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10 April 1972; revised 29 May 1972

World Dynamics: A Note

Abstract. *The results of Forrester's world model are shown to be very sensitive to changes in assumptions.*

In *World Dynamics* (*1*) Forrester presents a simple simulation model of the world. This model consists of five first-order differential equations in five very highly aggregated state variables. For example, the variable NR is defined as "natural resources." He also includes some auxiliary variables that indicate performance; these he calls "quality of life." Forrester performs several simulations and, based on the behavior of the quality of life in these simulations, makes several quite provocative policy recommendations.

For most of the scientific community, modeling the world with only five state variables is a dubious project. Recommending policies based on such a simple, operationally vague model is doubly suspect. Forrester argues that his simulations are not at all dubious, and 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. In this report I argue that this assertion is only true if the computer simulation is insensitive to different sets of plausible assumptions and I will show that the *World Dynamics* model does not demonstrate such insensitivity.

World Dynamics has been received very critically. Several reviews have taken Forrester to task for doing bad science. For example, Shubik (*2*) wrote ". . . the book is blatant and insensitive advocacy for unsubstantiated model building on a very large scale. . . . What is this book for? Its behavioral-scientific content is virtually zero. . . . None of his (Forrester's) book has any empirical content, yet the operation of all his models calls for large numerical inputs." These sorts of criticisms miss their mark; Forrester is not trying to do behavioral science. He has a less ambitious goal, to improve on the verbal and mental models that are now in use. And he would argue that computer models are always better than verbal or mental ones. His argument can be condensed into the following propositions:

1) People are quite good at perceiving relationships between various components of the world system.

2) People are not very good at deducing the whole system consequences of these individual relationships.

3) It is quite easy to use computer simulation to accurately deduce the consequences of any set of relationships. Therefore, verbal models or mental images are necessarily inferior to mathematical models.

4) Policy decisions are presently being based on nonmathematical models. Therefore policy can certainly be improved by reexpressing these vague models in a more exacting systems dynamics formalism.

It seems relevant to ask whether this conclusion is true. Does the simple translation of a verbal model into Dynamo improve its predictive ability?

Imagine, for a moment, one of Forrester's social dynamicists entering the political arena. There he would find decisions being based on an array of vague, hard to verify, mental models founded upon conflicting assumptions, and reaching different conclusions. As a first step the social dynamicist could reexpress each of the different mental models as a different simulation of his model. But unless all these simulations show substantially the same results, the dynamicist has done little to improve the lot of the decision makers. Instead of being faced with an array of unverified mental models, he is confronted with an equal number of conflicting computer simulations. To be of use then, the social dynamicist would have to go to a more sophisticated, complicated model whose components can be independently verified in some way.

Let's apply this test to the model in *World Dynamics*. Roughly there exist two ideological poles in the controversy about the future of the world.

1) The Malthusian view. The adherents of this view argue that the earth is endowed with some fixed, finite amount of resources. We only have so much agricultural land, so much petroleum, and so on. Further, Malthusians argue that anything that makes life better, be it better nutrition or increasing material standards of living, leaves birth rates constant and lowers death rates. New technology in this view can only temporarily alleviate shortages; population must inevitably overtake any increases in productivity. Eventually an equilibrium between high death rate and high birth rate is reached. This view is more completely expressed and defended in much of the conservation literature.

2) The technological-optimist view. The adherents of this view argue that there are no foreseeable limits on production of goods. Any particular scarcity will be eliminated by substitution technology. Further, the increasing stock of technology is seen to increase productivity and thus increase the standard of living. Increasing the standard of living is then supposed to produce lower birth rates. Eventually society is

seen to reach an equilibrium between a low birth rate and a low death rate. A more complete explication can be found for example in Barnett and Morse (*3*) or in Fredericksen (*4*).

Even a casual reading of *World Dynamics* shows that Forrester's model is fundamentally Malthusian. The quantity of natural resources is fixed, and the productivity of industry based upon them decreases with time. Agricultural productivity may be increased only by increasing capital investment in agriculture. The pollution output per unit of the material standard of living is irreducible. In several of his simulations Forrester invokes technology to, for example, reduce pollution output by some fixed fraction at some point in time, but this is hardly the constantly adjusting, powerful technology of the technological optimist. Birth rate in Forrester's model increases strongly with increasing food per capita. It decreases strongly with increasing pollution and crowding, and weakly with increasing standard of living.

To test the sensitivity of the *World Dynamics* model to changes in assumptions I have altered the model to conform to the technological optimist's view. This involved adding a new state variable, technology (*T*) and multipliers to express the effect of technology on the other state variables. Two birth rate multipliers were also altered. For the sake of consistency all these alterations are expressed in the systems dynamics idiom. If the reader is unfamiliar with the peculiarities of this formalism, he will find a brief explanation in the appendix. For a more complete discussion, see *Industrial Dynamics* (*5*). A complete listing of all equations changed or added will be found in the appendix.

The numerical values of these multipliers and constants were invented from whole cloth. They are meant only to reflect, in a reasonable way, the technological optimist's faith that, for example, soon we will be able to find a substitute for any diminishing natural resource.

The rate equation for technology is expressed in Dynamo notation:

$$T.K = T.J + (DT)\ (R.JK)$$
$$R.KL = (RN)\ (RCM.K)\ (RQLM.K)$$

where *RN* is a constant which represents the 1970 rate of increase of technology (RN was taken to be .04); RCM expresses the effect of capital stock per capita on the increase of technology. Increasing availability of capital is supposed to speed technological growth up to an asymptote. The exact form of RCM is shown in Fig. 1a.

The form of RQLM supposes that as quality of life declines society will invest more technology to improve that quality (see Fig. 1b). The effect of technology on the rest of the model is expressed through three multipliers.

1) FTM (Fig. 1c): All other things being equal a sixfold increase in technology over the 1970 level (taken as 1) increases the food ratio (FR) by a factor of 8.

2) PFTM (Fig. 1d): Again *ceteris paribus*, a fourfold increase in technology over the 1970 level decreases pollution output per unit of material standard of living to zero.

3) NRTM (Fig. 1e): NRTM reduces the natural resources input per unit material standard of living to zero when technology quadruples.

Two of the birth rate multipliers were also altered to conform with the technological optimist's assumptions.

1) BRMM (Fig. 1f): In Forrester's model, this multiplier reduced birth rates by a factor of 0.7. This is a weakly non-Malthusian hypothesis. Data (*5*) suggest however that it is not unreasonable to suppose this multiplier can drop as low as 0.4.

2) BRFM (Fig. 1g): This multiplier expresses the effect of food per capita on birth rates. Forrester assumed that a fourfold increase in food per capita would increase birth rates by a factor of 2. As an aside, given that world birth rate is about 45 per 1000 women per year in underdeveloped nations, a twofold increase must be hard for even the most extreme Malthusian to defend. BRFM was modified so that birth rates were unaffected by increases in food per capita above the 1970 level. This is a weak non-Malthusian position.

The results of the simulation are shown in Figs. 2 to 4. They are exactly what a technological optimist would predict. Technology increases productivity, which, in turn, increases the standard of living. This eventually drives birth rates low enough that a "Utopian" equilibrium is reached. In *World Dynamics*, Forrester argues that social systems are counterintuitive, that they show behavior opposite to what one would expect. As an example he introduces birth control into his model and shows that it only worsens the eventual equilibrium. Forrester's version of birth

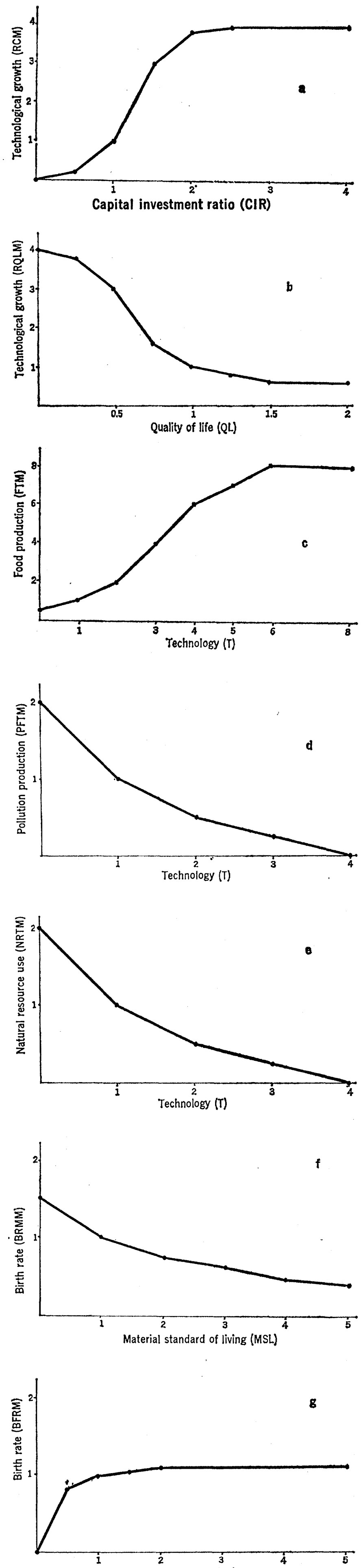
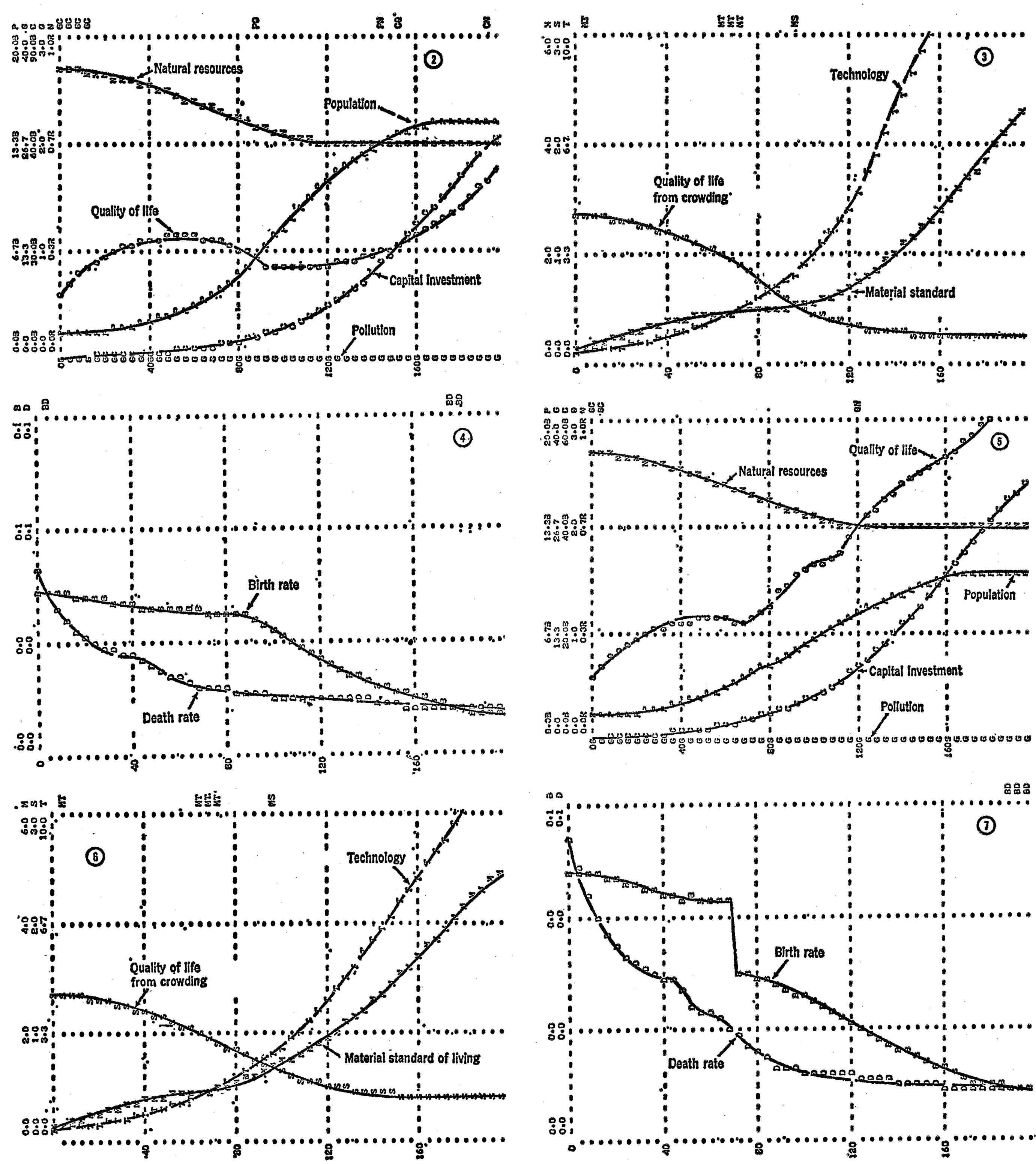


Fig. 1, a–g. Graphs of the form of the multipliers added to or changed in the *World Dynamics* simulation. All variables are unitless and are based on the assumption of *ceteris paribus*. The 1970 value is taken as 1.

control was added to my model and the results are shown in Figs. 5 to 7. The results are again exactly what the technological optimist would expect. Birth control allows the world to go through the demographic transition at a lower population level and greatly enhances the eventual equilibrium.

Forrester's model fails the test. It is completely unable to resolve the technological optimist–Malthusian controversy. In fact the output of the model under each of the different sets of assumptions is the same as was reached without the use of a computer. Thus, the *World Dynamics* simulation is far from useful as a policy tool, and, even within his own framework, Forrester was unjustified in making such strong policy recommendations.

The great strength of Forrester's methodology is its ability to assimilate expert opinion easily. A model with a larger number of more disaggregated



Figs. 2–4. Results of the *World Dynamics* simulation altered to include the assumptions of a technological optimist. The simulation starts at 1900 and runs through 2100. Figs. 5–7. Results of the technological optimist model with a reduction of the "intrinsic" rate of increase to .028 at 1970. Again the period simulated is 1900–2000.

state variables would allow experts in various fields to involve their knowledge more usefully. Such a model might be a practical policy tool. And in a way, such a model would be the good science that Forrester's reviewers were looking for.

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Appendix

The *World Dynamics* model consists of a system of difference equations. In the usual notation such an equation would be written:

$$X(t) = X(t - \Delta t) + (\Delta t) \cdot F[X(t - \Delta t),\ Y(t + \Delta t)] \quad (1)$$

where $F(t{-}\Delta t)$ can be thought of as the rate of change of X during the period from $(t - \Delta t)$ to t. There would be a similar equation for Y. Dynamo solves these sorts of equations in the following manner. At any given time step, say t, Dynamo has the store version of $F(t{-}\Delta t)$. In Dynamo this would be written $F.JK$. Dynamo updates X and Y with the use of Eq. 1. In Dynamo this is written $X.K = X.J + (DT)(F.JK)$. Then Dynamo computes $F[X(t),\ Y(t)]$. This is written $F.KL = F(X,Y)$. In the systems dynamics idiom F usually is a product of functions of single state variables. For example:

$$F(X,Y) = \phi(X.K)\ \psi(Y.K)$$

These multiple functions, ϕ and ψ, are entered into the program in a tabular form. This is done by the use of TABLE or TABHL statements. For example

$$PHI.K = TABLE(PHIT, X, 0, 1, .5)$$

and

$$PHIT = 1/.5/0$$

means that PHI has tabular values for X.K between 0 and 1 at increments of .5. These values are entered under the name PHIT. Between these increments Dynamo uses linear interpolation.

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24 March 1972; revised 26 May 1972

Double Moldavites in Southern Bohemia

Abstract. *Two noteworthy finds of moldavites were made in southern Bohemia. In both cases two moldavites are thrust into each other. The collision evidently took place during the flight of an inhomogeneous swarm of moldavites, still plastic but already displaying almost definite aerodynamic shapes. It is the first time such moldavites have been encountered, and the authors propose to designate them as double moldavites.*

In 1970 and 1971, two noteworthy finds of double moldavites were made in the fields of southern Bohemia. One of these double moldavites was found near Kamenný Újezd and the other near Slavče. In both cases two moldavites are partly thrust into each other. The one with the sharper and probably more solidified margin is partly plunged into the other moldavite. The collision probably took place while the moldavites were still plastic, before their infall to the earth's surface, as otherwise they would have been shattered.

The double moldavite from Kamenný Újezd (Fig. 1a) weighs 12.87 g. One part is of a drop shape, slightly olive green in color, and plunged almost per-

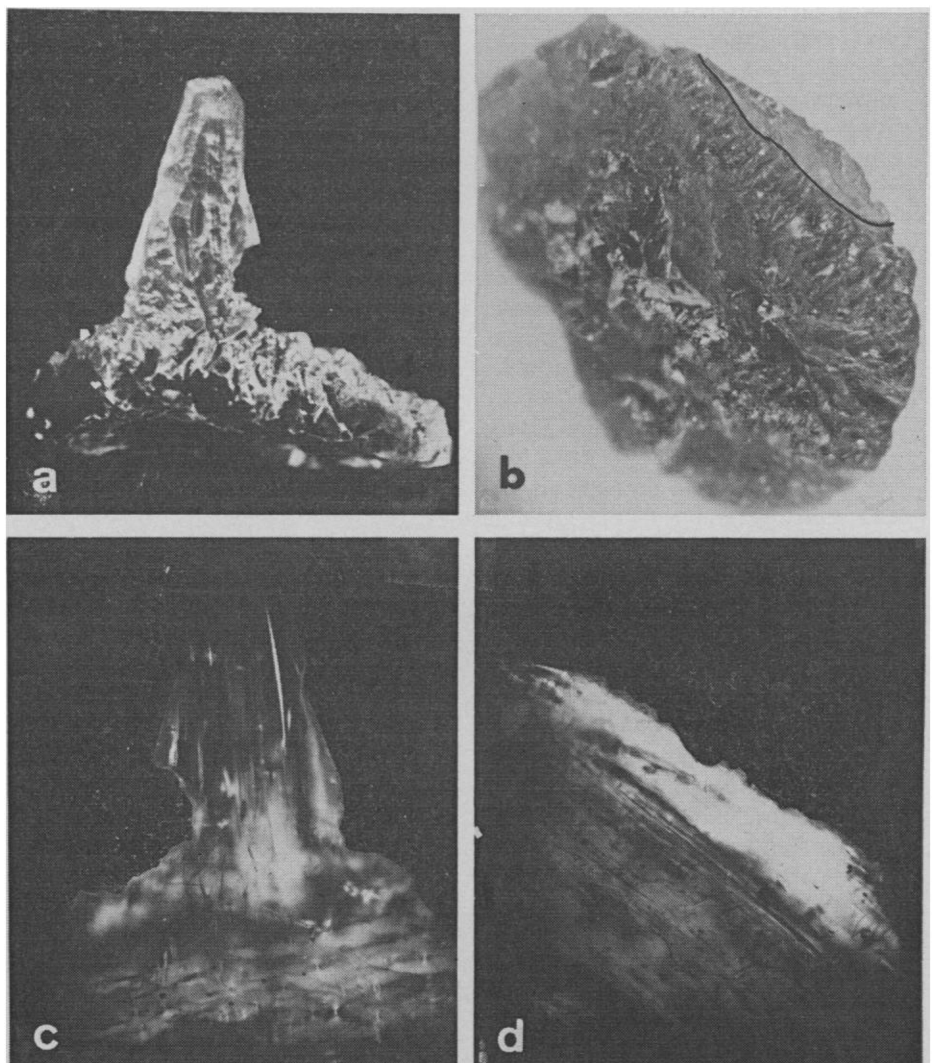

Fig. 1. (a) Double moldavite from Kamenný Újezd, Bohemia. A drop of moldavite has been thrust into the basic moldavite. (b) Double moldavite from Slavče, Bohemia. The boundary of the lighter moldavite piece is made distinct by a black line. The sculpture of both moldavites is different. (c) Double moldavite from Kamenný Újezd in benzene immersion, between crossed Polaroids. The increased anisotropy at the junction of the moldavites and the different interior arrangement of the moldavite matter can be seen. (d) Double moldavite from Slavče, between crossed Polaroids. The lighter, thrust-in moldavite is markedly optically anisotropic. All photographs are moderately enlarged.