International Institute for
Applied Systems Analysis
IIASA www.iiasa.ac.at

Understanding World Models

Keyfitz, N.

IIASA Research Memorandum
April 1977

RM-77-18

UNDERSTANDING WORLD MODELS

Nathan Keyfitz

April 1977

Preface

Representatives from 132 nations assembled in Vancouver in June of 1976 to convene HABITAT, the United Nations Conference on Human Settlements. The Conference was a global inquiry into solutions of the critical and urgent problems of human settlements created by the convergence of two historic events: unprecedently high rates of population growth and massive rural to urban migration.

Rapidly growing populations strain health and educational budgets, complicate efforts to utilize efficiently a nation's manpower, and exacerbate problems connected with the provision of adequate supplies of food, energy, water, housing, and transport and sanitary facilities. A better understanding of the dynamics and consequences of population growth, particularly its associations with resource and service demands, is therefore an essential ingredient for informed policymaking.

The Human Settlements and Services Area at IIASA is developing a new research activity that is examining the principal interrelationships between population, resources, and growth. As part of the preparatory work directed at the design of this activity, IIASA invited Professor Nathan Keyfitz, a distinguished demographer, to visit Laxenburg as a consultant. His address to the Institute's scientific staff on world models is summarized in this research memorandum and initiates a new publications series within the Human Settlements and Services Area .

Andrei Rogers
Chairman
Human Settlements and
Services Area
April 1977

Papers of the Population, Resources, and Growth Study

1. Nathan Keyfitz, "Understanding World Models," RM-77-18, April 1977.

2. Andrei Rogers, "Migration, Urbanization, Resources, and Development," RR-77-00, forthcoming.

Abstract

Computer models of the world system produce very different results, ranging from economic collapse and massive starvation in the 21st century to universal prosperity for double or triple the present world population. The strikingly different conclusions that arise make it urgent to compare them effectively with one another, and see what it is about them that produces such diverse policies. And even insofar as the policies are similar, one would like to know more about how they arise from the models.

This paper suggests a line of analysis that permits comparison of properties among such models. It takes up two ways of seeing what is in a model in addition to examining its documentation: first, making alternative transparent models that check the partial results of the complex model; and, second, 'black-box' experiments leading to a truncated linear form of the complex model. These two methods of assessment are designed to replace most of the documentation, and to allow the user to understand more effectively what assumptions he commits himself to in using the model.

Acknowledgements

Discussions at the International Institute for Applied Systems Analysis during a visit in September 1976 led to the argument here presented. The present version incorporates suggestions by Brian Arthur, Michael Balinski, Harold Barnett, Gerhart Bruckmann, Morris Norman, Andrei Rogers, Leonard Sagan, Karl Schuessler, and Frans Willekens.

Table of Contents

		Page
	Preface	iii
	Abstract and Acknowledgements	v
1.	THE ASSESSMENT PROBLEM	3
2.	ALTERNATIVE TRANSPARENT MODELS	4
2.1	Geometric Increase	5
2.2	Declining Rate of Increase	6
2.3	Demographic Transition	9
2.4	The Principle of Momentum	11
2.5	Conclusion from Transparent Models	12
3.	ANALYSIS OF THE MODEL AS A BLACK BOX	13
3.1	Explaining the Outcome	13
3.2	An Algorithm for Finding the Dominant Variable	14
4.	CONCLUSION	19
	References	23

Understanding World Models

Computer models of the world system are in wide use. They produce very different results, ranging from economic collapse and massive starvation in the 21st century to universal prosperity for double or triple the present world population. For the Meadows's (1972, Introduction), "If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime in the next hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity." At the other extreme, the Bariloche group (Herrera, n.d., about 1975, p. 138) finds no such difficulties of materials or foodstuffs: "The only problem of physical limitation which arises, and which is of a local nature, is the exhaustion of the supply of cultivatable land in Asia," and even this limitation does not arise until the middle of the 21st century. Leontief (New York Times, October 14, 1976) is more cautious: "No insurmountable physical barriers exist within the 20th century to the accelerated development of the developing regions." In respect of the proximity of the limits to growth Mesarovic and Pestel (1974) are intermediate between the extremes of the Meadows's and the Bariloche group. The spectrum of population growth can be filled out from other, less publicized studies. It seems that one can find a simulation that leads to any given degree of disaster.

Every one of the reports has policy implications. The feature common to all is the assertion, "Certain bad things will happen . . . unless you take such and such action to avoid them." Or else, and equivalently, "Certain good things are within your reach . . . but you must do such and such to attain them." The Meadows's concede that "The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual human potential," but they warn that this will take very drastic changes in the life style of those who have attained high income levels. For Leontief, "The most pressing problem of feeding the rapidly increasing population of the developing regions can be solved by bringing under cultivation large areas of currently unexploited arable land and by doubling and trebling land productivity. Both tasks are technically feasible but are contingent on drastic measures of public policy favorable to such development and on social and institutional changes in the developing countries."

For the Bariloche group there are no physical limits up to the year 2060. But if these were to arise, the rich countries could contribute by relieving the pressure on available resources and so help the poor countries indirectly. For these authors, "The obstacles which currently stand in the way of the harmonious development of humanity are not physical or economic in the strict sense, but essentially socio-political." They see the goals achieved, "not by very high economic growth, but by a reduction in non-essential consumption; increased investment; the elimination of socio-economic and political barriers which currently hinder the rational use of land, both for food production and for urban planning; the egalitarian distribution of basic goods and services . . . ." Mesarovic and Pestel (1974, p. 141) complement this; they find that we should consume less energy, own fewer goods, simplify our lives.

With their assertions that "Things will be good if . . ." or "Things will be very bad unless . . .", the models are brought into debate on the most urgent policy issues of the day. The strikingly different conclusions that arise make it urgent to compare them effectively with one another, and see what it is about them that produces such diverse policies. And even insofar as the policies are similar, one would like to know more about how they arise from the models.

For instance, nearly all recommend lower material consumption for the rich. If Americans ate less meat more grain would be released to Asians. But is that so? It has also been argued that if Americans ate less meat the grain would simply not be produced, because there would be no equally profitable market for it. We need to know more about methods that produce such opposite results if we are to think about the matter effectively.

1. THE ASSESSMENT PROBLEM

Variation in their policy recommendations makes the choice of model for a given purpose important, and the decision--like the choice of any other commodity--ought to be based on the properties of the models. But reasoned choice here offers peculiar difficulties, because though the models are simpler than the world system they describe each is still too complicated for anyone to grasp fully. What is badly needed is a method for comparing properties among world models.

Intelligent comprehension of the properties of world models ought to be assisted by documentation, yet there are some inherent limits to what a verbal account of the mechanics of the model can do. The five volumes that give the story behind the Mesarovic and Pestel (1974) work represent one of the more extended efforts to describe the computation in the clearest possible form. By and large each page is well and clearly written. Yet the reader finds himself overwhelmed long before he comes to the end of even the first volume. To hold in one's head the detailed account of the theory and data that went into the model is too demanding a task. Just as a human brain cannot perform the computation, so a human reader's mind is inadequate to gauge the impact of the assumptions and other inputs on the calculated outputs.

Some of the documentation may be highly relevant to the calculation; other parts may have no effect at all. The reader cannot judge, and in consequence users of the model usually neglect much of the written text. Even more effort could be put into writing up the descriptions without overcoming this difficulty, for the difficulty is intrinsic.

The present paper suggests a line of analysis that permits comparison of properties among such models. It takes up two ways of seeing what is in a model in addition to examining its documentation: first, making alternative transparent models that check its partial results; and second, "black box" experiments leading to a truncated linear form of the model. These two methods of assessment are designed to replace most of the documentation, and to allow the user to understand more effectively what assumptions he commits himself to in using the model. Assessment cannot avoid effort and expense. This effort and expense can be offset by elimination of all but the skeleton of the documentation customarily provided.

An important by-product of the experimenting here recommended is that it helps to produce a range of values for each output variable. To stop with one value for each input and hence for each output is to exaggerate grossly the degree of knowledge of the world system.

2. ALTERNATIVE TRANSPARENT MODELS

A general class of ways of enabling the client to understand better the model he is about to buy is to compare its results with alternative forms simple enough to be called transparent. The illustrations that follow will be applied to population submodels, but any other part of the global model that can be separated out (materials, energy, investment) can be similarly treated. A later section offers an alternative approach; it suggests an algorithm for discovering what part of a model dominates and is detachable.

The situation in respect of population, either in demographic projections or in world models, is that we are confronted by thousands of numbers for future times, showing 20 or even 90 ages, each according to sex, region, labor-force status, industry for those in the labor force, etc. With much consideration of detail the UN in 1968 arrived at 6.5 billion for the world in the year 2000, in 1972 at 6.2 billion. Can we judge such totals by formulas simple enough to be worked out on a hand calculator?

Experimenting on past data has shown that elaborate breakdowns have little effect on accuracy. Hence our transparent models will disregard most breakdowns and concentrate on total world population 25, 50, and 75 years from now.

2.1 Geometric Increase

Setting the 1975 world population P_{1975} at 4.0 billion and taking a rate of increase of 1.8 per cent per year, gives for the year 2000

$$P_{2000} = 4.0(1.018)^{25} = 6.2 \times 10^9 \ .$$

This is equal to the latest United Nations number for the year 2000, and below the 6.5 billion presented earlier for that year. Yet one can argue that it is almost certainly too high. For the present rate of 1.8 percent per year will go down. We stand presently at an historic high in the rate of increase of world population. The reason why the rate of increase must fall can be seen from the reason it has risen up to now.

The Net Reproduction Rate R_0 is the number of girl children expected to be born to a girl child just born,

$$R_0 = \int_0^\infty \ell(a)m(a)da,$$

where $\ell(a)$ is the probability that she lives to age a, $m(a)da$ the chance that she then has a child before age a + da. Thus R_0 is the ratio of the number living in one generation to the number living a generation before, as implied by the current rates of birth and death. If death is disregarded we have G_0, the Gross Reproduction Rate, as the same integral with the probability of surviving $\ell(a)$ omitted. If R_0 is the ratio of successive generations at the given rates of birth and death, then G_0 is the expected number of girl children of survivors at the given birth rates.

Then if we write

$$R_0 = \left(\frac{R_0}{G_0}\right) G_0 \quad ,$$

the first factor on the right is the suitably weighted probability of survival to maturity, the second factor G_0 is a pure fertility indicator. Up to now the main change for many countries has been the fall in the first factor, survivorship, while the second factor, fertility, has remained constant or fallen slowly. The survivorship cannot go above unity, and further declines in mortality--those past childbearing ages--make no great difference to the rate of increase. The rich countries have attained a probability of survivorship to maturity of about 0.97; the poor ones of about 0.90, except in Africa. As the limit of unity is approached the rate of increase of survivorship is bound to slow down. Any increase in survivorship beyond the 1970s is almost certain to be offset by a greater fall in fertility (Fig. 1).

The conclusion is that projecting the 1975 population at the 1.8 percent per year now shown, producing 6.2 million by 2000, must be an overstatement. Let us see what happens if we suppose a fall in the rate of increase.

2.2 Declining Rate of Increase

For dealing with changing rates of increase we need an expression that converts the trajectory r(t) of the rate of increase into a trajectory of the population. The definition

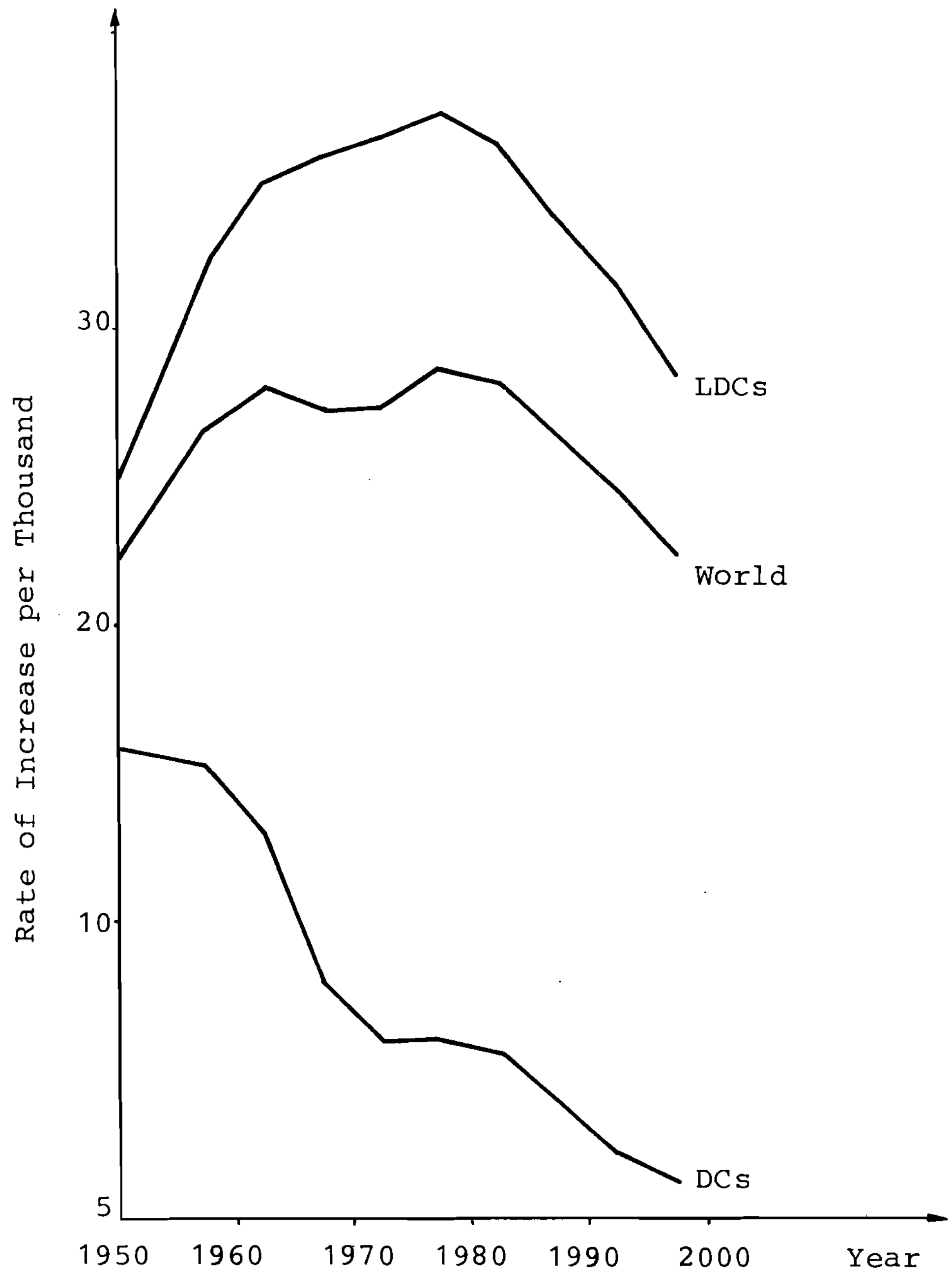

FIG. 1 Estimated Annual Rate of Increase, 1950-2000

of $r(t)$ is $\frac{1}{P(t)} \frac{dP(t)}{dt}$, and hence

$$\ln P(t) = \int_0^t r(u)du + \text{constant},$$

so therefore

$$P(t) = P_0 \exp\left(\int_0^t r(u)du\right). \qquad (1)$$

Use this to see what the ultimate world population would be if the rate of increase declined in a straight line to zero by the year 2050, starting at 1.8 percent in 1975. By the end of the century the rate would be 1.2 percent, by 2025 it would be 0.6 percent. The population at each point of time would be

t	$P_t/10^9$
1975	4.0
2000	5.8
2025	7.3
2050	7.9

Apparently the population in the year 2000 would be 5.8, and total subsequent increase for all time would be only a further 2 billion.

If everything is as above, except that the rate of increase drops to zero by the year 2025, we have lower figures:

t	$P_t/10^9$
1975	4.0
2000	5.6
2025	6.3
2050	6.3

so the ultimate population is only 6.3 billion.

If in the above we break our population totals into more or less developed countries (DCs and LDCs), the division will raise the result. For example, if the drop to stationary by the year 2050 starts with the DCs increasing at 0.7 percent and the LDCs at 2.4 percent, we have in billions

	DCs	LDCs	Total
1975	1.1	2.9	4.0
2000	1.3	4.8	6.1
2025	1.4	6.5	7.9
2050	1.5	7.1	8.6

Now the ultimate stationary world population is 8.6 billion. Recognizing heterogeneous subgroups has raised the outcome by 0.7 billion.

2.3 Demographic Transition

As a further approach, consider the demographic transition, in which in country after country a fall in mortality is followed after a longer or shorter time by a fall in fertility (Fig. 2). Between time t_0 and time t_1 the death rate d goes from d_0 to d_1 and the birth rate from b_0 to b_1 . Call A the area $b_0b_1d_1d_0$ in Fig. 2. Then by virtue of (1), since $r(t) = b(t) - d(t)$ is the difference between births and deaths, and

$$A = \int_{t_0}^{t_1} r(t)dt = \int_{t_0}^{t_1} [b(t) - d(t)]dt,$$

then $P_1 = P_0e^A$ shows the increase from population P_0 at t_0 to population P_1 at t_1. This is exact and does not depend on the similarity of the fall of births and deaths. But now let the birth and death curves fall in similar manner, so that b(t) is just d(t) displaced to the right. Let L be the lag in the fall of births behind the fall in deaths, and R be the common range of birth and death. Then

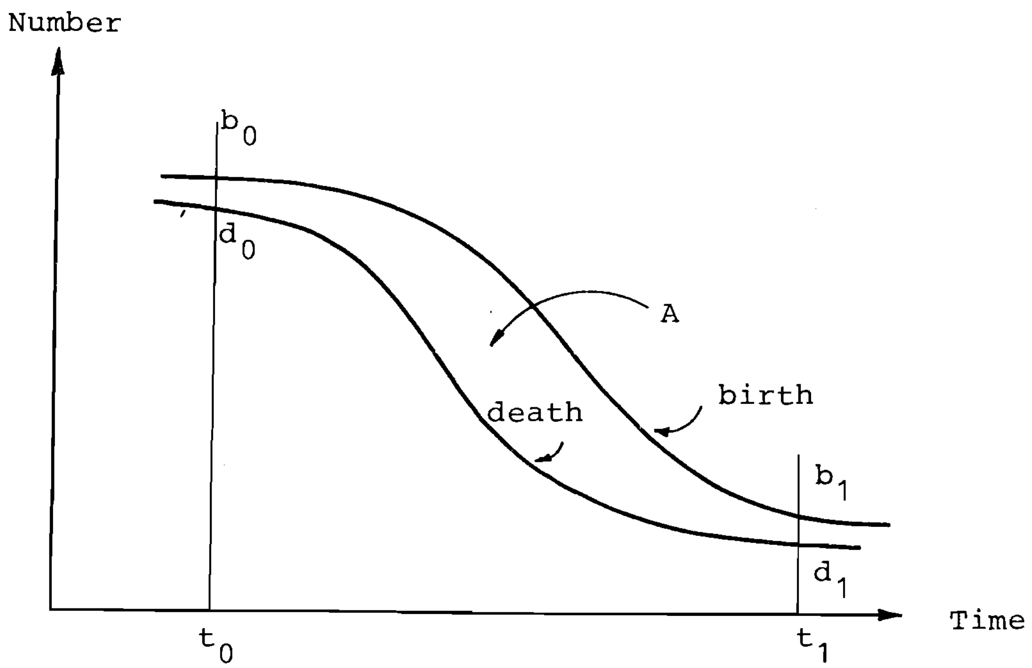

FIG. 2 A Stylized Version of the Demographic Transition

$P_1 = P_0 e^{LR}$. If the lag L is 20 years on the average and $R = 0.03$, we have

$$P_1 = 4.0e^{20(0.03)} = 7.3 \text{ billions.}$$

Let us disaggregate into less and more developed. Suppose 30 percent further increase for the developed, and 30 years' lag in the demographic transition of the less developed. Then

DCs	1.1×1.3	$= 1.4$
LDCs	$2.9 \times e^{30(0.03)}$	$= \underline{7.1}$
	Total	8.5 billions,

or about the same as the disaggregated version with rate of increase r(t) falling in a straight line to zero in 2050. Apparently recent demographic transitions have taken place more rapidly than early ones, and if this continues to be true 30 years is an upper bound for the future.

2.4 The Principle of Momentum

The above has taken little account of age. Despite experimenting that showed that projections without age came equally close to the true number that emerged 10 or 15 years later, one ought nonetheless to examine the effect of momentum due to age distributions being favorable to births following a long period of high fertility. If a country drops to zero fertility at a moment when its birth rate is b, its expectation of life e_0, its rate of increase r, and its mean age of childbearing μ, then the ratio of its ultimate stationary population to that at the moment of fall is

$$\frac{be_0}{r\mu}\ \frac{R_0 - 1}{R_0} \doteq \frac{be_0}{R_0} \quad ,$$

or if $b = 0.040$, $e_0 = 60$, $R_0 = 2.5$, we have the ratio 1.52.

If the less developed countries increase for an average of 20 years at an average rate of 2.4 percent, then drop to bare replacement, their ultimate population will be

$$(2.9)(1.024)^{20}(1.52) = 7.1 \quad .$$

Adding 1.4 for the developed countries gives 7.1 + 1.4 = 8.5 billions.

2.5 Conclusion from Transparent Models

Our conclusion from these and other simple models is that world population by the year 2000 will be 6 billion or less, and that it will ultimately level off to something of the order of 8 billion. Mass starvation would make the number lower; exceptional prosperity and increase of food supplies might make it higher or lower.

The advantage of such models is less that they are "correct" than that the reader can judge them for himself. Complexity in a model is a cost, and only if it buys more realism do we want it. The tradeoff is between simplicity and realism, and it is easy to pass the optimum point. One element that favors simplicity is the advantage of bringing the user's non-expert judgement into effective play. Another advantage is that less data are needed for fitting, so some observations are left over by which the quality of the fit can be judged (Arthur and McNicoll, 1975). A third advantage is that simpler models give less distortion due to poor observations (Alonso, 1968).

3. ANALYSIS OF THE MODEL AS A BLACK BOX

If in a (world or national) model one assumes that the amount of air pollution is proportional to income, and that a certain density of pollutants in the air is fatal, then it does not matter much what else is in the model: these conditions alone will determine an equilibrium point at what is the long-term ceiling on population, pollutants and income. This is an example of a dominant or determining input item.

3.1 Explaining the Outcome

Arthur and McNicoll (1975) examine the TEMPO simulation of 19 countries, and specifically the finding that "slower population growth, produced by declining fertility, translates directly into a more rapid growth of GNP per capita. This conclusion is extremely robust in the sense that it is relatively invariant under the diverse socioeconomic conditions encountered in the 19 different countries studied." But the invariance, it turns out, is due less to the nature of the real world than to a property of the Cobb-Douglas production function that TEMPO incorporated. With the Cobb-Douglas function output Y is equal to

$$Y = ae^{bt}L^{\alpha}K^{1-\alpha}$$

or

$$\frac{Y}{L} = ae^{bt}K^{1-\alpha}/L^{1-\alpha} \quad ,$$

where b is a constant to allow for improvement through time, L is labor, K is capital, and α is a constant less than unity, in practice often about 0.75. Then per capita income is Y/L, and on the right-hand side $L^{1-\alpha}$ is in the denominator. With a positive power of L in the denominator the curve is bound to be lower when L is greater, unless the effect is counteracted by capital K. But increasing population would diminish saving and so capital, thus strengthening the effect. In short the conclusion is built into the model. That is why such robustness appears in the application to 19 countries.

The Forrester (1971) model collapses at an early date due to the death of natural resources. This occurs because the natural resource level was set low and little allowance was made for substitution among resources. The Bariloche model on the other hand, assumes that natural resources are generously available. It proceeds by linear programming and has no difficulty in tracing out the path to the assumed ultimate condition of universal development.

Mesarovic and Pestel make few assumptions of their own, but invite the user to enter into interaction with the model and himself set the assumptions. This encounters the difficulty that the user does not know what assumptions to make. The model is played out as a game, with players taking the part of sectors or countries, and as such it is instructive--it gives a feeling for the interconnections of the variables, even though its conclusions about the future are conditional on the assumptions fed in by the user.

3.2 An Algorithm for Finding the Dominant Variable

The above cases are presented in over-simple form to illustrate how one or a few variables can dominate the model. It is unfair to say that the models were designed to show a particular simple outcome and that most of the variables were bells and whistles, like knobs on a computer that are not connected with anything. Yet the bare possibility that only one or two variables count, and all others are loosely connected with these, needs examination by some means more uniformly trustworthy than the casual approach of the preceding paragraphs.

We can think of the opposite kind of system, in which all the inputs have important effects on all the outputs, i.e., the system is strongly connected. This contrasts with the cases mentioned above, where the system is so loosely connected that one can immediately guess the dominant variables. In more representative instances with intermediate degrees of connectedness there may be a few operative variables and many that make no difference, but which are which is not obvious. For all such cases an algorithm or experimental procedure is needed to enable the model to be understood. It takes the form of an experimental decomposition of the action of the model.

To see how the decomposition works, consider any output variable, say $\bar{Y}$, income per capita in the year 2000. Then take an input, say the rate of increase of available energy $\dot{e}$, and try the model with low and high rates of increase of energy, say $\dot{e}_L$ and $\dot{e}_H$. Then $\bar{Y}$ is a function of $\dot{e}$, $\bar{Y}(\dot{e})$, and we run the model to ascertain $\bar{Y}(\dot{e}_H)$ and $\bar{Y}(\dot{e}_L)$. The difference $\bar{Y}(\dot{e}_H) - \bar{Y}(\dot{e}_L)$ is the effect of the energy assumption.

If the effect may be non-linear, we will be interested in the degree of non-linearity. This can be investigated by introducing a middle rate of energy increase, say $\dot{e}_M$, and calculating the second difference, $\bar{Y}(\dot{e}_H) - 2\bar{Y}(\dot{e}_M) + \bar{Y}(\dot{e}_L)$. More complex kinds of non-linearity can be found by observing $\bar{Y}$ for more values of $\dot{e}$.

Whether the effect is linear or not there may be interaction with other input variables. Suppose that food supply f is one such; we might suspect that the effect of energy is different in the presence of nutritional plenty and of nutritional scarcity. For this we would need to calculate four values of the $\bar{Y}$ function; the difference

$$\bar{Y}(\dot{e}_H , f_H) - \bar{Y}(\dot{e}_H , f_L)$$

would be the food effect in the presence of rapid energy increase;

$$\bar{Y}(\dot{e}_L , f_H) - \bar{Y}(\dot{e}_L , f_L)$$

would be the food effect in the presence of low energy increase. If the first of these is greater than the second interaction is positive; if the second is greater it is negative.

To find out what part of the input was important for what part of the output one would arrange such observations in a matrix. The rows of the matrix might represent the various input variables, say I_1, I_2, ..., and the columns the several outputs, say O_1, O_2, ... For the first analysis the elements of the matrix would measure the extent to which the particular output was affected by the particular input--positively, negatively, or not at all. The v_{ij} could be the degree of variation of O_j with I_i as measured by the difference, the partial derivative $\partial O_j/\partial I_i$, or the variance of O_j when I_i goes through its range, or some other measure obtained by running the model.

$$
\begin{array}{ll|llll}
 & & \multicolumn{4}{c}{\text{Output variables}} \\
 & & O_1 & O_2 & O_3 & \cdots \\
\hline
 & I_1 & v_{11} & v_{12} & v_{13} & \cdots \\
\text{Input variables} & I_2 & v_{21} & v_{22} & v_{23} & \cdots \\
 & I_3 & v_{31} & v_{32} & v_{33} & \cdots \\
 & \vdots & \vdots & & & \vdots
\end{array}
$$

Once the matrix is assembled, the next step is to interchange rows and (not necessarily corresponding) columns so that the large v_{ij} are on the left and at the top. Rules for this would have to be worked out. Suppose this gives the matrix

$$
\begin{array}{l|llll}
 & O'_1 & O'_2 & O'_3 & \cdots \\
\hline
I'_1 & v'_{11} & v'_{12} & v'_{13} & \cdots \\
I'_2 & v'_{21} & v'_{22} & v'_{23} & \cdots \\
I'_3 & v'_{31} & v'_{32} & v'_{33} & \cdots \\
\vdots & \vdots & & & \vdots
\end{array}
$$

where the prime values representing the new inputs and outputs are the same variables as before, but now relabelled in a different order. If it happens that only the first row has appreciable values of v', then everything is simple. This is still true if the first two or three rows are the only ones that are numerically important. Perhaps the matrix of the v' will appear in block form, in that certain groups of inputs will only affect certain groups of outputs.

The next step is to truncate the matrix, retaining only the rows and columns that have appreciable values of v'. If the matrix forms into blocks, then each block would be taken separately. In the new smaller matrix or matrices one might enter coefficients m_{ij} that represent the degree of change of an output caused by an input, perhaps in the form of regression slopes.

The algorithm, perhaps supplemented by judgment, leads to a simplified approximation to the complex model. The approximation can be simpler in containing only a few of the original input variables; the outputs are mostly related linearly to the inputs; some feedbacks are dropped. It is true that running the complex model to obtain the v's and the m's would be costly, but this would be offset by less need for documentation. If, moreover, the simplified version of the model turned out to be close enough to the full model to serve for many or all purposes, then savings in computer time would be considerable. One would of course have to make a test run of the simplified version to see how its output compared with that of the full model; if the comparison was unsatisfactory, one would add some further variables and test again.

The way of simplifying a black box model described above has respectable antecedents. In experimental designs used in agronomy for the testing of seed varieties and fertilizers, the black box is nature, and the simplified version is one on which policy advice is offered to farmers. Copernicus simplified the Ptolemaic model by changing the origin of coordinates from the earth to the sun. O. Rademaker has analysed the

Forrester-Meadows model in an attempt to simplify it by finding its dominant variables. Andrei Rogers (1976) has shown how to shrink population projections.

In some instances interactions between variables cannot be disregarded--A and B may be separately innocuous but disastrous together. Some variables operate only over a threshold-- a small amount does no harm, but beyond the threshold the effects are drastic (Holling, 1973). There are many cases where an elaborate system is resilient: it can absorb a disturbance up to a certain magnitude, but beyond that it fails to restore itself and becomes a system of a wholly different kind. Statistical techniques for investigating interactions and non-linearities of response are available.

To the general case for simplicity some special points can be added here. Alonso (1968) tells how the probability of a wrong conclusion goes up with the number of steps in the argument. He shows that adding variables is relatively harmless, leading as it does to a diminished proportional error; multiplying and taking to powers lead to increased proportional error.

Because of professional criticism, public circulation of methods and results, less need for haste to solve practical problems, theoretical work can better sustain long chains of argument, which is to say, complex models and computations beyond addition. In applied work, on the other hand, the methods are less often exposed to professional criticism, and results are less widely diffused; the result is more repetition of earlier errors and less learning from successes. Thus the arguments against complexity are much stronger in relation to applied work than to theoretical. Yet it is exactly in applied work that complex models are mostly used. Answers are required quickly to important policy questions; there is barely time to get a model on the computer. Thus systems modellers cannot afford to be patient. If economics does not know what is the relation of unemployment to labor-saving technology, then so much the worse for economics; some relation will have to be invented and dubbed in. If the sociology of consumption is still so primitive that it cannot tell us much about how goods become status symbols, nor about the degree to which less materials-consuming goods will serve to replace present goods in symbolic uses, then the matter will have to be swallowed up in general assumption relating income and materials. Social science is indeed slow in relation to the urgency of current problems. It is hampered by a tradition of looking at many sides of every question. World modellers are less hampered.

All this is an attempt to explain the paradox that social science, with the greater capacity to handle complexity, tries to avoid it, while practitioners have no fear of it at all.

4. CONCLUSION

Computer models are a new way of examining the implications of present trends, of forecasting the future, and of trying out policy alternatives before recommending one for adoption. Their strength is in relating everything to everything else, just as nature does, but they suffer from the defect that goes with this: they have to assume relations far beyond those in the body of presently agreed-on knowledge. Does diminution of the ozone layer increase skin cancer? We wish we knew. How much does falling infant mortality diminish fertility? When incomes of poor people increase, how much of the increase do they take out in more children, and how much in education and other benefits that ultimately reduce the number of children? Conflicting testimony on these matters suggests that judgement should be suspended, but a computer model will not run unless all cells are filled. Some number must be entered for every parameter of the model.

In default of knowledge some variables can be left exogenous. The population projection may be a separate module from the rest of the variables, as in the work of Leontief and some others. But then a price has to be paid: the assumptions regarding population can affect the outcome greatly, and one should try several alternative population modules. Only such experiment will tell how robust (i.e. invariant) the result is in relation to the population input. This is an aspect of what we recommend in the preceding pages.

Another variable often left exogenous is energy consumption. The official Statistical Abstract of the United States (U.S. Bureau of the Census, 1975, p.538) shows consumption to 1990, based on annual increases of 6 and a half to over 7 percent in the future. On this projection, made by the Federal Power Commission, consumption goes from 1,873 billion kWh in 1973 to 5,852 billion in 1990. Since some of the models show that such a level is impossible, and others in which energy use is endogenized come out with very much lower numbers, we need to know how much difference it makes if by 1990 the amount of energy is one half or one quarter of that officially projected.

If such experimenting is obviously needed for the endogenous part of the simulations, it is equally needed for the endogenous part. If an assumption has been made on the effect of a rise in relative price on materials use, their price elasticity, we had better try more than one price elasticity. Past elasticity provides only an uncertain indication for the future, and this is true for many other parameters in the complex model.

When the model is run with several variants of the population, energy, and other submodels or modules, as well as variants on the parameters of the equations relating these, then one ends up with a spectrum of answers to any given question. What will per capita grain supply be in the year 2000? (It is now about 700 pounds.) The answer is a range, comprehending all outputs that correspond to "reasonable" inputs. The forecaster should be willing to offer 2:1 odds that the figure will be (say) between 800 and 1000 pounds. The odds that his range will straddle the performance must be in considerable part subjective, but such a range or subjective confidence interval is the clearest way of communicating his impression of the reliability of the outcome. To imply that one's number for population or energy consumption or anything else in the year 2000 is exact can only be soothsaying.

But, it will be pointed out, the main use of the models is not for forecasting but for sensitivity analysis--if policy acts on such and such input variable the outcome will differ by so much. The absolute level does not matter, but only the difference due to the policy action. Yet in fact such differences vary just as much as levels. Nothing in mathematics says that a derivative of a function varies less than the function itself.

The case has been presented for a certain way of handling complex models. The architect of the model may well have made it as simple as he knows how, but it still contains dozens or hundreds of variables. Our method for getting to understand the model, and for effectively comparing it with others, is two-fold: (i) simple transparent models, of which an example was given for population, that parallel it and check its partial conclusions, and (ii) experiments on the complex model itself.

Since the models are computer-generated they differ from all previous work in social science in being largely inaccessible to the naked intelligence of the unequipped reader or researcher. Only a computer can generate the model, and it seems that a computer is required to understand it. The model treated as a black box is examined in the way that agronomists and others use statistical techniques to examine the black box of nature. Incidentally to running it a number of times with different inputs for this purpose, one can use the varied results to establish confidence intervals, even though these will necessarily be in part subjective. The object, after all, is to put some bounds on what will happen in the future; professedly exact prediction belongs to soothsaying rather than science. It is fortunate that for most purposes bounds that put some limits on future possibilities are all that is needed. If the limits are narrower than those that can be set by common sense the computer model has served us well.

The variety of models on the market is such that users are tempted to select the one whose conclusions accord with their preconceptions and then accept the assumptions of that one. The techniques presented here should aid in comparing properties of models, so that the user can select according to the realism of assumptions and mechanisms. If he does that then the conclusions can really tell him something.

References

Alonso, W. (1968), "Predicting Best with Imperfect Data," Journal of the American Institute of Planning, 34 (July): 248-255.

Arthur, W.B., and McNicoll, G. (1975), "Large-scale Simulation Models in Population and Development: What Use to Planners?" Population and Development Review, 1 (June): 251-265.

Forrester, J.W. (1971), World Dynamics. Cambridge: Wright Allen Press.

Herrera, A.O., et al. No date, about 1975. Catastrophe or New Society? Latin American World Model. Fundacion Bariloche, Argentina.

Holling, C.S. (1973), "Resilience and Stability of Ecological Systems," IIASA RR-73-3. Laxenburg, Austria: Interna- Institute for Applied Systems Analysis.

Leontief, W. (1976), Summary of report on "Future of the World Economy," issued by United Nations Department of Economic and Social Affairs. New York Times, October 14.

Meadows, D.H., Meadows D.L., Randers, J., and Behrens, W. (1972), The Limits to Growth. New York: Universe Books.

Mesarovic, M., and Pestel, E. (1974), Mankind at the Turning Point. The Second Report to the Club of Rome. New York: E.P. Dutton.

Rogers, A. (1976), "Shrinking Large-Scale Population-Projection Models by Aggregation and Decomposition." Environment and Planning A, 8 (December): 515-541.