G. E. Moore, *Principia Ethica* (Cambridge, England: Cambridge University Press, 1903).

[21] *Tech. Rev.*, p. 53.

located."[22] Many critics have reacted negatively to Forrester's pronouncements about the universal applicability of his methods, primarily because Forrester seems to be so sure of himself, and thus somewhat outside the scientific traditions of multiple hypotheses[23] and qualified conclusions.

Forrester shows little familiarity with the work of social scientists, demographers, economists, ecologists and others who have contributed to the theoretical and methodological foundations of modeling, and who support the process of model building and its application to public policy decisions. Forrester's footnotes refer the reader of *World Dynamics*, for example, to other books of his and to studies by several of his students. As Martin Shubik asks, in a letter replying to critics of his review of *World Dynamics* in *Science*, "Why are so few social scientists referred to by Forrester? Are there none whose knowledge is worth considering when building models of social, political, and economic processes?"[24]

In evaluating Forrester's assertion that his methods for analyzing physical systems are applicable without substantial modification to social systems analysis, it would be useful to ask questions such as: Under what circumstances are the methods useful in the modeling of physical systems appropriate to the analysis of social systems? Or, what aspects of social systems are amenable to analysis using the techniques of system dynamics? A strategy for carrying out such an inquiry might include, for example, picking a small social system, developing a quantitative model, running it through a computer, and then testing its value as a policy-making tool

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[22] Ibid.

[23] Platt, op. cit.

[24] Martin Shubik, Response to letters in "Letters," *Science*, Vol. 176 (14 April 1972), pp. 109-13.

against the nonquantitative mental models commonly used in "real-world" decision-making processes to ascertain which mode yields the highest degree of predictability and heuristic utility.

The results from such an investigation would not be at all easy to achieve. The actual use of output from a computer model will always proceed within the context of an economic, social, political milieu. Efforts to develop working models for social units the size of a large city have proven less than successful, as Dr. Garry Brewer's exhaustive examination of the San Francisco and Pittsburgh urban renewal projects[25] has shown. Furthermore, it is unlikely that citizens or planners will, when presented with computer model output that conflicts with their views on a particular problem, cancel previously held views about the way social and political systems behave. In fact, intellectual and ethical differences between those whose fundamental commitment is participation in the political process and those whose technical specialty is systems are far greater than might be expected *a priori*.[26] The technocratic style of social planning, characterized by "faith that technical analysis is superior to political process as a means of arriving at decisions,"[27] is not easily integrated with the day-to-day proceedings of governmental affairs. Thus on several major counts, ranging from scientific to political, Forrester's claim to universal applicability for his methods is contradicted.

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[25]Garry D. Brewer, *Politicians, Bureaucrats, and the Consultant* (New York: Basic Books, 1973).

[26]Ibid., p. 168.

[27]William Alonso, "Cities and City Planners," *Daedalus* (Fall, 1963), p. 827, quoted by Brewer, p. 101.

What Constitutes a Valid Model: Possible Criteria. One of Forrester's goals which is not at all objectionable is to put forth the World Model as a starting point for global modeling. By stating clearly his assumptions, Forrester hopes that other researchers will be able to suggest changes: to show that different assumptions are warranted, or that other variables could be included and provide more accurate results, or that more precise information is available and can be added to the data. While criticism of his approach and policy recommendations has been severe and widespread, though by no means unanimous, only a few critics have published "improvements" of the World Model. The two I will consider here advance different but mutually compatible criticisms of Forrester's work, based on the criteria for valid modeling employed by each author. Both address the problem of evaluating what conclusions may justifiably be drawn from modeling efforts and how those conclusions are to be used in formulating policy.

In reporting a study done at the Koninklijke Shell-Laboratorium in Amsterdam, Oerlemans, Tellings, and de Vries argue that Forrester's most objectionable structural omission is that of a fully functioning social feedback mechanism.[28] The researchers point out that the original "model structure does not leave sufficient scope for mankind to intervene when the world system develops in an undesirable way."[29] Such a criticism reveals a clear difference with Forrester in social and political assumptions, in views about the way human beings can be expected to respond to events. The Dutch group reworked the World Model, embedding their own assumptions in the new version. The model modification consisted of adding a social feedback loop

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[28] T. W. Oerlemans, M.M.J. Tellings, and H. de Vries, "World Dynamics: Social Feedback May Give Hope for the Future," *Nature*, Vol. 238 (4 August 1972), pp. 251-253.

[29] Ibid., p. 252.

onto the pollution level and "increasing the recoverable amount of resources at a cost,"[30] which resulted not in merely postponing global crises, but in eliminating them or substantially reducing their impact.

What Oerlemans and his associates showed is that the lack of social feedback can be remedied within the context of system dynamics methods. They do not suggest that their "model is a better one, with a higher forecasting value," but that their "results show that...one can construct a much more stable future outlook, which is less prone to crises than the World-2 and -3 models."[31] The fact that a less gloomy global future could be coaxed from a revised World Model does not mitigate these critics' theoretical and methodological criticisms, which are serious and damaging to Forrester's case.

One of the most important criteria for valid computer modeling, according to the Dutch group, is that "the results should be verifiable."[32] By this it is meant that "output from model computations should be comparable with data that have been gathered from measurements on actual processes or during experiments."[33] With respect to attempts at modeling the past, composed of events that have already taken place, such a condition is a reasonable one to impose. But there are, for example, certain epistemological problems involved in ascertaining, among other values, the aggregate global pollution level for 1900, which tend to deprive the World Model of some measure of its empirical validity. As for "modeling" the future under conditions imposed by this test, all that can be verified is the accuracy of the data on which one's projections are based.

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[30] Ibid., p. 254.

[31] Ibid., p. 252.

[32] Ibid., p. 251.

[33] Ibid.

It is perfectly possible to arrive at a multiplicity of models whose results fit the curves of available historical data, however patchy or imprecise they may be. Forrester and Meadows have produced a series of models whose behavior is a reasonable approximation of the ecological data obtainable from 1900 to 1970. Curve fitting, though reassuring to the modeler, constitutes only a necessary, not a sufficient, condition for valid modeling. Furthermore, because the World Model is highly aggregated, subsuming many nonempirical, unverifiable variables under one of a number of state variables--for example, under "Quality of Life," a catchall variable--it does not satisfy the Dutch group's criterion of verifiability.

The third criticism made by Oerlemans and his associates, closely related to the issue of empirical content, concerns what they call "lack of insight about system structure."[34] They argue that the theoretical structures which, when supported by established evidence, might serve an explanatory function in the description of global ecological behavior are for the most part lacking. Thus no theory and in many cases minimal evidence exists for many of the functional relationships central to the World Model. As Oerlemans writes, "it is questionable whether we can indicate the variables and relations that determine the behavior of the demographic and economic systems of the world."[35] In conclusion, the Dutch group notes that "the forecasting value" of their revision of the World Model "is still rather low and serious scientific research is required before any final views can be justified."[36]

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[34] Ibid., p. 252.

[35] Ibid.

[36] Ibid., p. 255.

Forrester's own goal in developing the World Model was, among others, to improve on the mental models on which decision-makers now rely, by providing a more precise, less ambiguous computer model. But as we have seen, even by improving Forrester's model with the addition of a more responsive social feedback function and more recoverable resources, which resulted in what for the Dutch group were reasonable scenarios for the future, their version was still far from satisfactory as a tool with which to make policy. Robert Boyd, a University of California zoologist, came to a similar conclusion using Forrester's own argument "that since decisions are being made on the basis of simpler and fuzzier verbal models, decision-making can only be improved by using computer simulation."[37] This assertion can only be true, Boyd reasoned, "if the computer simulation is insensitive to different sets of plausible assumptions."[38]

By adding a sixth state variable, "Technology," to the five on which the World Model is based, Boyd was able to model the expectations of the "technological optimist." He built in the necessary multipliers to calculate and express the effects of technical innovation and technological growth on the other state variables. The birth rate multipliers were modified to reflect the expectation that given a sufficient standard of living, the birth rate will decrease.

Boyd's new model is thus simply a quantified version of the views outlined above, just as Forrester's model is a quantified version of the relatively pessimistic views of the modern Malthusian. The new version of the World Model produced "exactly what a technological optimist would predict."[39]

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[37]Robert Boyd, "World Dynamics: A Note," *Science*, Vol. 177 (11 August 1972), p. 516.

[38]Ibid.

[39]Ibid., p. 517.

The optimists, whether their expectations are quantified or not, tend to argue that advances in technique will support virtually unlimited economic growth. Further, they expect that we will always be able to make substitutions in resources and materials, thus eliminating any particular scarcity. Increases in productivity will continue to result from expanding technological capacity, ultimately raising the standard of living and thereby lowering the birth rate. It is just this set of expectations that Boyd's model printed out.

It is not the particular structural character of Boyd's model that is important here; he was not trying to show that the technological optimist's world view is more reasonable than Forrester's apocalyptic Malthusian outlook. Boyd's point is that it was the assumptions which he built into his version of the World Model that provided the basis for the conclusions the computer printed out. The same, he argues, occurred with Forrester's model. Boyd writes, "the output of the model under each of the different sets of assumptions is the same as was reached without the use of the computer."[40] So we are still left with a fundamental disagreement as to which world view, and hence which model, is the most defensible. Boyd concludes that Forrester's model "is far from useful as a policy tool, and, even within his own framework, Forrester was unjustified in making such strong policy recommendations."[41]

Summary. We have seen that Forrester's convictions regarding the universal applicability of the methods of System Dynamics have led him to put forth untenable arguments both as to the internal validity of his model and with respect to the immediate utility of his conclusions for policy. Forrester assumed that the association of a numerical value with a social

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[40] Ibid., p. 518.

[41] Ibid.

event automatically describes that event more accurately than it could be described without a number. This assumption stems directly from his view that only what can be quantified--what can be incorporated into a computer model--is worth using as information in the decision-making process. Physical and chemical processes can be quantified usefully in this way, to a degree of precision limited by the nature of the events and by the quality of the measuring techniques employed. There is, to be sure, a large class of social, political, and economic events and processes that is amenable to quantitative analysis and thereby to inclusion in computer models. But the Forrester-Meadows global modeling project has demonstrated that the tendency to be preoccupied with the techniques of quantification, and to distrust the ambiguity and inexactness that often characterize human processes is counter-productive in the effort to understand those processes.

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