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An Analytic Simulation Model of Human Reproduction with Demographic and Biological Components*

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This paper reports a method of studying the determinants of human reproduction through an analytical simulation model of the process on a digital computer. The purposes of the model are both substantive amd methodological, since it investigates the quantitative effects on reproductive performance of changes in such factors as mortality, marriage patterns, use of contraceptives and their effectiveness, size of family desired, fecundity and pregnancy wastage. The paper will consist of five sections: a discussion of problems to which the model is directed, a brief description of population models, a description of the present model, a presentation of some illustrative results, and a discussion of the possible role of this model.

PROBLEMS OF STUDYING NATALITY

Identification of Variables

Since the interrelated factors that affect human reproduction – social, economic, psychological and biological – are numerous and operate with a differential impact over a period that may last as long as 35 years in human populations, their effects are difficult to evaluate. Generally, efforts made toward understanding the relationship of various factors to fertility and toward disentangling their influence have primarily considered social and psychological variables[1] and, to a great extent, have ignored the biological basis of human reproduction. The almost exclusive concentration on socio-psychological factors is understandable, since demographers with sociological training and orientation have been responsible for the major natality studies of recent years. The disappointing nature of the results obtained has generally been attributed to: (1) the relative imprecision of measurement of the variables in question, (2) the large number of social and psychological variables involved, and (3) the fact that the interaction among these variables confounds their relations to natality behaviour. It is, however, possible that, by overlooking the role of biological factors, social

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[1] See, for instance, P. K. Whelpton and C. V. Kiser (eds.), *Social and Psychological Factors Affecting Fertility*, Vols. I–V, New York, 1946–58; R. Freedman, P. K. Whelpton and A. A. Campbell, *Family Planning, Sterility and Population Growth*, New York, 1959; C. F. Westoff, R. G. Potter, P. C. Sagi and E. Mishler, *Family Growth in Metropolitan America*, Princeton, 1961; and C. F. Westoff, R. G. Potter and P. C. Sagi, *The Third Child*, Princeton, 1963.

scientists have handicapped their efforts to understand the role of social and psychological factors.

The operation of the socio-economic and psychological variables must, as Davis and Blake[2] have shown, be mediated through intermediate variables of a biological nature. The conceptual schema they developed departed from the commonly global treatment of 'the biological component' of reproduction or 'fecundity', and identified a number of relevant components. Thus, as they pointed out, the ages at which sexual unions occur, their stability, the frequency and duration of breast feeding, the frequency of coitus within and outside marriage, the use of contraceptives, or the frequency of induced abortions, while determined primarily by social and psychological influences, operate on reproduction through their effects on biological factors; they determine whether or not exposure to the risk of pregnancy coincides with the woman's most fecund ages, they affect the total span of time available for reproduction, they may reduce or increase fecundability (monthly chance of conception), and they may lengthen or shorten the intervals between births. Consequently, it becomes important to understand the quantitative effects on reproductive patterns produced by defined changes in any biological variable[3] and to study the interaction of biological variables with each other and with social and demographic variables. One approach to these problems is through the construction of models of human reproduction.

Problems of Measurement

Different studies of natality use a wide variety of indices, such as fertility rates specific for age or duration of marriage, completed family size, and birth intervals. More can be constructed theoretically. These indices are interrelated in complex ways that are not obvious. Undoubtedly, they are not equally sensitive to different changes in reproductive behaviour. The problems of choosing appropriate, sensitive indices of reproduction for studying determinants of natality trends and differentials, in addition to the difficulties of measuring the independent variables (socio-economic factors), may have contributed appreciably to the paucity of findings in such investigations.[4]

Investigators engaged in specific studies of human populations are limited in their choice of indices, both by the size of the group investigated and by the information obtainable. For example, the study of birth spacing is possible only if relatively accurate dates of marriage and of successive births are available. In most countries, such data are available only from special surveys. On the other hand, retrospective information on spacing obtained in censuses and surveys depends on memory and is confined to survivors of cohorts. Nor does such information easily lend itself to the calculation of annual natality rates. Consequently, few comparisons can be made of different indices

[2] K. Davis and J. Blake, 'Social structure and fertility: An analytic framework', *Economic Development and Cultural Change*, **4**, 1956, pp. 211–235.

[3] See, for instance, L. Henry, 'Fécondité et famille, modèles mathématiques', *Population*, **12** (1957), pp. 413–444, **16** (1961), pp. 27–48 and 261–282; R. G. Potter, M. L. New, J. B. Wyon and J. E. Gordon, 'Applications of field studies to research on the physiology of human reproduction', and N. B. Ryder, 'The measurement of fertility patterns', in M. C. Sheps and J. C. Ridley (eds.), *Public Health and Population Change: Current Research Issues*, Cambridge, Mass., 1965 (in press).

[4] D. Goldberg, 'Fertility and fertility differentials: Some observations on recent changes in the United States', in Sheps and Ridley (eds.), *loc. cit.;* and Ryder, *op. cit.*

on the same data, and the interrelationships among indices cannot be fully studied. In contrast, data obtained from simulation programmes are limited only by the capacity of the computer and the resources and ingenuity of the investigators.

Problems of Sampling Variability

Differences are to be expected in the reproductive performance of women subjected to the effects of an identical set of social, demographic and biological factors. The pattern of such variability, when known, constitutes a basis for estimating differences to be expected between samples, as well as the size of samples needed for a specific study, especially to evaluate comparisons among sub-groups. At present there is little, if any, empirical or theoretical information from which to estimate such distributions of natality indices. In the absence of such information, attempts to apply sampling theory to empirical natality data involve arbitrary assumptions about the form of these distributions, with little opportunity to evaluate the assumptions.

Furthermore, the main interest in natality studies is to identify and evaluate relationships between various factors and natality. The variability of such relationships in different samples is essentially unknown. Suitable experimentation with a simulation programme offers opportunities for studying the distribution of a variety of indices under different conditions, as well as changes in relationships from sample to sample.

APPROACHES THROUGH MODELS

The construction of models to study demographic problems offers opportunities not only for more precise conceptualization, but also for a form of experimentation. For example, the stable population model and its modifications have led to important insights into fundamental relationships and to some unexpected conclusions.[5] Theoretical models incorporating components of biological factors in reproduction have produced interesting results.[6] In both instances, however, the models are not readily amenable to investigating a large number of variables and the assumptions are confining for purposes such as we wish to pursue here.

The availability of high-speed digital computers has stimulated the exploitation of more complex models.[7] Many of the recently developed models utilize Monte Carlo methods. The term, 'Monte Carlo methods', denotes a class of procedures used to derive approximate or empirical estimates of distribution functions by simulating a random process for variables whose distributions cannot be obtained theoretically.[8] They depend essentially on sampling. The computer is programmed to generate a series of random numbers. A process is defined so that the occurrence or

[5] A. J. Coale, 'Factors in population growth', in Sheps and Ridley (eds.), *loc. cit.*

[6] For a review of such models, see M. C. Sheps, 'Applications of probability models to the study of patterns of human reproduction', in Sheps and Ridley (eds.), *loc. cit.*

[7] See, for instance, G. H. Orcutt, M. Greenberger, J. Korbel and A. Rivlin, *Microanalysis of Socio economic Systems: A Simulation Study*, New York, 1961; J. M. Beshers (ed.), *Computer Methods in the Analysis of Large Scale Social Systems*, Cambridge, Mass, 1965; J. M. Beshers, 'Birth projections with cohort models', *Demography*, **2** (in press); and P. Kunstadter, R. Buhler, F. F. Stephan and C. F. Westoff, 'Demographic variability and preferential marriage patterns', *American Journal of Physcial Anthropology*, **21** (1963), pp. 511–519.

non-occurrence of any specified event may be determined by matching the random number against an appropriate probability distribution. In general, the distribution is often cumulative, giving the probability (P_t) that a value is less than t. If t refers to time, P_t is the probability that an event occurs before time t. Then, if the random number generated lies between P_{t-1} and P_t, the event is taken to have occurred between time $t-1$ and time t. This is recorded and the programme is advanced one step. In a discrete situation the probability that an event occurs may be defined as p. If the random number generated is less than p, the event is taken to have occurred. Otherwise, it did not occur.

Thus Monte Carlo methods produce sample estimates of quantities and probabilities. Specifically, they may be needed, for example, when the probabilities are allowed to change with time and with prior events in a way that precludes attempts to obtain results by a series of numerical calculations.

THE PRESENT MODEL[9]

The approach used in the present Monte Carlo model was chosen so as to permit a high degree of flexibility in both the input and the output of the model, as well as allowing for the interdependence of the factors considered. The model thus allows the inclusion of a large number of variables that may vary with time and with a woman's previous experience. Most important, these factors can interact in a quasi-realistic fashion. It generates detailed reproductive histories of a group of women that can be analysed in practically any manner desired and thus permits the study of a number of indices.

The model population is a hypothetical birth cohort of women studied between the ages of 15 and 50 years. The life history of each woman in turn is developed sequentially and the relevant events are recorded. The probability of events such as marriage, conception and death may vary with age, parity and other features of a woman's history. The occurrence of any event is determined stochastically as described above.

States in the Model

The model includes two kinds of states into which a woman may pass. They are: (1) permanent changes of status such as death, sterility or becoming a family planner, and (2) temporary states, each with a probability distribution of length of stay. For simplicity we assume that all passages

[8] See M. Shubik, 'Bibliography on simulation, gaming, artificial intelligence and allied topics', *Journal of the American Statistical Association*, **55** (1960), pp. 736–751; and D. Teichroew, 'A history of distribution sampling prior to the era of the computer and its relevance to simulation', *ibid.*, **60** (1965), pp. 27–49.

[9] The model under discussion drew upon the experience and methods previously developed by E. B. Perrin and M. C. Sheps in 'Human reproduction: A stochastic process', *Biometrics*, **20** (1964), pp. 28–45; and E. B. Perrin and M. C. Sheps in 'A mathematical model for human fertility patterns', *Archives of Environmental Health*, **10** (1965), pp. 694–698. Monte Carlo models more restricted than the present one, but generating their results by a similar method were described by E. B. Perrin and M. C. Sheps 'A Monte Carlo Investigation of a Human Fertility Model' (mimeographed) and H. Hyrenius and I. Adolfsson *A Fertility Simulation Model*, Göteborg, 1964.

take place in the middle of a month and that passages into two different states cannot occur simultaneously. Consequently the order in which the probabilities are applied is important.

When a woman's life cycle is to be simulated, her age at death is determined first by drawing one random number. The age when sterility occurs, if this event precedes her death, is then found in a similar way. At present the probabilities of death and sterility are functions of age only.

All of the states shown in Fig. 1 are temporary states. The onset of sterility puts the probability of conceiving equal to zero, but does not affect passages into the other states of Fig. 1. The age at first marriage (if any) is found, marriage being defined to include any type of sexual union. It is assumed that a suitable partner with a specified age differential exists. When a woman marries, her reproductive history may begin. As long as she is married and susceptible to conception, she is subjected every month to the possibility of becoming pregnant. It is recognized that, in the absence of contraception, the probability of a conception in any month depends on the frequency and timing of sexual intercourse and on the physiological status of the woman and her mate. In the model it is assumed that these factors result in a probability that will be referred to as the natural

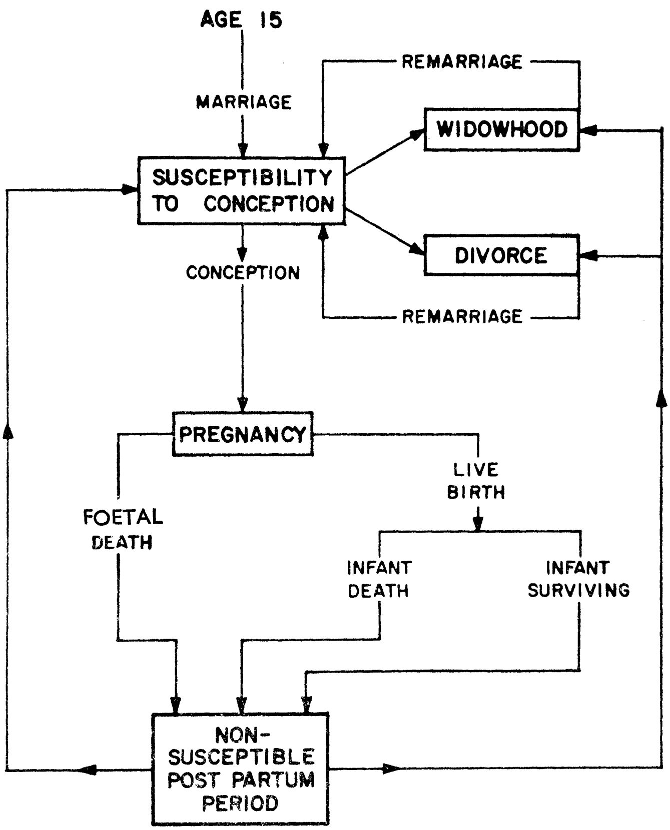

FIGURE 1. *Possible paths followed by surviving fecund women during reproductive ages, 15 to 50 years.*

fecundability of a married woman; the level of natural fecundability may vary among women[10] as well as change with age. This fecundability and the occurrence of terminal sterility are both functions of age in the model, but they are mutually independent.

A pregnancy may end in a foetal death (abortion or stillbirth), in a birth of a child that dies within a year, or in a live birth that survives the first year of life. The outcome of a pregnancy is determined when conception occurs. The probability of an infant death may depend on the mortality schedule or may be varied independently. If an infant dies, its age at death is determined from a probability distribution that is related to the selected level of infant mortality.

The duration of any pregnancy is a random variable whose probability distribution depends on its outcome. Following pregnancy, a woman is considered non-susceptible to conception for a period whose duration is also a random variable that depends on the outcome of the pregnancy. Various patterns of breast feeding may thus be postulated, with corresponding anovulatory periods. Adjustments are made in these periods in the case of an infant death. From the non-susceptible state a married fecund woman passes directly into the susceptible state again, and is then exposed to the same sequence of possible events.

Marriage may be dissolved by widowhood or divorce, divorce being defined to include dissolution of a union for any reason other than the death of the marital partner. The probability of widowhood depends on the age differential between spouses and on the male mortality schedule; that of divorce depends on age and the number of previous marriages. Every month a married woman is exposed to these risks. Though actual passage into the states of widowhood or divorce is recorded only while a woman is susceptible to conception (see Fig. 1), the probability that such a passage occurs during a non-susceptible period is allowed for in the calculations. Both widowhood and divorce are subject to re-marriage. The probability of re-marriage for widows depends on age and parity. For divorced women it is conditional on age and the number of previous marriages.

Superimposed on these states is the permanent characteristic of being a 'family planner'. A woman may become a family planner at the beginning of her first marital union or immediately after any live birth, the probabilities depending on parity. The input for family planning includes the number of children desired by planners and the level of contraceptive effectiveness which may vary with parity. When a woman becomes a family planner she resorts to contraceptives and her natural fecundability is reduced by the effectiveness of the contraceptive. If she has not yet had the number of children she desires, she may cease contraceptive practice after a variable period to plan a pregnancy. After every subsequent pregnancy, planned or unplanned, she is still a planner.

As is evident from the foregoing, the simulation programme requires as 'input' a series of quantities which are listed in the Appendix as constants, conditional probabilities of certain passages, and probability distributions of age at defined passages or of the durations of stay in defined states. Any run or cohort is thus defined by the various levels of input used.

From the data generated in the model a number of indices may be derived such as the number of women passing into the various states of the model during each year of age, the number of

[10] M. C. Sheps, 'On the time required for conception', *Population Studies*, **18** (1964), pp. 85–97.

women becoming family planners by parity, the number of marriages per woman and distributions of the duration of first marriages and all marriages, age-specific birth rates by marital status and by number of marriages, distribution of number of births by marital status for all women and women surviving to age 50, similar analyses by duration of first marriage and by family planning practices, number of births to surviving women by age and by marital duration classified according to marital status and age at marriage, gross and net reproduction rates, and summary measures of birth intervals.

To simulate and analyse the reproductive history of 1,000 women takes approximately four minutes on the IBM 7090.

AN APPLICATION OF THE MODEL

To illustrate possible uses of the model and some of the problems that have been encountered, we shall present some results from an early attempt to simulate real data.[11] Since appropriate data for input are not always available, we have in some cases had to estimate required inputs on rather broad assumptions and have then made adjustments in the values to obtain more realistic results.

Mortality probabilities at a variety of levels are easily derived from tables available from both actual populations and models, and values for a cohort can be postulated by combining age-specific survival rates from different life tables. Published estimates of the age-specific incidence of secondary sterility are available,[12] as are estimates of other biological parameters (fecundability, pregnancy wastage, duration of pregnancy and post-partum non-susceptibility);[13] we have also derived estimates from unpublished analyses of data to which we have been given access.

For probabilities of first and subsequent marriages the data are considerably less satisfactory than they are for mortality. When available they are often incomplete and usually published only on a period basis. Also, estimates of age at marriage and of marital instability are frequently derived from information about women currently married and their use requires assumptions about the experience of women not currently married. While indications about the frequency of family planning, the size of families desired,[14] and the effectiveness of contraceptives are available in the literature many assumptions are involved in any choices for input.

In our first efforts we attempted to simulate natality levels characteristic of the female population of India. In these original attempts the states of divorce and family planning were omitted. We could find little evidence that divorce has an appreciable effect on natality levels in India and, further, its incidence appears to be low. The reported low incidence of family planning

[11] For a discussion of the usefulness of such an attempt, see M. C. Sheps, 'Applications of probability models . . .', in Sheps and Ridley (eds.), *loc. cit.*

[12] L. Henry, *Fécondité des mariages: nouvelle méthode de mesure*, Paris, 1953, p. 99.

[13] See, for example, L. Henry, 'La fécondité naturelle, observations, théorie, résultats', *Population*, **16** (1961), pp. 625–636; M. C. Sheps, 'Pregnancy wastage as a factor in the analysis of fertility data', *Demography*, **1** (1964), pp. 111–118; and Potter *et al.*, *op. cit.*

[14] For a comprehensive review of recent literature, see W. P. Mauldin, 'Application of survey techniques', in Sheps and Ridley (eds.), *loc. cit.*

in India led us to attempt to simulate Indian natality levels without contraceptive practices. In addition, we wished to construct a basic model on which the impact of various levels of family planning on natality for India eventually could be studied. Table 1 presents a number of natality indices for four consecutive cohorts in the model, obtained by introducing modifications described below.

TABLE 1. *Selected natality indices of experimental cohorts attempting to simulate Indian natality*

	A	B	C	D
	Cohorts			
	NATALITY INDICES			
Mean number of live births				
Total cohort	7·32	6·69	5·55	5·60
Women surviving to age 50, first marriage intact	8·93	8·15	6·84	7·23
Gross reproduction rate	3·99	3·58	3·02	3·06
Net reproduction rate[1]	2·58	2·36	1·96	1·98
Age specific birth rates[2]				
15–19 years	168	145	134	191
20–24 years	378	370	309	285
25–29 years	370	351	285	272
30–34 years	326	280	234	228
35–39 years	243	191	177	163
40–44 years	131	112	88	96
45–49 years	21	22	14	19

[1] Net reproduction rate $= \dfrac{\text{Total No. of births } ({}_{15}P_0) \times 0{\cdot}487}{1000}$

where ${}_{15}P_0 = (1 - {}_5q_0)(1 - {}_5q_5)(1 - {}_5q_{10})$.

[2] Five-year birth rates are weighted means of annual birth rates calculated as:

$$\frac{\text{No. of births to women aged } x \text{ to } x+1}{\text{No. of women surviving to age } x+1/2} \times 1000.$$

Identical inputs were used in all four cohorts for mortality and certain other contingencies. The probabilities for the occurrence of death, widowhood and infant deaths were derived from the United Nations Model Life Table No. 24 ($e_0^0 = 42{\cdot}9$).[15] The probability schedule used for widow re-marriage was derived from data reported by Dandekar,[16] and the age differential between spouses was set at seven years, based on data reported by Driver.[17] For the duration of pregnancy,

[15] United Nations, Department of Economic and Social Affairs, *Age and Sex Patterns of Mortality, Model Life Tables for Underdeveloped Countries*, ST/SOA/Series A, Population Studies No. 22, New York, 1955.

[16] K. Dandekar, 'Widow remarriage in six rural communities in western India', in *International Population Conference: New York*, 1961 (London: International Union for the Scientific Study of Population, 1963), pp. 191–207.

[17] E. D. Driver, *Differential Fertility in Central India*, Princeton, 1963, p. 59.

percentage of foetal deaths and onset of permanent sterility, use was made of published data for non-Indian populations,[18] there being little direct evidence to indicate wide variation between populations. Summaries of the inputs used are given in the Appendix.

The distributions that were varied in the four cohorts included age at first marriage, fecundability, and the duration of the post-partum non-susceptible period. The initial probabilities of first marriage, utilized in Cohorts A, B and C, were estimated from data collected as part of the Harvard-Ludhiana Population Study.[19] The values of fecundability used in the first trial (Cohort A) were obtained by modifying an estimate of Henry.[20] The inputs for the lengths of post-partum non-susceptibility were derived from estimates of Dandekar [21] and of Henry.[22] As may be observed in Table 1, the resulting natality level in Cohort A was high and resembled more closely the natality of Hutterite women than that of Indian women. While many explanations for such results may be valid, we were inclined to suspect primarily the estimates of fecundability and of the length of the post-partum period.

A more realistic treatment of fecundability, namely allowing it to vary between women, would reduce the birth rate. At this stage of our investigations, however, we did not wish to introduce this complication into the model. To achieve a similar result, therefore, we used a lower value of fecundability in succeeding runs. The data for Cohort B show the effect of this change only. The resulting natality level, while slightly lower, still appeared unreasonably high.

There were a number of reasons why we next turned our attention to the post-partum non-susceptible period. First, theoretical investigations point to this period as an important factor in determining natality levels of non-contracepting populations.[23] Second, the relatively long intervals between births observed among Indian women have been ascribed by various students[24] to such social practices as the prolonged separation of spouses and coital abstinence following birth of a child, as well as prolonged lactation apparently leading to protracted amenorrhoea followed by a number of anovulatory cycles. Consequently, in Cohort C, the length of the post-partum non-susceptible period was equated with the distribution of the duration of lactation estimated in the Harvard-Ludhiana Study.[25] This change, which raised the mean length of the non-susceptible period from 12·9 to 20·4 months, resulted in a considerable reduction in the natality level. The

[18] Data for length of pregnancy and percentage of foetal deaths were drawn from F. E. French and J. M. Bierman, 'Probabilities of fetal mortality', *Public Health Reports*, **77** (1962), p. 835; data for the age of permanent sterility are from Henry, *Fécondité des mariages. . . .*

[19] These data were kindly provided by R. Potter and J. B. Wyon.

[20] Henry, 'Fécondité et famille . . .', **12.**

[21] K. Dandekar, 'Analysis of birth intervals of a set of Indian women', *Eugenics Quarterly*, **10** (1963), p. 76.

[22] Henry, *op. cit.*, p. 434.

[23] Sheps, 'Applications of probability models . . .', in Sheps and Ridley (eds.), *loc. cit.*

[24] See, for instance, C. Chandrasekaran, 'Physiological factors affecting fertility in India', in *International Population Conference: New York*, 1961 (London: International Union for the Scientific Study of Population, 1963), pp. 89–96.

[25] The mean duration of amenorrhoea itself, however, is estimated as 10·8 months for this study group. See R. G. Potter, J. E. Gordon, M. Parker and J. B. Wyon, 'A Case Study of Birth Interval Dynamics' *Population Studies*, **19**, 1965 p. 86.

various natality indices for the cohort indicated a closer correspondence to available Indian data.[26]

It was felt, however, that the marital distribution used in these runs was questionable. The inputs had given the probabilities in five-year age groups for Cohorts A, B and C. Because the programme provides for linear interpolation of probabilities given, the resulting mean age at marriage was above 18 years, a value rather high for India. Moreover, the distribution implied that approximately 98% of surviving women would eventually marry. Accordingly, we introduced a modification, giving the probabilities in one-year intervals and producing the somewhat lower mean age at marriage of about 17·3 years and a probability of 94% for marriage of surviving women. As may be seen in Table 1, virtually no change in the natality indices resulted for the cohort as a whole. Apparently the reduction in age at marriage was essentially offset by the lower proportion marrying. As compared with Cohort C, the most marked effect was the increase of 0·4 in the mean number of children of surviving women with first marriages intact.

Incidentally, the results obtained for age-specific birth rates have other interesting features. Table 1 shows an interdependence of cohort rates at different ages which illustrates the methodological problems to which the model can be applied. Thus, the introduction in Cohort D of an earlier age at marriage without any other differences from the input for Cohort C produces not only an anticipated rise in the rate at 15–19 years, but also small (and decreasing) reductions in the rates for the several succeeding age groups.

Natality levels in Cohort D are a better approximation to Indian data, but they are still high, particularly after the age of 35 years. The improved fit obtained by postulating a very long non-susceptible period, is consistent with one hypothesis that has been advanced to explain Indian natality levels. A similar result could, however, have been obtained by other changes in the input such as introducing some family planning or abortion, providing for lower and heterogeneous values of natural fecundability, or by varying the incidence of secondary sterility. In Table 2 we illustrate the results of a set of runs produced for another purpose in which certain of these factors were modified. In these runs the mean age at marriage had been shifted upwards from the 17·3 years of Cohort D to one of 21·3 years. In comparison with Cohort W, Cohorts X, Y and Z show the results of introducing heterogeneous fecundability, varying the incidence of sterility or the probability of foetal loss respectively. These particular changes resulted in reductions in natality levels comparable to those previously achieved by lengthening the non-susceptible period. Changing the incidence of sterility to give a mean age of 37 years reduced the mean number of children born to the total cohort by 7%, introducing heterogeneous fecundability reduced the mean by 9%, and doubling the incidence of foetal wastage reduced the mean by 13%.

It cannot be claimed that we have as yet succeeded in replicating Indian natality levels. It seems reasonable to assume that existing rates in India are affected, to a degree, by some resort to

[26] United Nations, Department of Economic and Social Affairs, *The Mysore Population Study*, ST/SOA/Series A, Population Studies No. 34, New York, 1961; V. M. Dandekar and K. Dandekar, *Survey of Fertility and Mortality in Poona District* (Gokhale Institute Publication No. 27, 1953); N. V. Sovani and K. Dandekar, *Fertility Survey of Nasik, Kolaba and Satara (North) Districts* (Gokhale Institute Publication No. 31, 1955).

TABLE 2. *Selected natality indices obtained by varying the incidence of sterility, heterogeneity of fecundability and probability of foetal loss*

	Cohorts*			
	W	X	Y	Z
	PARAMETER VALUES			
Mean age at onset of sterility	41	41	37	41
Coefficient of variation of fecundability	0	0·63	0	0
Probability of foetal loss	0·25	0·25	0·25	0·50
	NATALITY INDICES			
Mean number of live births				
Total cohort	4·42	4·01	4·13	3·84
Women surviving to age 50, first marriage intact	5·98	5·14	5·34	4·94
Gross reproduction rate	2·48	2·22	2·23	2·11
Net reproduction rate†	1·56	1·42	1·46	1·35
Age-specific birth rates‡				
15–19 years	2	3	3	1
20–24 years	248	232	252	211
25–29 years	260	236	251	228
30–34 years	226	199	203	194
35–39 years	170	148	133	139
40–44 years	93	78	62	78
45–49 years	19	17	12	16

*In all cases mean age at marriage was 21·3 years, and the long post-partum period was used. Other values as in Appendix.

†See footnote 1, Table 1.

‡See footnote 2, Table 1.

family planning. Furthermore, to the extent that we approached the Indian levels, we cannot claim that this validates the particular inputs we selected. If we further lowered the mean age at marriage as should be done, a higher birth rate would result.

To study these problems further, other modifications in input are being planned. The results so far achieved have served to indicate the direction in which further work must be undertaken, as well as providing information about the effect of the parameters tested.

EXPECTED USEFULNESS AND LIMITATIONS OF THE MODEL

The special features of this model, which are expected to contribute to its usefulness as an analytic tool, are its combination of demographic, social and biological factors, the detailed specification of their components in several instances, and the use of individual women as the 'experimental' units for simulation.

Simulating and recording a detailed history for each woman has several advantages. Together with the ability to change individual factors rather than postulating series of age-specific fertility rates, this method permits the free response of these rates and other measures of reproduction to the interplay of the factors involved. Moreover, it is possible to derive any desired index of reproduction for the cohort and to add new analyses to the programme without changing the method of generating the data. Since we retain all details of each woman's reproductive history, various sub-groups of the cohort may be studied and compared at any age or marital status.

On the other hand, the use of individual women as the experimental units makes the programme time-consuming and therefore expensive. We believe that it has great advantages for the purposes described here; in fact, we do not think that the same richness of information would be available otherwise. For many other purposes, however, less complex models would serve. It may prove advantageous to employ simpler models together with this one.

The ability to alter fecundability, pregnancy wastage rates, marital patterns, mortality patterns, etc., individually and in combination permits direct study and quantitative estimates of their effects and interactions. Thus it is possible to undertake detailed studies of such problems as:

(1) the effects of changing mortality on marital patterns, birth rates and rates of population growth;

(2) the effects of changing patterns of age at marriage, of marital stability and of re-marriage on birth rates; and

(3) the role of changing rates of spontaneous foetal wastage and of changing patterns of breastfeeding on birth rates.

Such investigations have obvious promise for demographic theory.

Furthermore, they may have important practical applications for population policy. The model offers a vehicle for exploring the implications of various policies that seek to decrease the birth rate by manipulating specific social and demographic factors. Thus it is possible to investigate directly the effects of such measures as the adoption of family planning or sterilization programmes, the liberalization of abortion laws, or various policies designed to raise the age at marriage.

As indicated in the preceding section of this paper, the model can be used to test hypotheses adduced to explain observed natality rates. Furthermore, by exploring the possible range of variation that may be produced by individual factors, it may assist in the selection of variables studied in a survey. Methodologically, the ability to know fully the conditions under which the data are generated provides a vantage point, impossible with real data, for evaluating the behaviour of the different indices. It should, therefore, be easier to develop appropriate criteria for the choice of sensitive indices as well as improved analytic methods to identify factors producing differential natality.

The inclusion of probability distributions for various events and the use of Monte Carlo methods provide an opportunity to investigate variability in natality patterns. Consequently, information bearing on sampling variation is made available, particularly with respect to variation in relationships between factors. Furthermore, the distributions of a variety of measures of reproduction under defined conditions may be observed in detail.

Direct applications of the results to population data, however, may be limited. Of necessity the model falls short of realism in many respects. Perhaps the most important of these is the mutual independence of many of the events. For example, mortality rates are independent of marriage or parity, natural fecundability is independent of parity of gravidity, etc. In addition, the fact that the data relate to a birth cohort of women and not a current population presents possible difficulties of interpretation. On the other hand, even unrealistic results should have implications for studies of populations and for sample surveys. It is hoped that they may also suggest new hypotheses that can be tested in future studies.

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APPENDIX

INPUTS REQUIRED FOR COMPUTER SIMULATION PROGRAMME	VALUES USED IN EXPERIMENTS REPORTED[a]		
1. Constants:			
(*a*) age differential between spouses	Seven years		
(*b*) contraceptive effectiveness	Not used		
(*c*) desired family size	Not used		
2. Probabilities of:			
(*a*) foetal wastage	0·25		
(*b*) infant death	Model Life Table No. 24 ($e_0^0 = 42{\cdot}90$ years)		
(*c*) divorce[bc]	No divorce		
(*d*) re-marriage			
(1) for divorced women[bc]	Not appropriate		
(2) for widows[bd]	Available on request		
(*e*) becoming a family planner	No family planning		
(*f*) natural fecundability	Cohort A:		
	Age in years	Age in months (t)	P
	15–20	180–240	$0{\cdot}10 + 0{\cdot}0025(t\text{-}180)$
	20–30	240–360	0·25
	30–35	360–420	$0{\cdot}25 + 0{\cdot}00083(t\text{-}360)$
	35–40	420–480	$0{\cdot}20 + 0{\cdot}0017(t\text{-}420)$
	40–50	480–600	$0{\cdot}10 + 0{\cdot}0008(t\text{-}480)$
	Cohorts B, C, and D:		
	15–20	180–240	$0{\cdot}05 + 0{\cdot}0025(t\text{-}180)$
	20–25	240–300	0·20
	25–40	300–480	$0{\cdot}20 - 0{\cdot}00083(t\text{-}300)$
	40–50	480–600	$0{\cdot}05 - 0{\cdot}00042(t\text{-}480)$

3. Probability distributions of age at:		
(*a*) death for males and for females	Model Life Table No. 24 ($e_0^0 = 42{\cdot}90$ years)	
(*b*) sterility	41·0 ± 7·6 years	
(*c*) first marriage	Cohorts	
	A, B, C	D
	18·2 ± 1·5 years	17·3 ± 2·8 years
4. Probability distributions of lengths of:		
(*a*) pregnancy		
(1) foetal death	2·5 ± 1·6 months	
(2) live birth	9·1 ± 0·6 months	
(*b*) post-partum states	Cohorts	
	A and B	C and D
(1) foetal death	2·5 ± 0·7 months	1·7 ± 0·5 months
(2) surviving live birth[e]	13·4 ± 5·5 months	20·9 ± 11·7 months
(*c*) use of contraceptives by family planners	Not used	

[a] When probability distributions are used, the means ± standard deviations are given for the underlying distributions and not for the data generated by the programme. Detailed distributions are available on request.

[b] By age.

[c] By marriage order.

[d] By parity.

[e] In the case of an infant death, the age at death is first determined from the appropriate distributions. The length of the post-partum period depends on: (1) the number of months a child lives and (2) whether the child dies before the value selected from the post-partum distribution for a surviving live birth. In the latter case, the number of months the child lives plus one month is the length of the post-partum period.