This paper, presented to the Stockholm Seminar on Population, Resources, and the Environment in September 1973, presents a review of a number of models in that field, focusing particularly on the interactions between the three. Particular emphasis is placed on the models behind the books, "World Dynamics" and "Limits to Growth," on which the author has conducted extensive experiments, and which, in his opinion, do not justify the "doomsday" conclusions made from them.

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INTRODUCTION

In the past decade the world has seen several new waves of Malthusian predictions. What makes the most recent crest different from previous ones is the use of mathematical models and the computer. These two modern tools, regarded by laymen as somehow having special powers, plus the publicity arising from their use have produced what is popularly known as the "Doomsday Model." The popular message of this type of model is simple and Malthusian; mankind is currently outgrowing the capacity of the planet to support it and thus will experience future disasters with falling levels of material welfare and falling numbers of people on the world unless there are profound changes in the nature of current technologies and values. Some of the more extreme predictions suggest that because of the long delays inherent in mankind's corrective mechanisms, there is no way to avoid such disasters, others prescribe zero population growth and zero material growth as a means of avoiding catastrophe. These predictions have come from developed nations, where growing discontent with current trends and values provides a sympathetic audience for such predictions. The models' message, in the context of those countries, is to stop growing to maintain or reduce present levels of living while reducing sharply the material content of such levels. The focus of these discussions is "the American way of life" or its counterpart in other developed countries and the prescriptions are basically aimed in that direction. Little is actually said about the less developed nations of the world other than the ever-popular words of wisdom "don't populate."
The practical implications of the prescriptions are quite ominous for the less developed nations; no growth in the material standard of living combined with a very long lag in any practical reduction of population easily produces for them the Malthusian result, while at the same time the developed nations are predicted to be able to survive with far less drastic problems. This is certainly not an acceptable outlook for the world community of nations.

It is thus very important to look closely at the basis for these predictions and the models involved. Moreover, when one looks more carefully at the field of population and resource analysis one discovers a number of well thought out studies that are worth serious attention, if only in a comparative sense, but which have been unfortunately not been given much attention. Finally, one finds that in response to the message of the "doomsday" models that there have been several attempts to redefine objectives and to work out future scenarios that meet both the resource limitations and at the same time satisfy objectives of providing all mankind with at least certain minimum levels of welfare.

In this paper we shall take a critical look at world models (most of the doomsday models fall into this category) at the more conventional population and resource analyses and at the attempts to work out suitable alternatives. The paper does not pretend to be exhaustive. There are a large number of existing models, the selection has been based upon their intrinsic interest, the publicity that they have gained and their availability to the author. The common characteristics of all the selected models are first that the time span is at least to the year 2000, and generally beyond, and second that there is a population projection which is linked to the economy and/or resource requirements in either direction. Thus, we omit
purely demographic projection models, the purely economic models; and the short-run models.

A common model begins with a projection of population, generally for a period of about 50 years. Given the nature of population dynamics and the fact that the time constant for human populations (that is the time it takes for a given demographic change to work itself through the population) is on the order of 70 years, it is fairly easy to make such a projection, and given the nature of uncertainty in long-term projections, the forecast of population is by far the most accurate element in any model. The next step is to link these population projections to demands on resources (in varying degrees of aggregation) or to macro-economic variables such as consumption and investment and thus the growth of output. Finally, in the more innovative cases the projections of material standards of living are connected back to demographic variables such as birth and death rates, thus completing the cycle. The more conventional of these models study the interactions in both directions and try to predict the magnitudes of the future on this basis; while the world models add resource constraints which in turn generally prevent the orderly growth of the system and thus conclude either that the future projection must be drastically modified, or that there must be immediate and significant changes in policy that will modify the interactions of population and resources.

A feature often present in both types of models is a consideration of environment. The environmental dimension is much more difficult and has thus far proven to be a serious, but not critical, element in the consideration of the future; i.e., in some runs of the doom models pollution is the cause of disaster, but with relatively small changes in policy such scenarios can be avoided. \footnote{1}
It should be made clear that this paper is an attempt to look at different types of models. Their common characteristics are the links between population, resources and (sometimes) environment. It is not intended that the models in their entirety be compared directly with each other. Clearly, they are designed for different purposes; each is judged more on how it answers the questions it was designed to address and on how it represents the population resource-environment nexus. World models (or doom models) address the global problems of mankind. Their weaknesses seem to arise from chronic underspecification. Conventional models look at countries or sectors. These too are usually underspecified and they implicitly assume the rest of the world to be infinite and unchanged. This latter fault perhaps limits their usefulness in the long run, but certainly does not rule them out as guides for medium-run policy action.

Running through many models, particularly the more celebrated ones, we find the theme of systems dynamics. This is an innovative tool which enables one to have insights into the workings of systems that would not be possible with conventional methods. Its great success has been with micro systems where, as long as the system was correctly and completely specified, it has proven far more incisive and encompassing than conventional tools. Its efficacy on macro systems, where specification is by necessity incomplete, is still very much a matter of debate. A great deal is made of the counterintuitive nature of systems and thus the necessity of using systems dynamics. It is basically a simulation method, not radically different from conventional projection model systems. It is extremely flexible and much easier to use than most, but when used for macro systems suffers perhaps more than usual from the problems that plague all simulations. In most micro
systems it is fairly easy to agree on an exact specification, to model each interaction, and even in some cases to verify by experiment. In macro systems such is not the case. Rarely, if ever is there agreement as to what is the correct specification of the system. Computer space does not allow an exhaustive specification and attempts in this direction have thus far proven to be intractable. Verification experiments almost never can be carried out and it has proven almost impossible to avoid an incorporation of subjective bias into macro models. Perhaps most importnat, primarily because of chronic underspecification, a multitude of models can all be equally "proven" using accepted measurement techniques on the same body of data. Systems dynamics and its associated computer tools make it extremely easy to build a model and thus to "discover" a fundamental truth which in reality arises from a misspecification. Properly used however it can be a powerful analytical tool.

Works to be Considered

In this paper we shall look at 11 documents relating to models of population - resources and environment. Of these, three fall into the world model category: World Dynamics, Limits to Growth, and Models of Doom. Six can be classified as conventional: Coale-Hoover, Tempo, Bachue, Bangladesh, U.S. Population Commission, and IBRD-Mexico. Of these the Coale-Hoover is included, not because it is recent, but because it is the first serious attempt in modern times to deal with the connection between population and resources and as such many other models are descended from it. Finally, we consider two documents which represent attempts to reformulate the objectives of growth and development and to build future models upon this foundation: The Latin American World Model, and the Japanese World
Model. These are particularly important because they start with the implied doom model message that the Western way of life is probably no longer viable and they seek to discover if some other way of life is perhaps more viable. There are, of course, other groups engaged in similar work but we have chosen the non-Western attempts as being potentially more representative for mankind as a whole.

Not discussed in this paper, but worthy of mention, are the efforts of several other groups. Under the direction of Tinbergen and Linnemann in the Netherlands work is underway on the agricultural section of a world model. At Case Western Reserve under Mesarovic and at Hannover under Pestel an "alternative world model system" is being created which appears to have great promise. Finally, under Leontieff at Harvard a world model system is being built from a series of input-output systems. Its basic structure is similar to that of the model used by the U.S. Population commission.

I. WORLD DYNAMICS

The model in this book (technically termed World 2), produced in 1970, was developed by Jay W. Forrester of MIT and later adopted by the Club of Rome. As such it is the first of the world model and represents a good, but hasty, look at the overall problem of the relation of population, resources, and environment in the context of the entire world. Its value lies in the fact that it called attention to the possibility of a conflict between the continued growth of the world population and the world economy on one hand and the limitations of resources and of absorption of waste on the other.

The model consists of four key variables: population, natural resources, capital stock, and pollution (this variable in all the world models
does not refer to short-lived pollution such as smog, but rather the long-lived pollutants such as DDT and mercury). Each of the four variables is related to the others through behavioral relationships. A fifth variable, capital investment in agriculture, determines the amount of food available to the world. There are a large number of intuitively specified links between the five variables, most of which have little or no effect on the workings of the model unless certain extreme assumptions are made to activate them. In the standard run of this model population increases gradually until it reaches a level somewhat over five billion in the year 2020, after which it declines at about the same rate. The material standard of living, which essentially reflects the per capita availability of fixed capital rises until about 1990 and then falls fairly smoothly. The population growth rate is determined chiefly by this material standard of living and also by the density of population (termed crowding). Since the growth of population is simply the difference between the birth and death rates, the key relationships are the effects of material standards and crowding on these rates. According to the assumptions of the model, the death rate is much more sensitive to these variables than is the birth rate, being pushed up from the normal of 28 per thousand to the mid-thirties by crowding, and then to the mid-forties by a falling material standard of living. At the same time the birth rate drops slightly from the normal 40 and then rises as living standards fall. The other two variables affecting the birth and death rates are food and pollution, these have a potential for making significant shifts, but, in the normal extrapolation of current trends, play little or no part.

In World 2 we clearly see the effect of crowding and material well being on demographic rates. These however are very simplistic relationships
and have been criticized as such, particularly on the grounds of non-
reversibility. As specified the functions work in both directions, that
is as material standards and crowding rise and fall, even though the
observations available to the model builder were only for rising trends.
This implies that as incomes go up birth rates will fall, a phenomenon that
is reasonably well documented, while at the same time if incomes fall, birth
rates will immediately go up again, a proposition which does not appear as
reasonable. Similarly while crowding acts weakly to lower birth rates, it
does not follow that uncrowding will raise them. Moreover, while the effect
of crowding on death rates may have been evident in the days of the Black
Death, it does not follow that such would now be the case and that uncrowding
would reduce the death rate, nor does it follow that whatever the effect of
crowding on demographic variables is, that the effect is independent of
levels of income.

Thus while the effects of economic and social variables on population
may have been taken into account in the model, though in rudimentary fashion,
one cannot treat the results as definitive predictions. Far more work must
be done, as indeed the author freely admits.

What about the opposite interactions; the effects of population
levels on economic and social variables? The key variables in this part of
the model are natural resources and capital stock. These determine the
material standard of living, which as we have seen, affects the demographic
variables of the model. Natural resources are given to the system in a fixed
amount at the beginning of the model and are steadily used up by the process
of creating capital stock. Capital stock grows according to the difference
between the rate of investment and the rate of depreciation. In the initial
stages of the model this growth rate is about 0.4% per annum and it falls steadily as natural resources are used up until ultimately reaching the limit of -2.5%, which is the constant rate of depreciation. No matter what assumptions are made, natural resources eventually run out and the system stops growing.

There are many apparent links from the population section to the capital investment and natural resources parts of the model, but in actual model practice these links are either self-canceling, or negligible. The speed of rise and fall of the "world system" depends almost exclusively on the amount of natural resources remaining and the level of capital investment. This latter relationship is set up so as to increase the rate of resource usage as the capital stock grows. While this may be a plausible aggregate representation (one of many possible) of past secular trends, it rules out the feasibility of policy changes in the model designed to "save" the system. The problem is not the model or the intrinsic nature of the world, but that the relationship is an underspecified aggregate. For example, an increase in the productivity of capital would be expected to reduce the investment rate and thus the usage of resources. In the World 2, such a change increases the effective capital and thus the standard of living and thus the usage of resources. Besides, the higher the level of capital stock the greater the level of pollution so that any attempts to get more production from a given amount of resources or to increase the amount of resources for that matter produce "pollution crises" which themselves bring on the collapse. Therefore it does no good in the context of the World 2 to increase the natural resources available either in a lump amount or on a gradual basis, collapse cannot be avoided. The fact
that an increase of resources or a rise in the productivity of capital still brings collapse, and in some cases faster, is cited by Professor Forrester as an example of the "counterintuitive nature of social systems." We would suggest that it may be more that the model builder has failed to understand and specify in sufficient detail the real workings of particular subsystems, particularly that of capital.

Thus, we have the World Model in which there is a link from resources to population that operates partially but not entirely satisfactorily and a link from population to resources that is virtually non-existent. The model indicates a high probability of collapse, not because this is the way the world necessarily behaves, but because of the particular manner in which the model was specified.

II. THE LIMITS TO GROWTH

Professor Forrester recognized many of the shortcomings of his model and urged continued research into the problem. While many critics were loudly pointing out the flaws in the model (and some criticism was frankly emotional rather than scientific) a group of Forrester's students at MIT (under the leadership of Dennis Meadows) began to modify and improve the original (World 2) model. This group produced a model (World 3), the results of which were published in March 1972 in a book entitled The Limits to Growth. Whereas World Dynamics presented a discussion of the problem and the conclusions as well as a completely documented version of World 2, Limits to Growth contains only the conclusions from World 3 and through no fault of the Meadows group, was presented to the world in a spate of popular publicity. The clear message of doom (at least for the "American way of Life") was
ascribed to the work and the obvious suggestions of critics (such as resource cornucopia) were answered with computer runs "showing" that such advice was not of any benefit to the world. While World 3 and its technical background have always been available from the MIT group, formal publication will be more than two years after Limits, a delay that is perhaps inconsonant with the immense publicity given to Limits. This is perhaps unfortunate for the model and for all population-resource models in general, for as the group began to make the model itself available to a few researchers, it became evident that the World 3 model was in need of more work and that the sensational conclusions ascribed to it were for the most part unjustified. Having been prematurely overpublicized, it will be difficult in the future for this or any other serious piece of work with similar pessimistic conclusions to get the serious attention it deserves.

In World 3, as in World 2, the central parts of the model are the population subsystem and the capital stock-natural resources subsystem. There are other state variables, such as pollution, service capital, and land, but in general these play the same minor roles as they did in World 2. The general nature of the model is the same. The population system has weak inputs from the capital and resources system, but the equation links from population to capital and resources, although existent, virtually cancel out the effects of these variables. There is thus an essentially self-generated capital stock whose growth is determined by the parameters chosen for it and whose end comes when natural resources are so depleted as to require the diversion of capital to resource extraction rather than to making new capital. Eventual collapse has thus been built in regardless of what happens to the rest of the model.
The population subsystem of World 3 has considerably more detail than did World 2. In itself it is fairly well constructed, using four cohorts in the standard version and 15 in a more detailed version. Each cohort has its own demographic parameters and the overall system is probably as good as most in terms of the prediction of overall population size up to 50 years in the future. The links from the rest of the model to the population subsystem are for the most part non-functioning in standard runs of the model.\textsuperscript{21} Births are regulated through a variable called total fertility while deaths are controlled by life expectancy. Fertility is specified to be determined by social and industrial output per capita, and by life expectancy. What turns out to have virtually all the effect in the actual running of the model is the change in the level of income.\textsuperscript{22} This is hardly more than the classical relationship between the birth rate and income and, as in World 2 the model builders treat it as a reversible relationship.\textsuperscript{23} With deaths the situation is similar. Life expectancy is modeled to be determined by pollution, crowding, health service availability and food availability. In the actual running of the model the largest impact comes from crowding (although in the early part of the model there is a one shot decrease in the death rate caused by the general improvement of health in the 1930's). The crowding multiplier is a function both of population density and also of income level, the latter being capable of changing rapidly, the former very slowly. The authors reasoned that plagues result from crowding at low income levels and thus as income falls because the world runs out of resources,\textsuperscript{24} a "Black Death" hits the population of the World 3. This is as close to disaster as either World 3 or World 2 gets, and it is built in, rather one suspects, as the result of assuming reversibility on all curves than on
purpose. Again we have the situation of a population system that is internally well defined, but whose links to the rest of the model need strengthening.

In the capital section however, even the internal mechanics are in need of repair. This is the key sector of the model, the one that is primarily responsible for the familiar overshoot and collapse which has given rise to so much controversy.

When looking at the capital sector, one is immediately struck by its "counter-intuitive" behavior. In one experiment an attempt is made to prolong the collapse by increasing the productivity of capital. Intuition says that such an increase (through the lowering of the ICOR) should give more output for a given amount of capital and thus be less intensive in the usage of non-renewable natural resources and thus prolong the time for which such resources can be used. The model, however, gives the opposite result, instead of a collapse in year 120, industrial output begins to fall sharply after only 70 years! The authors then go on to imply that this is an argument for not varying this constant in the policy simulations on the grounds that the model is too sensitive to the ICOR, but the counter-argument might also be made that this is a good reason to examine closely the reasons why the model so behaves. Moreover, if one is "counter-intuitive" and increases the ICOR (thus lowering the productivity of capital) the model gives the world an extra 50 years before collapse. One could say the model is counter-intuitive, but Occam's razor would suggest that the capital sector may not have been specified correctly.

In the capital sector of World 3 industrial capital is assumed to be the source of all capital goods and of a sizeable fraction of consumer goods. Thus, unless there is industrial capital the model can only function
at a primitive peasant society level where everything that is produced is food and services. (Even here the model is not clear as it requires $40 per capita of capital to produce services even when industrial output is zero. Perhaps a better definition of the services sector would be to allow this subsistence level of services to be produced without capital.) Industrial capital in the model is generated on a residual basis from industrial output, which itself is generated comes from industrial capital. This very tight loop is interrupted only by the need to supply capital to other sectors, the need to use capital to extract natural resources, and depreciation, and continues so long as there are natural resources still available. The main parameters that determine the dynamic characteristics of this loop are ICOR, the lifetime of capital (ALIC) and the fraction of capital necessary to obtain resources (FCAOR).

$$\frac{d(IC)}{IC} = A\left(1 - FCAOR\right) - \frac{1}{ICOR} - \frac{1}{ALIC}$$

(where IC is industrial capital)

The parameter A contains two variables that, in practice, are slightly sensitive population but in general move only after a collapse. In a normal run the value of this equation is about 4-1/2% per annum.

Looking briefly at the formulation of FCAOR, the natural resources limitation, it is a function of natural resources remaining in the system. This function is such that FCAOR is .05 until the natural resources reach 50% of their original level at which point it jumps to .10 and then rapidly to .70 as the fraction remaining drops to 20%, finally reaching 1.0 at 0% left. Critics have argued about the rapidity of growth of costs (especially since they have in general fallen over the past 70 years) and the concept that it is industrial capital that must be diverted to obtaining natural
resources. The usage rate of natural resources, is the product of population (the more people you have the faster you use resources) and the per capita usage rate. The latter is a rising function of industrial output per capita which tends to taper off at high levels of income. The result is a steady depletion which is accelerated by an increase in population or standard of living, with only very weak provisions for slowing down and no provisions for replenishment of any kind. Under this kind of formulation a collapse result is inevitable. Note that this is the only link between population and the capital and resources systems. The model does not consider consumption, prices, consumer utility or any of the many linkages that modern economics would suggest as having an effect in determining capital formation and resource use. All World 3 has is a steady drain on resources which is determined by how many people there are and how rich they are. Since changing the size of the population is a long-run question and the amount of resources given to World 3 is fixed and relatively small, it is difficult to avoid a doom conclusion.

Consider now two suggestions of model critics, the lowering of the ICOR and the increasing of the lifetime of capital. Suppose the ICOR were 2.0 (instead of 3), then the growth of capital, by the above formulation, jumps to 11.3%. Similarly if ALIC were 20 instead of 14, the rate of growth of IC would be 7.3%. Both cause faster growth and both thus bring the system into a collapse faster. Even supposing there was an infinite supply of natural resources, this formulation leaves something to be desired.

The key problem here is that of the industrial capital investment rate. As defined in World 3 is a residual, and only changes because some other demand for industrial output changes. There are no direct links with
the depreciation rate, and this gives the system its counter-intuitive behavior. There are no links with population or its growth rate, nor are there any links with demand or expectations of demand. The investment function, simply says that the system invests whatever is left over no matter how large or small and no matter how related this supply is to the needs of the system. This is an archaic form of the investment function, similar to the "investible surplus" idea. But that theory relates to subsistence economies and refers to agricultural output, not industrial. Moreover, even if one subscribed to the idea that the investors of the world are motivated to invest whatever they can get their hands on, the behavior would have to be modified somewhat by calculations of short-run profit which itself has to be related to demand of the system.

To be fair to the authors of Limits, there are a number of "equilibrium" runs shown both in the book as well as in the technical report. These imply a number of extremely difficult direct and immediate policy choices by the leaders of the world if the model is correct and if the world wishes to arrive at some kind of non-collapse equilibrium. Moreover, it is highly unlikely that such choices would be made in time even if everyone accepted the conclusions of World 3 as gospel. Therefore, both World 2 and World 3 must be implicitly regarded as doomsday models.

III. MODELS OF DOOM

One of the groups to whom a copy of the technical report for World 3 was made available was the Science Policy Research Unit at the University of Sussex. They made a careful analysis of the Limits model, criticized each
parameter in detail and created a number of modifications of their own. Early in 1973 they published a book of their findings under the title *Models of Doom*. The work is recommended for understanding in detail both the philosophy and mechanics of Limits, we consider it briefly here because it has made a number of modifications to the model in an attempt to make it more realistic. These modifications are in general those which have occurred to most critics, increasing the amount of resources, lowering the sensitivity to pollution, changing the productivity of agriculture, etc. No structural changes have been made, however, to the key sectors of population and capital or to the links between them. Its primary purpose is a critique and as such it works within the framework of the models it criticizes.

This paper has dwelt at length on world models. This is because they have received a large amount of publicity, and because they have in general made them detailed specification available to interested researchers. The general conclusion is that although they call attention to a potentially serious problem for the world as a whole, as models they have significant shortcomings. We turn now to a series of more conventional models that look at the interactions between population and resources. These models do not try to predict the future of mankind, but they do enable forecasts to be made of possible future behavior, particularly in the shorter run. As discussed above, they should not be compared with the world models, but rather looked at in terms of their specifications.

IV. COALE-HOOVER

This model is included because it was essentially the first to look at the links between demographic trends and the workings of a national
economy. Published in 1958, the model argued that economic growth is critically dependent upon investment and thus upon savings and that savings is affected by the fertility of the population. Fertility is taken to be independent of changes in the level of economic well being, or at least not within the framework of the model. The model, therefore, focuses on the linkage from population to the economy, the two main sectors themselves being conventionally defined. The key linkage is through savings and investment. The savings equation is defined so as to produce higher rates of saving at higher levels of per capita income. In a situation of two possibilities, with identical terminal year incomes, the one with the lower rate of population growth in the period will have a higher per capita level of income and thus a higher rate of saving. Beyond this the investment function is divided into two parts, one productive the other termed "welfare." It is the latter that depends on the size and the rate of growth of population, but it is the productive investment that is the resultant residual from savings. This productive investment then determines the growth of the economy. From this very simple and illustrative model have come many variations by many authors, one even going as far as to state that there is a direct relation between the debt service ratio of a country and the magnitude of its population control programs. Such was not the intention of Coale and Hoover who merely wanted to draw attention to the intuitive relationship between the size and growth of the population and the rate of advancement of economic welfare.

This approach has been criticized in more recent years for a variety of reasons. These can be summarized as first pointing out that personal saving comes from groups whose fertility is likely to be low already and whose
consumption patterns are not likely to change with changing fertility, second by observing that among lower income groups a lower dependency burden results in a higher per capita consumption, without affecting savings, and finally that the amount that governments currently spend on population size dependent welfare investment is so relatively small that changing this type of activity over a wide margin has little or no overall effect on overall investment.

V. TEMPO

A direct descendant of the Coale-Hoover approach is the GE-TEMPO model created under the direction of Dr. S. Enke. The original version of the TEMPO model had the Coale-Hoover savings function, essentially:

\[ S = aP + bY, \]

where \( a < 0 \) (\( p \) = population, \( y \) = income)

so that a higher population served to lower the savings of the economy and thus the investment and growth. A later version added a link from population to the labor force and thus to production. The current version, TEMPO II is considerably more sophisticated. The population section of the model consists of 65 cohorts, each with its own specific survival rate, an amount of detail which perhaps is unnecessary. Births are assumed to be a function of fertility, a variable which can be affected by expenditures on family planning (and in the aggregate by migration). Such expenditures, however, are an exogenous policy variable and thus are not a link from the economic to the population section. They do, however, come from available public sector resources and thus are a subtraction from resources that can be put into capital stock and thus growth. Since the magnitude of such expenditure depends on the size of the population (the policy variable being an acceptance rate) this constitutes a link from population to the rest of the model.
The economic sector of the model consists of a modified Cobb-Douglas production function that utilizes capital, educated and uneducated labor, and assumes exogenous technical progress. There is a public sector that allows channelling of resources into population related activities and a foreign sector that allows foreign aid, but these are largely for the purpose of accounting and explanatory convenience. The labor force is derived from the population figures and the portions that are educated and uneducated depend on expenditures on education. Here again the expenditure is the product of the size of the population in the appropriate age groups and the policy target rates for enrollment in each of four levels of education. Thus educating the labor force, which increases its productivity in the production function costs resources which could otherwise be invested in capacity. The key link from population to growth is, as before, the savings function, which in this version is expressed as a consumption function:

\[ C = aYD + bP \]

where

\[ b = d \left( \frac{YD}{P} \right)^e \]

\[ 0 \leq e \leq 1 \]

YD is disposable income and P is population. This formulation clearly depends on the value assigned to the parameter "e". If it is unity, then consumption is solely a function of income and there is no population link. If it is zero then we have the Coale-Hoover system similar to TEMPO I. Such a formulation is designed to allow the model to meet the criticisms of various authors (generally by setting "e" close to 1.0) and at the same time is in a form which would permit estimation on LDC data so as to ascertain whether "e" was significantly different from unity. In terms of sensitivity analysis,
it is clear that, in the model, growth of income per capita will be quite sensitive to changes in this parameter and that it is through this parameter that demographic changes are principally transmitted to the economic subsystem.

VI. IBRD - MEXICO

A far less ambitious model is one that has been used in the IBRD for routine long-run projections, a typical example of which can be found in an analysis of the likely trends in Mexico to the year 2000. In this analysis the central projection is that of population, an analysis of which is carried out by five-year cohorts with country specific mortality and fertility data. Fertility assumptions are then introduced so as to produce three projections - continuation of present trends, moderate effort on fertility reduction, and optimistic assumptions on fertility reduction. In general, the moderate effort projection is used as a framework upon which to place the economic and resource projections. Thus the linkages all go from population to resources and to the economy, there are no linkages back to the population projection; this remains fixed throughout the analysis. In the Mexican case the key resource constraints were land, water, and energy. For each of these a projection of potential supply was made, and in the case of water this was done on a regional basis. Each supply estimate was then compared to the likely demands for the particular resource over the range of population projections, and in the Mexican case it was found that only energy would be a constraint. This constraint, however, is assumed to be satisfiable from imports, and thus the analysis then turned to an exercise in exports and balance of payments projection. At the same time, rough
targets for output were made so that the general framework and magnitude of the macro-economy can be seen. This then forms the foundation for an assessment of employment potential utilizing known employment trends and elasticities on a sectoral basis. This can then be compared with the potential labor force in 2000 to arrive at an idea of the magnitude and gravity of the unemployment situation in that year. Finally, given the potential number of people and their location an analysis is made of the potential deficit in social capital and the costs of filling it. This latter set of figures can be fed into a public sector model, which itself is linked to the macro-model and can thus be used to estimate necessary fiscal policy. This model differs from most of those discussed in this paper in that it looks only at a target date and does not try to simulate the system (other than the time dependent population and external debt sections). It is thus much less deterministic while at the same time being more closely focused on the qualitative and semi-quantitative aspects of economic and social policy.

VII. BANGLADESH MODEL

A more deterministic system has been built by Professor Dorfman of Harvard as part of the East Pakistan Land and Water Resources Study. This model starts with three exogenous population projections to the year 2000 (ranging from 2.5 to 3.25% per annum) and then seeks to determine what is necessary in the way of growth of GDP, domestic savings and taxation, and foreign aid in order to achieve an employment rate of at least 95% at target dates. As in most of the models discussed in the paper, there are no links from the economy to population, rather population is determined a priori and is the framework upon which the rest of the analysis is based. Moreover, the
model requires that an actual growth path be calculated from the present to the target date. The economy is divided into seven productive sectors, each of which is constrained to follow a sector share of total output derived from international cross sections. Every five years an iterative calculation is made, using sectoral productivity trends from cross section analysis, to arrive at the level and composition of income that will meet the employment targets. This level of income then uses cross section estimates of saving to determine the internal resource generation and similar estimates of ICOR's to arrive at the demand for such resources. The deficit then becomes the total foreign capital inflow - private flows plus official aid necessary to achieve the target. This type of model therefore does not consider the impact of population on physical resources and assumes that there is no practical limitation on the supply of such resources. It is essentially an employment-population driven financial analysis.

VIII. U.S. POPULATION COMMISSION

A fairly well developed model was utilized by the U.S. Commission on Population Growth and the American Future. For looking at the period 1970-2020, this is perhaps the most detailed and sophisticated of the national models. Like many others, however, its direction of causality is from two alternative exogenous population projections to a whole host of economic, physical and social considerations. Moreover, it concentrates on the United States, and although it acknowledges the rest of the world, it does not in general look beyond the national framework. Specifically, it ignores most of the global problems raised by the world models even though the U.S.A. would be one of the chief contributors to the problems, raised by those models.
Starting with two population projections, the analysis then posits two different economic growth paths. The high alternative assumes productivity to grow at 2.5% per annum and work hours to decline by 1/4 of 1% per year (this generally expresses the current trend). The low growth alternative has the same productivity but man-hours declining by 1% per year. The two population and the two economic projections give four alternatives with income per capita ranging from two to four times current levels.

The key vehicle for carrying out the projections is an adaptation of the Maryland Interindustry Model. This 185-sector model was modified in several ways in order to be able to use it for long-run analyses: technological coefficients were introduced to allow the coefficients of the matrix to reflect anticipated technological changes, certain linearly decreasing functions (appropriate for short-term forecasts but not long-term ones) were replaced by exponential delay functions, and specific pollution and treatment cost coefficients were introduced. Moreover, the model was given a new set of consumption functions that related to demographic as well as economic characteristics, a public sector set of equations responding to similar variables, specific relationships for about 20 commodities believed to be crucial over the period, and an explicit pollution section. This enlarged model thus allows a fairly detailed analysis of the economic, resource, and environmental impacts of different population and output trends.

Such a framework represents perhaps the most useful and meaningful way of looking at developed countries. However, its data and operational requirements are inappropriate for lesser developed areas as are certain parts of the analysis (typically those dealing with pollution and physical resource constraints). The beginnings of a valid world model might well be made by
combining this model with similar analyses for Japan and the Common Market.\textsuperscript{34/}

This would then define the magnitude of the resource and pollution problem for the world as a whole and would give an indication of the demand on resources that the developed nations will be placing on the rest of the world. The lesser developed nations require models less sophisticated and ones that concentrate more on the interactions flowing from economic factors and resources to demography. Only after we have well worked out models of both types, and more importantly have been able to model the interactions between rich and poor on the world, will we be able to approach an operationally valid world model.

IX. ILO - BACHUE MODEL

Perhaps the best designed model for dealing with the poorer nations is that being built by the International Labor Organization. Called Bachue,\textsuperscript{35/} it is a carefully worked out systems analysis that seeks to focus on the links between population and economics in both directions, specifically concentrating on the economic determinants of demographic variable, which as we have seen above, are not treated in the conventional models and are as yet limited in the world models. The treatment is extensive, and unlike the world models, it closely adheres to findings in the fields of sociology, demography, and economics. As this is an ongoing study in an ambitious long-term project, there are no "results" as yet,\textsuperscript{36/} in fact, the modellers have been careful not to draw premature conclusions either about the structure of underdevelopment or the future of mankind. The model has been extensively worked out both in the demographic section - with age, sex, location and education cohorts, and also in the economic section with interindustry analysis covering seven sectors. The usual links from population to the
economy are found in this model, however, much more important are the specific links from economic variables to demographic ones. Births, deaths, migrations, labor force participation, and demand for education are all related to variables outside the population section.

As it now exists, Bachue is a carefully delineated system potentially capable of performing a detailed analysis and projection of a less developed country. The biggest job is still before it, however. This is to obtain data for a specific country and verifying that the specified interactions do indeed exist and that, moreover, they are important and necessary parts of any forecasting system. Bachue is potentially the best of existing national models capable of dealing with long-run trends and interactions between population and resources in LDC's, but it is still far from being an operational tool that can provide specific information on long-run outlooks or that can provide specific answers to the questions raised by the world models. The key question, which Bachue has the framework to address even now, is how quickly the demographic variables, and particularly the level of fertility, react to economic and resource changes. The world modellers imply that the reaction time is too long to prevent collapse, the optimists claim that it does not matter because technology will save the world. It may well be that demographic variables will act quickly enough to make most of the doom prophecies irrelevant. Bachue seems to be an appropriate framework for looking at this question.
X. LATIN AMERICAN WORLD MODEL

We come finally to two models which are interesting more for their objectives than for their structural content. Both the Latin American model and the Japanese model are attempts to answer the problems raised by the world models, not by improving the data or changing the structural equations (although these are certainly elements) but primarily by changing the objectives of society placed in the model. Thus instead of asking can mankind survive ever increasing levels of material income on a finite world, they ask can there be a future where particular regional life styles are viable. The Latin American model starts from the premise that every individual has the right to certain minimum levels of food, shelter and material goods. This is considered to be the foundation of the model, a foundation which can be reached through the removal of "socio-political constraints." Once this initial condition is satisfied, then growth is permitted on a regional basis in accordance with regional preferences subject, however, to absolute constraints of the environment and resources; it is assumed that the initial conditions do not violate any environmental or resource constraints. The model uses five regions, two developed and three less developed, and after assuming the two groups are independent, explores the possibilities of interaction with the purpose of furthering the goals of the poorer groups. The hope of the modellers is to demonstrate that the achievement of certain minimum goals for all mankind is materially and technically possible and in doing so demonstrate that the whole business of doomsday models and predictions is essentially an affair of the developed countries, they will cause it and they will suffer from it, a large part of the less developed world already being in the state of misery with which doomsday popularists scare their wealthy readers.
XI. JAPANESE WORLD MODEL

With this model we come around the circle of world models. This model (or series of models) is being created by the Japanese members of the Club of Rome (the group that supported the research for World 3). The theme of the studies thus far undertaken is not collapse, but rather a search for feasibility. The first model seeks to answer the same question as does the Latin model - how can the needs of the whole world be satisfied in a material sense. For this purpose the model uses nine regions and six output sectors and looks at the flows necessary between regions (both trade and aid) that would be necessary to satisfy these needs. A particular focus is the redistribution of industry to less developed nations. From this a world production scheme, compatible with resource and environmental constraints can be derived. Another type of model by the same group seeks to answer the question of the viability of Japan and her particular set of values in the context of the World Model. This starts with the 56-sector input-output model and calculates the long-term outlook for the economy in a manner somewhat similar to the U.S. model. Population does not play a very large part on the model, it appears to be conventionally defined and the linkages go only from population to demand.

CONCLUSIONS

This paper has presented the highlights of a number of models concerned with the interactions between population, resources, and the environment. It has dealt at length with the world models because of the considerable interest they have generated. We have argued that these models
are generally underspecified and at present serve the purpose of calling attention to the global problems arising from population growth and possible limitations of natural resources. We have then gone on to discuss a series of national models, where the interactions are specified in varying degrees of detail, but which do not consider the global problem at all. Such models, most of which are still being actively worked upon, show promise of being able, eventually, to throw light on these interactions, particularly where our knowledge is very deficient, in the less developed countries. Most models have a series of interactions from population to economics, but even here when one gets into the questions of employment and income distribution the answers and the relationships are far from clear. Few models have the interactions that go in the opposite direction—from economics to population. Yet these are the keys to a viable alternative for the vast mass of impoverished humanity.

It is clear that excessive rates of growth of population are an impediment to economic and material progress and yet the conventional wisdom seems to say that unless there is economic advancement, population growth rates will not fall. Historical evidence shows the birth rate falling continuously as per capita income grows—this curve is embedded in World 3. In a completely specified world model, the key to global equilibrium would be the rate of decline of this curve; it is clear that the historical rate is much too slow to avoid widespread global misery. However, it is only through investigations such as those which form an integral part of the Bachue system, that we can shed some light on this type of interaction and will be able to discern which areas of it are amenable to policy.
REFERENCES

1. Specifically in World 3, the model behind Limits to Growth. Based on experiments conducted on this model by the author of the present paper.

2. It is the opinion of this author that some (by no means all) of the more spectacular findings of the "Limits to Growth" model have arisen from these types of phenomena rather than from fundamental characteristics of the human race.


11. Economic and Social Change in Mexico - A Basic Report, Volume 4, the Future, IBRD Staff (not publicly available).


14. Statements as to the way in which the Forrester Model (World 2) and the Limits model (World 3) work have been derived from the author's own, fairly exhaustive, testing of the actual computer models involved.

15. Ibid.


17. See particularly Chapter IV of Limits.

18. The Dynamics of Growth in a Finite World, Meadows et al. (forthcoming). This is the technical background to The Limits to Growth, Meadows et al, Potomac Associates 1972. This technical report has gone through at least three versions and countless extensions of the publication date. At this writing the publication is scheduled for mid-1974, more than two years after the Limits to Growth.


20. Except of course in the extreme case of infinite resources, where pollution and/or agricultural land scarcity provide the collapse.


22. Ibid.

23. The key variable seems to be DTF (desired total fertility) and most of its variation comes from IOPC (industrial output per capita) via a delay system. See equations 122, 127, and 128 and Figure II-49 in Chapter II of the technical report.

24. Figure II-19 in Chapter II of the technical report.

25. Technical report - Figure VII-10 and page VII-24.


27. Technical report p. III-78, and experiments by the author of this paper.

28. Specifically, if prices rise demand should fall. World 3 implicitly assumes demand per capita to be fixed and thus equilibrates the system by increasing costs.

29. Particularly Chapter 2.

30. "Conventionally" should be regarded as referring to economics.
31. Such a conclusion was drawn from an early descendant, TEMPO I.


33. This model was built in connection with the IBRD basic economic mission to Mexico in 1972.

34. This is, in effect, what is now being carried out under Leontieff.

35. Bachue is the Colombian goddess of Love, fertility and harmony between nature and man - a fitting title for an investigation into the long-run future of mankind.

36. Preliminary runs indicate that considerably more research is necessary.