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One way to assess a tool is to explore the merits of the purposes it serves. Another way, suggested by Lee, is to evaluate its *intrinsic* qualities. I suggest that technologies serve human purposes *and* have humane qualities.

1) Machines do monotonous, dirty, heavy-duty, in short, alienating work which most people would rather not do. And, there is a lot of such work that needs to be done.

2) Machines do work that is humanly necessary *and* cannot be done otherwise; here purpose and means are inseparable. For example, most medical technologies *cannot* be replaced by insight, hands, training, or whatnot.

3) Often technological means are significantly more economical *per unit of use* than other means. They are, hence, a prerequisite for coping with a wide spectrum of human needs in the face of scarcity.

Thus, when the purpose is right and the technology appropriate, and when its often undesirable side effects are either small or correctable, technological tools are often the most human *and* humane way to proceed.

AMITAI ETZIONI
Department of Sociology,
Columbia University,
New York 10027, and
Center for Policy Research, Inc.,
475 Riverside Drive,
New York 10027

Modeling the World

The conclusion stated in Robert Boyd's abstract of his critique of Forrester's world model (11 Aug. 1972, p. 516) would be correct upon the addition of a single word. The abstract would then read: "The results of Forrester's world model are shown to be very sensitive to *absurd* changes in assumptions." Changes in Forrester's assumptions should not violate the second law of thermodynamics.

Boyd's "technological-optimist view" includes two obviously invalid assumptions. These are multiplier 2, "a fourfold increase in technology over the 1970 level decreases pollution output per unit of material standard of living to zero," and multiplier 3, "NRTM [natural resource technological multiplier] reduces the natural resources input per unit material standard of living to zero when technology quadruples." Both of these assumptions contradict the second

law of thermodynamics by ignoring the unavoidable degeneration of useful forms of energy into unrecoverable heat pollution. They also ignore the necessity of changing useful energy into waste heat in order to reverse the natural entropic change from order to disorder during the use of natural resources.

If we grant the technological-optimist his premise of an essentially inexhaustible source of energy, his indefinitely increasing technology and material standard of living (Boyd's figures 3 and 6) require an ever-increasing transformation of natural resources with increased energy input, consequent entropy, and heat pollution. According to Budyko (*1*), a small increase in the energy balance would be sufficient to melt the polar ice (0.2 to 0.6 watt/m^2, which is a few tenths of 1 percent). Although Budyko's mathematics appear to be correct, the assumption of such an increase is obviously open to question. Nevertheless, if we were to sustain the present annual rate of energy increase, enough heat would be generated to melt the polar ice in less than a century, and the technological heat input would exceed the present radiation balance in 220 years, according to McDonald (*2*).

The technological optimist would have us move toward such a climate sooner. That we will reach it is absurd, but so is the technological optimist's enthusiastic prognosis. Try as he may, the technological optimist cannot escape the necessity of a mass-energy, steady-state technology. Forrester's world model is open to question, but ultimately his conclusions are correct. Reasonable changes in Forrester's model may significantly alter the timetable, but not the destination. We need technological realism rather than technological optimism or pessimism. Qualitative progress can continue indefinitely, quantitative progress has its natural limits. The longer we wait to substitute qualitative for quantitative progress, the greater will be the threat to future generations.

PAUL E. DAMON

Department of Geosciences,
University of Arizona,
Tucson 85721

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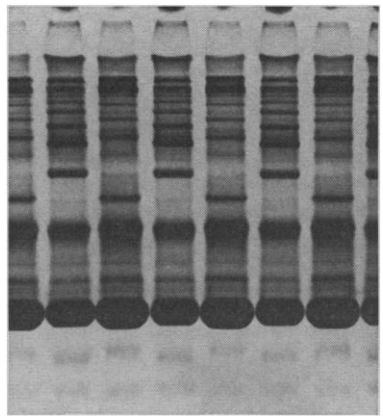
1. M. I. Budyko, *Sov. Geogr. Rev. Transl.* **10**, 429 (1969).
2. G. J. F. McDonald, in *Environment, Resources, Pollution and Society*, W. Murdock, Ed. (Sinauer Associates, Stamford, Conn., 1971), p. 334.



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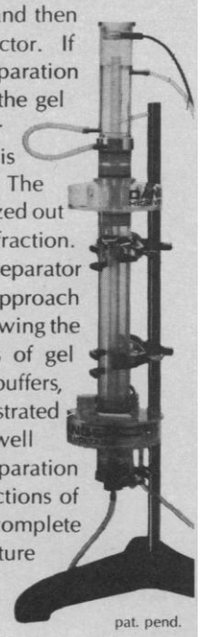

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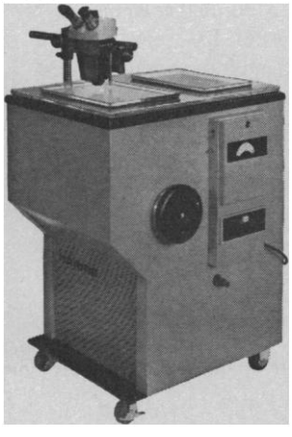

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On the basis of its presumed sensitivity, Forrester's world model has been criticized by R. Boyd for not being able to discriminate between neo-Malthusian and technological-optimist policies. To summarize his position, if two slightly different versions of the same model give conflicting results, the model is not useful as a policy tool. The models in *World Dynamics* are not policy tools. However, they can still contribute significantly to a resolution of this controversy by focusing attention on what are often only implicit assumptions.

No model can decide between sets of assumptions only on the basis of its predictions. We are all equally ignorant of the future. Models can be more or less valid only in their representation of historical trends. A model cannot predict the future. However, it is worthwhile to require of a model that the assumptions it embodies be susceptible to reasoned argument and, if possible, empirical verification. Boyd's note demonstrates that Forrester's world model passes *that* test by clarifying differences in basic assumptions to the point where specific well-defined questions about the assumptions can be posed and possibly answered. Among these questions are the following:

Is technology an object, a stock which grows for all time and at no cost, or is it a social process which competes with other processes for available social capital? Further, what are the delays involved in the development and implementation of technologies?

Is there necessarily a negative relationship between technological advance and pollution generation or resource use rates? Is it possible to increase the world's stock of capital using no new resources and generating no pollution?

Do the birth rate multipliers act without delay, or is there a lag between perceptions of the social environment and their eventual effects on family structure?

A model cannot answer these questions, but it can help explore the implications of more or less credible assumptions about the answers to them.

The clarification of assumptions also contributes to the discussion about the sensitivity of the model. Sensitivity is intuitively expressed by the idea that small perturbations in the model lead to small or large changes in model behavior. The addition of a new level whose purpose is to remove two of the pressures (resource depletion and pollution) operating in the original model seems to violate the assumption of small perturbations. Indeed, Boyd claims that pollution generation and resource usage rates could go to zero at a finite level of technology. If resource use and pollution generation rates are decreased (to model technological advances) but remain finite, model behavior is not seriously affected [see figures 5-8 and 6-1 in *World Dynamics* (*1*)].

Boyd's remedy, disaggregation and increased complexity of structure, may increase academic confidence in the model. However, there is a trade-off with comprehensibility and no guarantee that the model will be less sensitive to alternative sets of assumptions. Nor is there a guarantee that there will be any fundamental change in the behavior modes of the model.

R. JOEL RAHN
Thayer School of Engineering,
Dartmouth College,
Hanover, New Hampshire 03755

Reference

1. J. W. Forrester, *World Dynamics* (Wright-Allen, Cambridge, Mass., 1971), pp. 105, 114.

In the second letter, R. J. Rahn summarizes my paper inaccurately; much of his criticism seems to stem from this misunderstanding. It was not my intent to show that Forrester's model was sensitive to small perturbations; the word "sensitivity" has a specialized use in engineering, and my use of it was unfortunate. My argument may be more correctly summarized in the following way:

In the controversy about the world population problem there are two major positions, that of the neo-Malthusian and that of the technological optimist; each has a sizable portion of the intellectual community among its adherents. With neo-Malthusian assumptions, the world model yields results which are qualitatively the same as those the neo-Malthusians produce without the use of computers; with assumptions of a technological optimist, the model yields a technological optimist's results. Thus in the absence of any additional empirical input, the model does very little to help us decide between the two positions.

Rahn quite rightly points out that models have very useful instructional and heuristic properties. It was not

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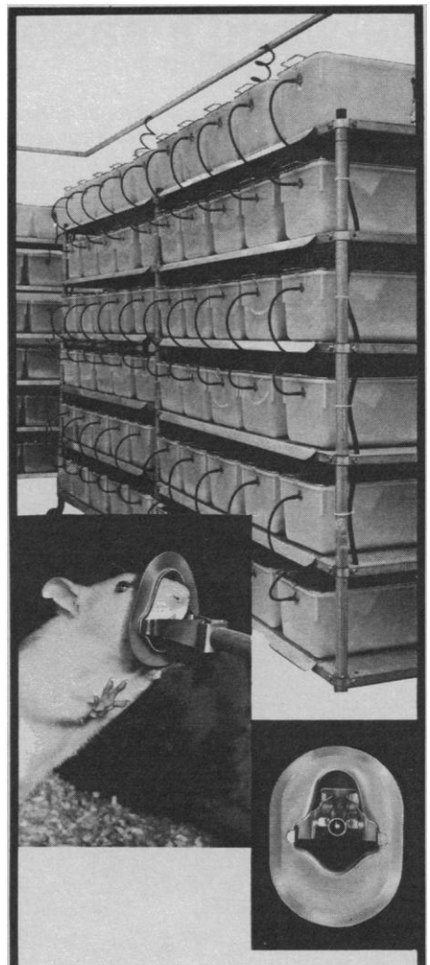
my intention to imply that Forrester's model was not useful for clarifying ideas (particularly to those with technical training) or in generating new research questions. A few caveats are in order, however. If there is uncertainty about a large number of the interactions incorporated in the model, the number of different, plausible simulations will become bewilderingly large. Disaggregation could help by making the variables less operationally vague; but, as Rahn points out, this entails its own costs. I am prepared to accept the possibility that there are some systems for which mathematical modeling is not especially fruitful and that the world system might be one of these, but only time will tell. The possible benefits certainly justify the attempt.

There seem to me to be two ways to read P. E. Damon's critique. One could regard it as an attack on the technological optimist's position. If this is the case, he ought to argue with them and not me. On the other hand, the point may be that I have misrepresented the mainstream of the technological optimist thought—specifically, that there are few who would assert that natural resource use or pollution generation can be reduced to zero. I have decided that this is at least partially true. Many technological optimists argue that the quantity of resources has actually increased during this century. For example, was uranium a resource 50 years ago? This view could be represented in Forrester's model only by a negative rate of use. Thus the zero rate suggested in my report is conservative. On the other hand, it probably is unfair to reduce pollution output to zero. However, I have done runs with a maximum reduction from present levels by a factor of .01, and the results were identical to those of similar runs with the multiplier used in my report.

Damon says, "Forrester's world model is open to question, but ultimately his conclusions are correct." I believe our present ignorance of the nature of the world system makes this more a statement of prejudice than of scientific fact, and while I share Damon's prejudice, I am unwilling to have it sanctified by the computer.

ROBERT BOYD
Department of Mechanical Engineering, University of California, Davis 95616



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