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World Dynamics Revisited: a Realistic World Model Simulation

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Abstract—This paper investigates and reviews the world models introduced by J. W. Forrester of MIT. A survey of responses to the model and current trends in the global modeling approach are also provided.

From the review, it is noted that the assumptions used in the MIT models tend to reflect a generally pessimistic point of view. On the other hand, several critics of the models tend to be overly optimistic. This paper presents a modified world model in which two new variables (technology and pollution abatement) are introduced into the original model, adding to the existing variables (natural resources, population, pollution, capital investment and agriculture). The objective is to reflect a more realistic point of view. Two cases are considered in the analysis: in the first case it is assumed that advances in technology can reduce the rate of pollution generation to some extent, but not completely. In the second case, it is assumed that advances in technology do not have any effect on reducing pollution.

Results obtained from these two applications of the modified world model indicate that there tends to be a smooth growth toward an equilibrium without the need to adopt unrealistic policies.

INTRODUCTION

World modeling is a topic which has attracted much attention from researchers in a variety of disciplines such as economics, political science, social science, engineering and operations research. It is an approach which attempts to investigate the world system according to the past and present interactions among various important world variables. The goal is to provide long-range forecasts of such global trends as population growth, resource availability, economic development and environmental conditions. World modeling may be considered as an analytical tool for evaluating various policies that might bring about more favorable world futures.

In this approach, computer models are constructed to simulate the complex world system. A modeler usually constructs a computer simulation model by identifying various world variables to be included in the model, determining causal interdependencies among the variables according to his assumptions and, then, assigning appropriate equations to these relationships. The model may need to be modified a number of times before it can be considered satisfactory. In general, the model should be "validated" to make sure that it performs consistently with past behavior of the world. This can be done by using historical data to simulate the world for a period of time, e.g. during the past several decades. It is also important to "calibrate" the model by adjusting the variables, coefficients, or assumptions used so that it will appropriately reflect the modeler's viewpoints. The ability of the computer to keep track of the interactions between numerous variables, each of which can affect, and simultaneously be affected by, the others, is the major strength of the world modeling approach. The computer also allows decision-makers to perform several "what if" scenarios of the world system with relatively longer time horizons as compared to verbal or mental models. According to the U.S. Office of Technology Assessment [1], the world modeling approach is used for long-range analysis and policy development by organizations such as the Joint Chiefs of Staff, Department of Energy, Environmental Protection Agency and several international governments.

During the past 20 years or so, several world models, ranging from simple to very complex, have been developed by various research groups. Among these, the world dynamics model developed by J. W. Forrester of MIT [2] has been, perhaps, the most widely publicized (and criticized). In his book Forrester employs the "system dynamics" method of computer simulation in analyzing the world system. The objectives of his study were to gain insights into the limits of the world system, and to identify the dominant world variables and their interactions that most influence the long-term behavior of the world system. His model treats the world as a single geographic unit with five interacting subsystems—population, natural resources, capital, agriculture and pollution. The underlying assumption is that the world system with finite resources (such as natural resources, land for food production, space for habitation, and capacity to absorb pollution) cannot indefinitely sustain the exponential growths of population, pollution, industrialization, and resource depletion. Results from Forrester's analysis indicate that, if these exponential growths were allowed to continue, mankind would be moving into a crisis stage as the world's rapidly growing population and industrialization exhaust natural resources and pollute the environment. He has proposed certain policies which would tend to prevent such a crisis. Forrester's work has stimulated a large number of responses. Major criticisms of his model have been based on his use of unvalidated data and overaggregation of the model. In an attempt to improve Forrester's original model, Meadows *et al.* [3] introduced a much more detailed version. The assumptions and data used in this revised model were based on existing data in the professional literature. However, the results from both models were strikingly similar, even though there were some real differences in the approaches. The models proposed by Forrester and Meadows *et al.* (usually referred to in the literature as World 2 and World 3, respectively) were regarded by their critics [4–11] as being highly pessimistic due to the assumptions made and data used.

The debate about World 2 and World 3, which took place mostly in the 1970s, has stimulated a strong interest in the use of the world modeling approach to analyze the world system. Since then, several other world models [11–18] have been developed with varying degrees of complexity; with different levels of aggregation of the world system; and, in general, with more optimistic assumptions than those used in World 2 and World 3. Many of the models (including [12–18]) have been systematically modified up to the present day and are constantly in use.

Currently, trends in the world modeling approach are shifting toward higher levels of disaggregation, increasing the model size in number of parameters and equations used, a shorter time horizon, and more emphasis on economic factors with less attention to the other world variables. Thus, it appears that tradeoffs usually have to be made between the model size and the model scope (i.e. number of world variables considered) in order for the model to be computationally tractable. In this regard, Cole [19] indicates that the current world modeling practice tends to have shifted from being "an attempt to describe the long-run evolution of the global system" to "an attempt to describe the present global economy".

While a great deal of debate has been directed to technical issues like model disaggregation, time horizon, model size and scope, and the technique used, we feel that it is equally important to focus on the model viewpoint and assumptions used. Rather than attempting to predict the world future according to limited scopes, we feel that it is more meaningful to investigate various alternatives and their probable effects on the world as a whole. The objective of our study is thus to identify long-range policies which would result in a smooth global equilibrium rather than a collapse. We will adopt assumptions that, according to our viewpoint, are not as pessimistic as the World 2 (and World 3) viewpoint, nor as optimistic as several of its critics. In order to demonstrate our viewpoint in a comparable manner with World 2, we propose a modified World 2 model in which two more variables, technology and pollution abatement, are added to the original version. We chose World 2 over World 3 because they provide basically the same conclusions but World 2 is publicly available. The model code is listed in Forrester [2] and can be easily reproduced. With our proposed modifications, we feel that the modified World 2 model may be used to evaluate various policies and their probable effects on the long-range evolution of the world system on an aggregate level.

Brief reviews of World 2 and World 3 models are presented in the next two sections, followed by responses to the models from various research groups and current trends in the global modeling approach. We then propose our modifications of World 2 and present the results obtained from these modified versions.

WORLD 2 MODEL

The World 2 model utilizes five interacting subsystems: population, pollution, natural resources, capital investment and agriculture. The following assumptions were made in establishing relationships among these variables:

—crowding, pollution and a high material standard of living decrease the birth rate while food production increases it;
—the death rate is decreased by food production and an increased material standard of living, but it is increased by pollution and crowding;
—capital investment in agriculture causes food production to rise rapidly at first and then more slowly;
—the rate of capital investment increases with increased material standard of living;
—capital investment increases pollution, which in turn reduces food production;
—increased pollution increases the time required for pollution to be absorbed by the environment;
—quality of life is increased by food production and material standard of living, but it is decreased by pollution and crowding.

The World 2 computer program was originally coded in a simulation language called DYNAMO [20] and run by Forrester [1] in accordance with the above assumptions. Figure 1 shows the so-called "standard run" of the World 2 model in which the collapse of the world system is caused by natural resource depletion. In this figure, population and capital investment grow until natural resources decline far enough to inhibit expansion. As resources decline still further, the world is unable to sustain the peak population. Population then declines along with capital investment. Quality of life falls because of the pressures created by the shortage of natural resources. In addition to the standard run, Forrester carried out several other computer runs with different values of the variable coefficients. However, most of them indicate that the growth of population and capital will be checked. They differ on which factor operates first—natural resource shortage; pollution; food shortage; or population collapse from war, disease, and the social stresses caused by physical and psychological crowding.

Forrester also attempted to find policies (assumptions) that would project a transition to an equilibrium with a high quality of life, but without an intervening collapse of population and capital. However, to achieve such an equilibrium (shown in Fig. 2), there would have to be drastic reductions in birth rates, in pollution, and in natural resource usage. While this is not surprising, the model also indicated that a 40% reduction in capital generation would be necessary to control

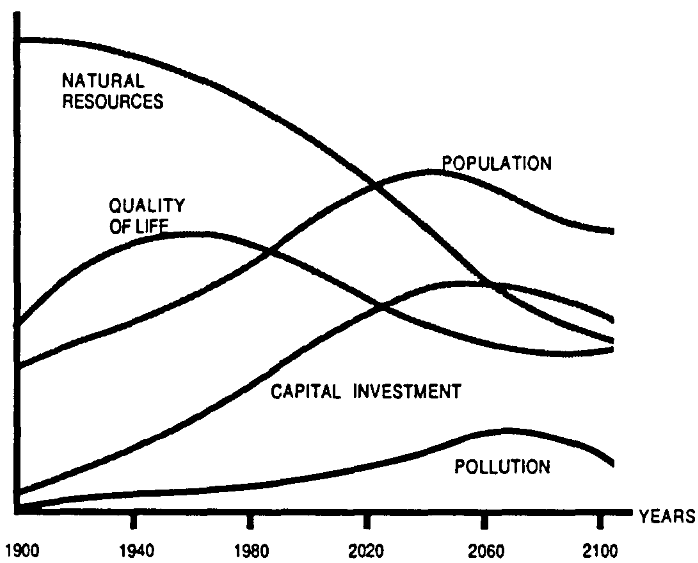

Fig. 1. World 2 standard run.

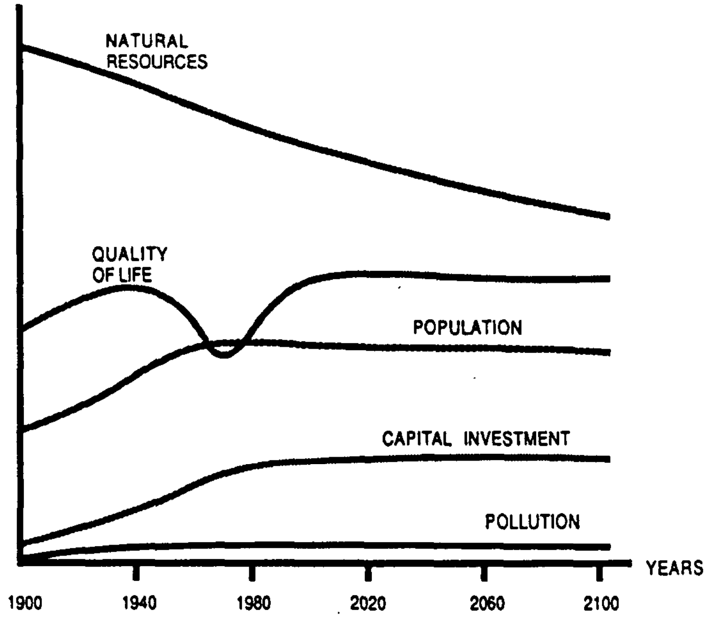

Fig. 2. World 2 equilibrium run.

population growth and pollution. Similarly, due to the assumption that food production tends to increase population, a 20% reduction would be required in this variable.

WORLD 3 MODEL

The World 3 model has the same basic structure and underlying assumptions as World 2, but it contains about three times as many mathematical equations wherein many of the numerical relationships are estimated from empirical data. The World 3 standard run, carried out by Meadows *et al.* [3], as shown in Fig. 3, is strikingly similar to the original World 2 model; that is, growth is followed by collapse. The Meadows team performed several other runs incorporating changes in parameters or relationships which were expected to produce desirable results. However, most resulted in collapse from either pollution, crowding, starvation, or resource depletion.

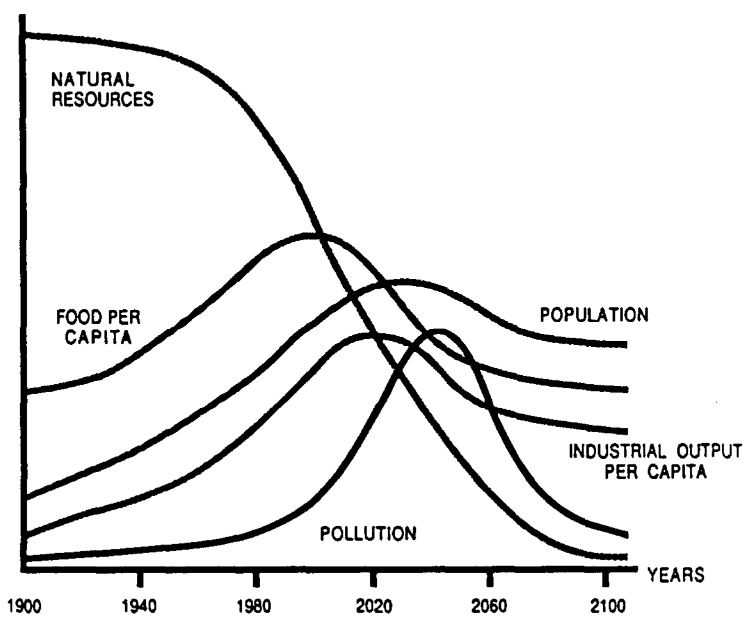

Fig. 3. World 3 standard run.

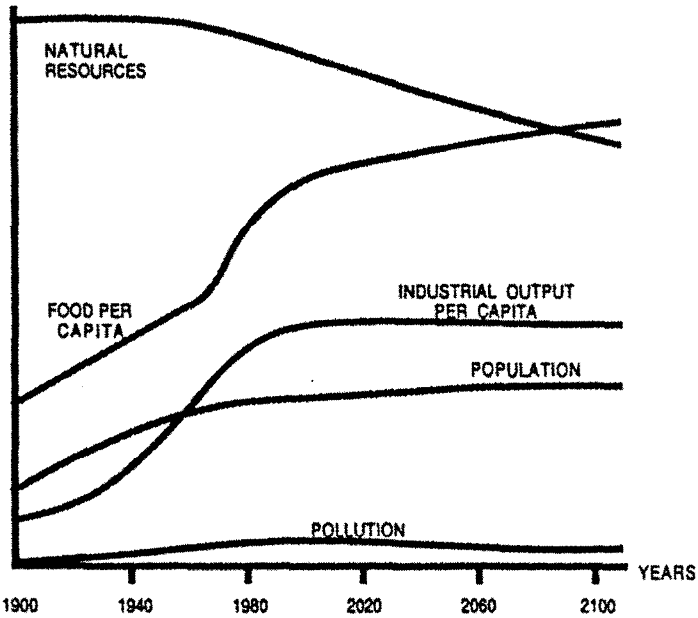

Fig. 4. World 3 equilibrium run.

In order to achieve the state of global equilibrium, drastic reductions in pollution, in natural resource consumption, and in birth rates were also recommended by the Meadows team. Their recommendations did not require a reduction in food production, which was needed in World 2 for equilibrium. However, it was suggested that capital be diverted to produce sufficient food for all people, even if it was uneconomical to do so. The World 3 equilibrium run is illustrated in Fig. 4.

RESPONSES TO WORLD 2 AND WORLD 3

The forecasts of the World 2 and World 3 models tend to challenge a fundamental principle of modern civilization: indefinitely prolonged economic growth. This resulted, earlier on, in a large amount of criticism directed at the MIT group. Some of the models' critics, such as Kahn *et al.* [21], and Beckwith [22–23] are, themselves, experts in the growth-oriented principle. One of the strongest criticisms came from the University of Sussex group [4] which evaluated every subsystem of the World 3 model. This led to a rather severe and long-lasting disagreement between the two groups.

The controversy created by World 2 and World 3 models can be regarded as "optimism vs pessimism". The Forrester–Meadows teams' viewpoint is, to a large extent, pessimistic. According to their assumptions, the quantity of natural resources is fixed, while the birth rate increases strongly with increasing food *per capita* but decreases strongly with increasing pollution and crowding. Such assumptions are not acceptable for the optimists. One of the major differences between the Forrester–Meadows teams and those opposing them arises in considering the effects of technology. Technology, in the pessimistic view, can only temporarily alleviate collapse. Eventually, an undesirable equilibrium between high death rate and high birth rate is reached. However, the technological optimists consider that advances in technology will increase productivity and thus increase the standard of living. Increasing the standard of living is then supposed to produce lower birth rates. Similarly, the problems of natural resources and pollution can be solved partially, if not completely, by advanced technology. Eventually, society is seen to reach a more desirable equilibrium between a low birth rate and a low death rate.

The four major objections raised by several critics of the world models are summarized below, followed by more detailed discussion of each criticism and its sources:

—underestimation of the availability of nonrenewable resources;
—underestimation of the benefits from technological advances;
—underestimation of the effectiveness of pollution control programs;
—treatment of the world as a single unit.

Natural resources

In World 3, behavior of the model depends heavily on the use of natural resources. It is assumed that easily accessible, high grade reserves of many nonrenewable metallic ores are being, or already have been, quickly depleted. However, Jones [5] indicates that the potential availability of most metals is far greater than World 3 suggests. According to the optimistic viewpoint of Kahn *et al.* [21], more than 95% of the world metal demand is for five metals that are essentially inexhaustible: iron, aluminum, silicon, magnesium and titanium. Advances in technology and extensive recycling would probably make seven other metals (copper, zinc, manganese, chromium, lead, nickel and tin) inexhaustible. Similar arguments are provided by Beckwith [6] and Page [24]. This does not, however, mean that the problem of resource depletion can be safely ignored. After considering different types of energy resources such as fossil fuels, uranium for fission reactors, controlled nuclear fusion reactors, solar energy converters, and so on, Jones [5] concludes that the pessimistic view of World 3 as well as the optimistic outlook for world energy should be replaced by a somewhat more conservative view. The type of energy generators which excessively deplete nonrenewable natural resources, dangerously pollute the environment, or have other undesirable consequences should be curtailed. Also, efforts should be directed towards the development of pollution-free, efficient utilization of renewable resource-based energy generators. A key implication of these findings is that extensive research efforts should be carried out to identify substitutes for nonrenewable natural resources. This would obviously reduce the usage rate of such resources.

Technology

In World 2, one of Forrester's computer runs assumed that the usage rate of natural resources would be reduced due to advanced technology. The results predicted a pollution crisis. In World 3, although technological developments were considered to be absolutely vital for the future of society, the Meadows team did not have much confidence in technology. They did not consider its possible and desirable outcomes, such as pollution control and substitutes for natural resources. This view reflects a strong disagreement with several technological optimists such as Cole *et al.* [4], Herrera *et al.* [11] and Kahn *et al.* [21], who believe that proper uses of technology should lead to equilibrium rather than collapse.

As an example, Boyd [7] demonstrates that if technological effects had been incorporated into World 2 according to the optimistic viewpoint, equilibrium would have been reached. In his modification, Boyd added a new variable called technology and altered two questionable birth rate multipliers. He assumed that advanced technology will reduce the rates of natural resource usage and pollution generation to zero. Also, factors such as cost and lead time for research, development and implementation of technology were not considered. Thus, it is clear that this model is highly optimistic since technological advances can hardly be regarded as free gifts. Boyd, however, did not consider himself an optimist. His modifications were made simply to illustrate the extremely optimistic point of view.

Pollution

With regard to pollution, we feel that World 3 tends to overestimate the cost and underestimate the potential effectiveness of pollution control measures. The effect of public concern due to pollution was not considered in the World 3 model. However, Oerlemans *et al.* [8] discusses evidence of "social feedback" which may have strong stabilizing effects on pollution. That is, as people sense the deterioration of the environment and quality of life due to pollution, they will not simply watch such a degradation without taking action; rather, social pressure will be generated to counter this threat and to reduce pollution. Smith [9] cites several examples in which the public acted to control pollution: improved treatment of sewage, precipitous on industrial chimneys, banning of soft coal, development of alternative insecticides to replace DDT, and controls on industrial emission of toxic metals such as mercury. The highly publicized "ozone hole" represents a more recent example of public concern.

Thus, the general argument made by the critics of World 2 and World 3 is that both models lack limits to the growth of pollution. In one of the computer runs, World 2 assumed that if pollution could be reduced by as much as 90% of its expected value, then crowding would become the limit to growth. However, a reduction in pollution cannot be achieved without capital investments. Thus, pollution abatement must compete with material standard of living and food supply for capital.

Regional disaggregation

In World 2 and World 3, the world is treated as a single geographic unit. This approach led to an intense debate. The major criticism is that the models ignore the differences between rich and poor countries, which display striking contrast in regard to population, growth, food production, resource consumption, pollution generation, capacity for technological innovation and so on. Various regions of the world are so diverse in both population and food production that they need to be differentiated in any forecast of world futures. However, while this problem was raised, only a few critics of the models attempted to provide alternative approaches in which the world is treated as a disaggregated unit. This is understandable since disaggregation would involve a tremendous number of equations and relationships among variables.

To avoid treating the world as a homogeneous system, Mesarovic and Pestel [12] constructed a computer model of the world (which involves about 100,000 equations) as a multilevel system of ten regions. Unlike World 2 and World 3, which treat the entire world as overshooting its limits at one time and then collapsing, this model considers various regions as encountering different limits for different reasons at different times. Based on the results obtained from the model, Mesarovic and Pestel recommend a five-point program that emphasizes a global approach, investment aid to developing countries, balanced economic development for all regions, and effective pollution policy, and worldwide diversification of industry. This policy is somewhat more realistic and desirable than the proposals of World 2 and World 3 which call for a rapid stabilization of global economic growth. However, this model has not attracted as much attention as the Forrester–Meadows projects, partly due to the lack of documentation to permit its reproduction and detailed evaluations. The project was eventually turned into a commercial enterprise with versions sold to Egypt, Iran, and West Germany, among others.

The Mesarovic–Pestel model has also stirred considerable interest and controversy. It appears to underestimate the amount of sustainable global industrial growth that could be achieved by the wise use of present and prospective technology. Pollution, identified in World 2 and World 3 as one of the major factors which could contribute to collapse, is not considered in this model. According to Hopkins [25], the Mesarovic–Pestel proposal of relatively unconditional, massive development aid ignores the psychological and cultural complexities involved in political decision making. To facilitate major increases in development aid, proposals must keep costs within bounds that developed countries can manage. Such proposals also need to provide assurance that developing countries will assume the reponsibility of using the funds wisely, e.g. to reduce the gross domestic inequalities that so hinder development. Meadows [26] notes that any direct commodity transfer from the rich to the poor such as food aid, except in times of emergency, is likely to be counterproductive; it sets up a pattern of dependence and discourages the forces of self-help, innovation and leadership. An extended version of the Mesarovic–Pestel model, referred to as the World Integrated Model (WIM), is described in Hughes [27].

CURRENT TRENDS IN WORLD MODELING

World 2 and World 3 share three important characteristics: the models are (1) global, (2) long-term, and (3) represent multiple areas of global development including economy, population, agriculture, natural resources and the environment. As shown in the previous section, most of the debates concerning World 2 and World 3 took place in the 1970s. Since then, several other world models, in addition to the WIM, have been developed in accordance with the viewpoints of various research groups. Many of the models (including [12–18]) have been systematically modified and are in use to the present. Bariloche [11], FUGI [13], and SARUM [14] represent direct responses to the Forrester–Meadows teams. Among these models, the trends include an increasing regional disaggregation, a shorter time horizon, an increase in size (number of equations and parameters used), and more limited scope (i.e. some of the world variables such as population and pollution are not considered). These efforts have also shifted the emphasis from the long-run evolution of the global system to the present global economy [19].

Methodologies adopted in various world models include system dynamics, input–output analysis, the econometrics model, and optimization-based techniques. As an example, the MOIRA (Model of International Relations in Agriculture) model, developed by Linneman *et al.* [16], represents every nation but only focuses on the agricultural aspects of the global system. The Bariloche model [11], often referred to as the "third world" model, incorporates four regions (the developed countries, Latin America, Africa and Asia) and five sectors (agriculture and nutrition, education, housing, capital goods and other consumer goods). The model is basically an econometric system, with an optimization approach to examine the potential for a more balanced world. In contrast to World 2 and World 3, the Bariloche model adopted assumptions which are, in general, highly optimistic.

The FUGI (Future of Global Interdependence) model [13, 28] was developed to examine Japan's role in a future global society. The SARUM model [14] was initially established by the U.K. government in an attempt to review the controversy created by the Forrester–Meadows teams. The conclusion from the SARUM initial study is that problems of limits to growth appear to be institutional rather than physical. LINK [17] is primarily an econometric model which attempts to link a number of national and regional econometric models together. The projections from LINK are generally short-term, running 3–8 years into the future. Like WIM, all of the models mentioned so far fail to consider pollution in their analyses. Both FUGI and SARUM have focused on economic issues and paid relatively less attention to other issues. According to its objective, the United Nations world model [15] was built specifically to analyze the impact of prospective economic issues and policies on international development strategy. The model utilizes input–output analysis with a relatively shorter time horizon (1985–2000). Population, regarded by World 2 and World 3 as one of the major factors in the global system, is not included in FUGI, SARUM, or the United Nations model. A new and interesting approach in defining geographic units is provided in GLOBUS [18], which limits itself to 25 nations regarded as major factors. Among major world models, GLOBUS is probably the only model which addresses political concerns explicitly. More comprehensive reviews of several world models are provided in [1], [19] and [29–32].

The field of world modeling, as shown by numerous publications and proposed models, is still very active since the introduction of World 2 almost two decades ago. None of the models is likely to be considered complete or free from criticism. In the field of world modeling, it is never possible to include everything that one thinks might be desirable.

According to Richardson [32], the decision to adopt a highly disaggregate model often results in the exclusion of important sectors such as pollution and population. Also, increasing a model's complexity usually increases its number of parameters, run time, and debugging time at an exponential rate. This, more often than not, results in less time for other important activities such as sensitivity analysis, model validation and documentation. According to Roberts [33], a model which is simple, easy to understand and convincing, usually has a good chance of being accepted. Thus, sufficient efforts should be devoted to model documentation so that a nontechnical audience can understand its assumptions and how these assumptions lead to the model's conclusion(s). It is a modeler's responsibility to make himself understood so that debates can be made on assumptions rather than on technicalities.

In his 1982 review paper on world modeling trends, Forrester [34] indicates that world simulation models should be global or national (not regional); rely on mental data (i.e. unmeasured data which may be derived from observations, knowledge and judgments) whenever written and numerical data are not available; and have relatively long time horizons, perhaps 100 years. In his opinion, disaggregation by regions does not give sufficient additional insight to justify the complication; it tends to overlook the complex decision-making process which is usually national-specific. Instead, he suggests a two-level approach: an aggregated world level, and a detailed national level to enable each individual country to find alternatives which are consistent within the framework provided by the aggregated world level. At the world level, attention should be paid to policies that can be implemented on a world-wide basis (e.g. policies that prohibit nations from increasing production by dumping pollution into the atmosphere or ocean). Policies involving actions within countries would best be left to those nations.

Forrester also criticizes simulation models that rely heavily on numerical data and, thus, tend to shorten the time horizons or omit important factors from consideration whenever this type of data is not available. He points out that the availability of numerical data will always be limited in the complex field of world modeling. Thus, modelers should be willing to use written and mental data in their simulation models in those situations where sufficient numerical data cannot be found.

MODIFICATIONS OF THE WORLD 2 MODEL

While many debates have been directed towards such issues as regionalization, time horizon, model size and scope, and the approach used, we feel that it is equally important to debate the viewpoints and assumptions used in a model. For example, in order to reach an equilibrium state, both World 2 and World 3 recommended actions which are, to many critics, highly undesirable. For example, reducing world food production by as much as 20%, as required in World 2, is likely to be rejected, especially by underdeveloped countries. World 3 suggests voluntary redistribution of available wealth. This would also tend to be politically unrealistic and difficult to implement.

Using our approach, if such recommendations proposed by World 2 (or World 3) were not acceptable, we would ask if there are any alternative policies, based on one's viewpoint, which could be adopted so that an equilibrium state might still be reached. Rather than attempting to predict the world future according to limited scopes, we feel that it is more meaningful to examine and evaluate various alternatives for their probable effects on the world as a whole.

The specific objective of our study is thus to identify policies which we consider not as pessimistic as the Forrester–Meadows teams' scenario, nor as optimistic as several of their critics. We propose a modified World 2 model in which two more variables, technology and pollution abatement, are added to the original version. Our choice of World 2 is based on several considerations. First, World 2 is probably the most accessible and best documented among major world models. The model code is listed in Forrester's *World Dynamics* book [2] and, thus, can be reproduced easily. Second, World 2 stresses the "big-picture" approach in which a framework may be established to solve world problems. More detailed policies may then be evaluated after common and attainable objectives have been agreed upon among nations. Third, in debating a modeler's viewpoint, it is important to use a simulation model that has similar scope and considers similar environments in order to achieve meaningful conclusions. For example, it may be misleading to use the WIM model to debate World 2 results since pollution, considered in World 2 as the variable which can lead to the collapse, is not included in WIM. Finally, the choice of World 2 over World 3 is based mainly on our observation that the latter is more complex and yet provides basically the same conclusions as World 2.

World 2 utilizes DYNAMO, a popular continuous simulation language based on the system dynamics approach. It is especially suitable to large-scale systems which emphasize the system as a whole rather than as individual components. It has been used to solve other complex problems such as production and inventory control [35–37], corporate planning [38–39], and project modeling [40]. The major strength of DYNAMO is that it is designed for the person who is problem-oriented rather than computer-oriented. It makes available easy-to-use computer facilities so that the user can focus his attention on building a model with minimum distraction from the computer requirements. Other more recently developed languages such as SLAM II [41], which appears to be similar to DYNAMO, or DARE-P [42–43], adopted by the GLOBUS model, may also be used in world modeling simulation.

After a careful investigation of the World 2 model, we felt that the following modifications should be made to express a more realistic point of view: (1) add two new variables (technology and pollution abatement), and (2) modify the birth rate.

Addition of technology

In adding technology as a new variable, we made the following assumptions (see [2] for descriptions of the various coefficients mentioned here):

(1) The rate of advance in technology is 4% per year with the level of technology in 1900 as the starting point.

(2) As quality of life declines, society will increase research and development (R&D) investment, which will increase the level of technology and hence improve quality of life.
(3) Increasing availability of capital will speed technological growth up to an asymptote. At that level, the rate of growth will become very small.
(4) Technological growth will reduce the usage rate of natural resources to some extent, but not completely. All other things being equal, four times the growth in technology will reduce the natural resource usage rate by a factor of 0.1.
(5) Advances in technology will reduce pollution to some extent. If technology improves as much as 4 times, the rate of pollution generation will be reduced by a factor of 0.1. (An even more conservative point of view assumes that technology does not help reduce pollution at all since technology itself tends to create pollution. Thus, in the second run of our model, we will assume that technology does not help reduce pollution.)

Addition of pollution abatement

The following assumptions were made in conjunction with a new variable, pollution abatement:

(1) Pollution abatement is introduced by the perceived decline in quality of life due to pollution.
(2) As quality of life due to pollution decreases, capital investments will increase gradually at first, until pollution reaches alarming proportions, at which level capital investments will increase at higher rates. As pollution approaches a level that is perceived as intolerable, the top priority will be given to pollution abatement. (According to this assumption, certain types of pollution may be unobserved initially. However, as their harmful effects on the environment become apparent, pollution abatement will take place. Thus, the longer pollution is allowed to exist, the greater the cost of reducing it to an acceptable level. Examples include nuclear power plant pollution and destruction of the ozone layer. The threat to the ozone may have existed for decades but was first discovered in 1983 [44]. However, significant public debates on this problem only started during the past few years.)
(3) Food supply, material standard of living, and pollution abatement all compete for capital. People living in poverty are less willing to divert efforts toward pollution abatement than those people whose material standard of living is high.
(4) As pollution is reduced to a certain level, it will become increasingly difficult and more expensive to reduce further.

Modifications of the birth rate

In World 2, it was assumed that increasing the material standard of living by 5 times would reduce the birth rate by a factor of 0.7. However, with effective birth control programs, we feel that it can reasonably be reduced to as low as 0.4. Similarly, World 2 assumed that a 4-fold increase in food *per capita* would increase the birth rate by a factor of 2. This tends to be a highly pessimistic value. We assume that, due to effective birth control programs in several developed and developing countries, an increase in food *per capita* has no effect on the birth rate. Forrester [45] also suggested that population be controlled in order for breakthroughs in technology to have meaningful and desirable effects.

RESULTS FROM THE MODIFIED MODEL

With the modifications discussed above, our model was coded in DYNAMO (the code may be obtained by contacting the authors), and run under two different scenarios. In the first scenario, it is assumed that technology, in addition to pollution abatement, helps reduce pollution. In the second scenario, technology is assumed to provide no help at all in reducing pollution.

Our simulation runs extend from 1900 to 2300 in order to reach the point where all variables appear to stabilize. Such a long projection may not provide any meaningful forecast since the world system is a dynamic one. However, as noted earlier, our purpose is not to predict the world future, but rather to evaluate alternative policies and their probable long-term effects on the world system. Thus, we feel that a duration of 400 years (rather than 200 years as in World 2 and World 3) is reasonable.

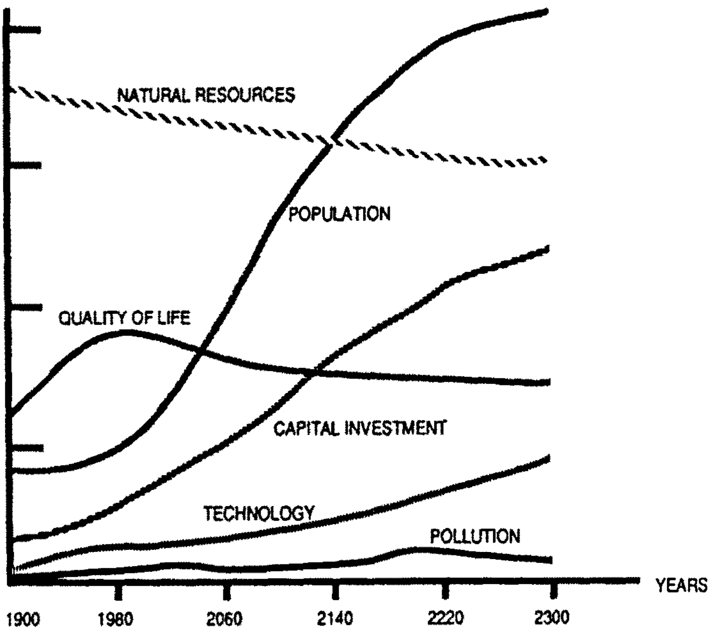

Fig. 5. Plots of various parameters (technology helps reduce pollution).

Technology helps reduce pollution

In Fig. 5, six variables—natural resources, population, quality of life, capital investment, pollution and technology—are plotted. From the graph, natural resources keep decreasing but with a much smaller rate than assumed in World 2. This is due to the assumption that technology can reduce the usage rate of natural resources to some extent. If the assumption is appropriate, then the shortage of natural resources will be postponed long after the year 2300. Population increases to approx. 7 billion in 2300, at which point the graph tends to level off. Capital investment exhibits a similar pattern to that of population. Quality of life peaks around the year 1960 (similar to World 2) and deteriorates slowly through 2300. With the assumption that the two major forces of technology and pollution abatement can reduce pollution, it appears that pollution is kept to a very low level. As expected, technology keeps advancing through the year 2300.

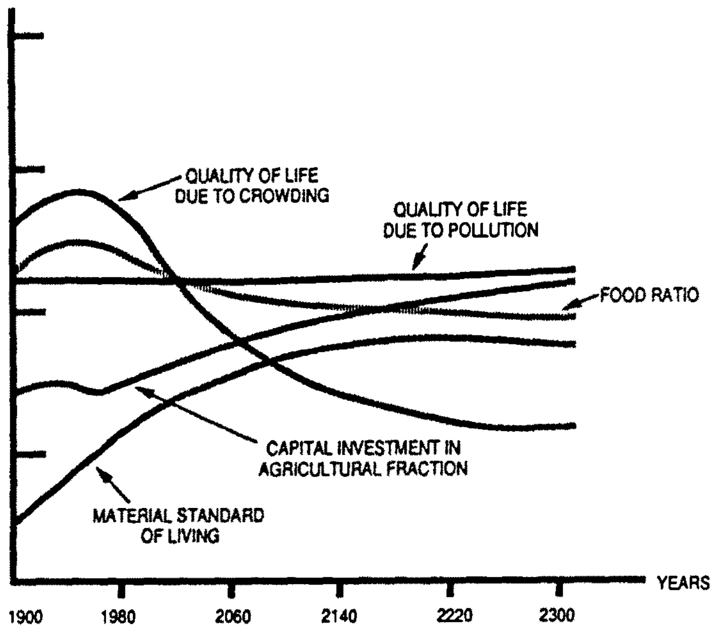

Fig. 6. Plots of various parameters (technology helps reduce pollution).

In Fig. 6, five variables are again plotted—food ratio, material standard of living, quality of life due to crowding, quality of life due to pollution, and capital investment in agriculture fraction. Quality of life due to crowding decreases through the year 2300 due to an increase in population and tends to level off after that. Food ratio peaks around 1940 and decreases slowly after that. Quality of life due to pollution is kept at a rather low level as a result of pollution being minimized. Material standard of living increases slowly and then tends to level off around the year 2180. Capital investment in agriculture fraction decreases during the early years and then gradually increases over the remaining years.

Technology does not help reduce pollution

This run expresses a less optimistic point of view in which we assume that technology affects only the usage rate of natural resources but does not help reduce pollution. The outputs of this case are plotted in Figs 7 and 8.

In Fig. 7, the five graphs exhibit patterns similar to those in the previous case (i.e. Fig. 5). However, here population reaches a maximum value of only about 5 billion in the year 2180 and then remains stable at this level until the year 2300. Pollution is kept at its minimum level during the early stage, but then increases at a slow rate and tends to level off around the year 2260. This is consistent with the assumption that pollution abatement will take place when pollution reaches a level perceived as unacceptable.

In Fig. 8, the patterns of the graphs are seen to be similar to those in Fig. 6. Quality of life due to crowding keeps decreasing and levels off around the year 2180. Quality of life due to pollution also decreases due to an increase in pollution, but remains stable around the year 2220 since pollution is likely to be stabilized by that time. There is a smaller fraction of capital invested in agriculture as compared to the previous case since capital is also needed to reduce pollution.

DISCUSSION AND CONCLUSION

In this study, we have proposed a modified World 2 model in which two new variables—technology and pollution abatement—are added to the existing variables in the original World 2 model. The assumptions adopted in our model are, we feel, not as pessimistic as those of the Forrester–Meadows teams nor as optimistic as several of their critics. We attempted to investigate alternative policies which might generate a long-term global equilibrium. In a first case, we assumed

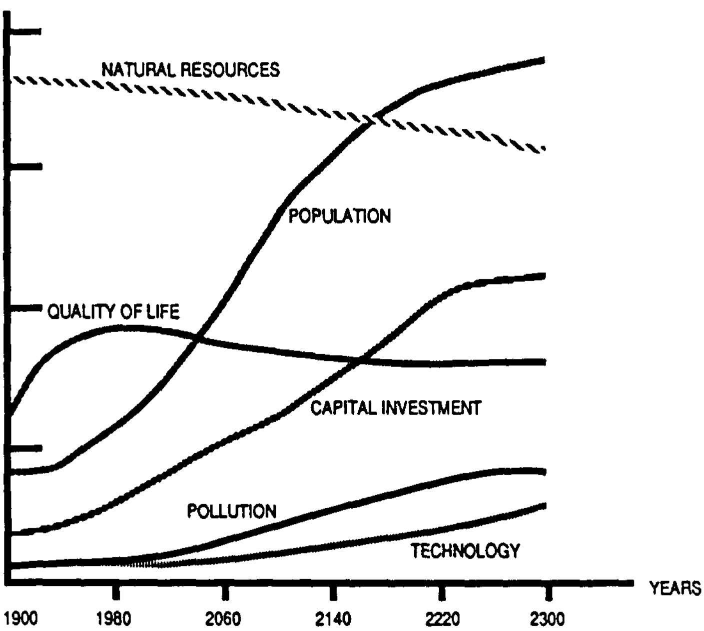

Fig. 7. Plots of various parameters (technology does not help reduce pollution).

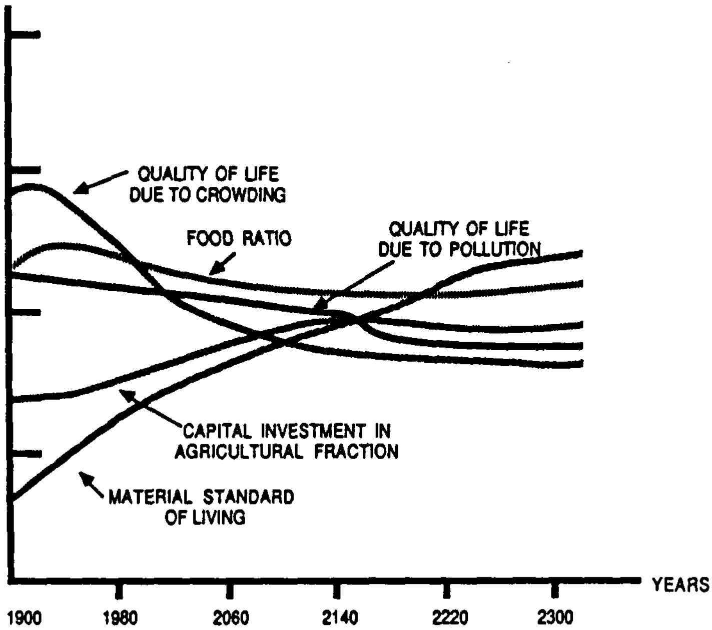

Fig. 8. Plots of various parameters (technology does not help reduce pollution).

that technology helps reduce pollution to some extent, while in a second case technology was assumed to offer no help at all in reducing pollution.

The inclusion of technology and pollution abatement resulted in an outcome different from that of World 2 (and World 3). The modified model indicates a smooth growth toward equilibrium, with what we consider to be more realistic policies being proposed. The assumption that technology can help reduce the usage rate of natural resources is crucial to avoid the collapse caused by the shortage of natural resources. The chance of reaching an equilibrium state rather than a collapse will depend greatly on effective birth control programs and pollution control policies.

We feel that the public, in general, will play the most crucial role in dealing with long-term pollution problems. They must have a clear picture of world problems and an understanding of how to control them in the most effective possible ways. In this regard, the Forrester–Meadows teams have made a highly significant contribution. The controversy created by World 2 and World 3 resulted in a much higher public awareness of the global system than had been the case before. By being "pessimistic," the models have created a great deal of attention and, thus, a sense of responsibility regarding such phenomena as natural resources depletion, birth control and pollution generation.

Our modified World 2 model may be employed as a tool to investigate long-term global behavior on an aggregate level. Since the introduction of World 2, numerous debates have been directed to technical issues like regionalization, time horizon, model size and scope, and technique used. In our opinion, it is also important to debate a model's viewpoint and the assumptions used. World modeling should be directed to the forecast of long-term evolution of the world system, rather than attempting to predict short-term behavior with a limited scope.

Most world models developed thus far have not addressed social and political issues, two important forces that shape the world's future. This is likely due to the difficulty in identifying proper relationships among variables, and the belief that there is insufficient data to allow any meaningful simulation investigations of social and political effects. To many researchers, mental models are still considered superior to computer models in dealing with such problems. However, mental models can be even more incomplete and illogical than computer models. Thus, while assumptions used in computer models are required to be stated clearly, precisely and in response to the modeler's intentions, mental models often suffer from concealed, ill-defined and conflicting assumptions. It may, therefore, not be possible to review and challenge how a mental model was generated. Furthermore, mental models are especially unsuited for determining the future dynamic consequences of (the adopted) assumptions since they tend to focus on only one or a few parts of the system at a time rather than on the system as a whole. In this regard, the discipline of forcing social and political relationships into a formal computer model can help clarify what was originally intended in the mental model(s).

We thus feel that an important research direction in world modeling involves incorporating social and political effects into the model. Considerable research and model experimentation would have to be undertaken to identify causal relationships between social/political variables and existing elements of the model. The form of the relationships would have to be clarified and translated into a systems dynamics framework. Means would need to be identified to "normalize" the parameters of the relationships, as was done for other elements of the model. Finally, the new model sectors dealing with social and political effects would have to be "fine tuned" and "calibrated" so that they could be linked to the total world model, thus becoming an integral component of a comprehensive, interacting feedback system model.

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