A DYNAMIC SIMULATION MODEL OF GROWTH AND FEMALE REPRODUCTION OF BEEF CATTLE

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

MARGARET RUTH SCHUETTE

1976

ABSTRACT

A DYNAMIC SIMULATION MODEL OF GROWTH AND FEMALE REPRODUCTION OF BEEF CATTLE

By

Margaret Ruth Schuette

This thesis describes in detail the development of a computer model which simulates the growth in body weight of beef cattle in response to user-prescribed sets of normal and subnormal feed levels; and the reproductive performance of beef females as affected by age and body condition. Although oriented towards the cow/calf operation, it includes all age and sex classes of beef cattle and may be operated selectively to study a particular group of animals--mature cows, growing heifers, and growing and mature steers and bulls.

Programed in FORTRAN, the model is composed of a main executive routine which envelopes a series of subroutines which, in turn, comprise the herd demography, nutrition dynamics, and reproduction dynamics components. Aside from setting the initial conditions and parameter values, calling the primary subroutines, and controlling the printing of simulation results, the executive routine is designed for continuous, multiple computer runs. It also permits variable parameter values to be changed at any user-specified time during the run. The herd demography component accounts for aging and weight changes of the various populations and shifts animals from one function group to another in accordance with the herd management parameters. Given roughage and concentrate allocations with their respective TDN levels, the nutrition component determines the feed intake and the utilization of energy for maintenance, lactation,

and growth by cattle subpopulations. The reproduction component then computes the age and weight at puberty, the post-calving interval to first estrus, the pregnancy rates, and the calving rates and times of females according to their age, weight, and body condition.

Upon testing, the model was found to be relatively stable when the time increment used was between 0.03846 and 0.050 years. Larger values resulted in the underestimation of feed intake by growing cattle over the time interval. With normal feed inputs, simulated growth results compared favorably with actual growth data. Reproductive performance also appeared to be within the bounds of reality.

Two sets of simulation runs were made to test the effects of various subnormal feed levels upon growth and reproduction of females. The first set consisted of six trials where TDN values varied from 99 to 75% of normal while feed dry matter allocations remained normal. The second set was the inverse; TDN values remained normal while the dry matter allocations varied from 99 to 75% of normal. In both sets, as total energy intake decreased, age at puberty and post-calving interval to first estrus increased while pregnancy rates decreased. Weights at puberty decreased in the first set, but remained constant in the second set. From these and other preliminary trials, it would appear that changes in TDN induce a greater response from cattle than do changes in allocation level.

All of the equations and information used for model development as well as the data against which the model was tested were abstracted from various research reports.

Although weak points do exist, a number of recommendations have been made towards improving and expanding the model--that it might become a valuable instrument for teaching and research.

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Margaret Ruth Schuette

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Animal Husbandry

1976

To

my family

and K. M. S.

with love.

ACKNOWLEDGMENTS

I wish to express my appreciation to Dr. R. J. Deans for his guidance during my graduate studies, to Dr. M. R. Jaske for his cooperation and assistance in this simulation project, and to Dr. T. J. Manetsch for his interest and guidance in this project. Appreciation is also expressed to the Department of Systems Science and Electrical Engineering for the use of their computer facilities, and to Premier Corporation of Fowlerville, Michigan for the use of their beef herd data and for their financial assistance.

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INTRODUCTION

For years, animal scientists have been searching for more efficient methods of producing beef, as well as ways to produce a more efficient beef animal. In the past fifty years, Western countries have seen much progress towards this goal through improved management, nutrition, and breeding of the beef herd. However, the recent high feed-grain prices, feed shortages due to drought, and the diethylstilbesterol controversy are cause for a reexamination of current methods of feeding cattle. Can the feedlot operator afford not to feed costly high energy rations? What are the long term effects of underfeeding upon the breeding herd? What is the best alternative for the producer when a feed crisis does occur? Extensive research studies may answer some of these questions, but they are expensive in terms of time and money and cannot easily test the many policy alternatives. Computer technology, however, offers a system where many pieces of information can be combined into a program which can generate alternative solutions to problems such as those mentioned.

The purpose of this thesis is not to specifically answer these questions, but to describe the development of a computer simulation model that, when expanded, would be capable of analyzing various beef management policies. In its present form, this model is designed to simulate the effects of low quantity and/or low energy value of feed intake upon the growth of beef cattle and the reproduction of beef females over a given time horizon. Although this model has been incorporated into the beef enterprise model by Jaske (1976), this model can be operated as an independent unit and will be discussed as such. The reader should note that male reproduction is not considered in this model since bulls are a small fraction of the herd population and artificial insemination is readily available. Emphasis has, therefore, been given to the growth and reproduction of females.

The model was developed solely from information available in the literature. Therefore, the parameters used and the simulation results are not necessarily characteristic of Michigan or of the Midwest.

I. LITERATURE REVIEW

Nutrition-reproduction

Interest in the effects of poor nutrition upon reproduction in cattle began with work by Hart, *et al.*(1911) where in two trials dairy heifers and cows were fed four different rations made up of corn, wheat, and oat plant parts and a mixture of the three. The most striking results were that the corn-fed group reached first postpartum estrus in four to six weeks and produced strong vigorous calves, but the wheat-fed group reached first estrus in ten to eighteen weeks and produced small weak calves.

Further experimentation by Hart, *et al.*(1917) was done using different mixtures of wheat and corn plant parts and alfalfa hay. Except for the ration containing hay, the higher the wheat content, the poorer the reproductive performance. Because knowledge about animal nutrition was limited, the researchers attributed the poor performance of wheat-fed animals to poor mineral content and toxic substances in the wheat embryo.

As new information became available through the discovery of essential vitamins and minerals, Hart, *et al.*(1924) reexamined their earlier work and concluded that the wheat-fed cattle had suffered from vitamin A and calcium deficiencies.

Research up to that time had therefore suggested that heredity, nutrition, and hormones were important factors in reproduction: that there was some optimum state of nutrition necessary as reflected by the increased fecundity of animals fed more heavily before and during the breeding season (Murphey, et al., 1925).

Many of the early studies on the effects of underfeeding upon reproduction were done with rats. In their reviews of these studies, Friedman and Turner (1939) and Guilbert (1942) reported that low levels of energy and protein severe enough to cause marked retardation of growth in the immature animal or weight losses in adults results in cessation of estrus and failure to ovulate. They also reported that a vitamin A deficiency causes death of the fetus or birth of non-viable young.

Cattle, sheep, and swine were also adversely affected by low intake of energy, protein, and vitamin A (Friedman and Turner, 1939; Guilbert, 1942; Phillips, et al., 1945; Reid, 1949; Reid, et al., 1951; Robertson, et al., 1951; and Van Horn, et al., 1951). There was apparent disagreement concerning the importance of the level of protein intake by cattle and its relationship to reproduction. Guilbert (1942) reported "irregularity of estrus" in cattle fed low levels of protein even though Friedman and Turner (1939) had stated that attempts to study the effects of a single dietary ingredient were complicated by an apparent lower palatability of the ration causing below normal feed intake. Another factor which might have complicated such studies was that forages low in protein were also low in phosphorus, although under common cattle management conditions, the possibility of protein deficiency was remote (Reid, 1949). And yet, Phillips (1942) stated that ruminants were able to systhesize protein by means of rumen bacteria; thus their protein requirements were less exacting than those of animals with simple stomachs (monogastrics).

In order to better understand the effects of low levels of nutrients, particularly energy and protein, upon reproduction in female cattle, a number of experiments have been conducted over the years which study various phases of the female's reproductive and life cycles. A number of studies have been made on the effects of various levels of energy upon puberty (or first estrus) in dairy heifers (Crichton, et al., 1959; Sorenson, et al., 1959; and Reid, et al., 1964) and in beef heifers (Wiltbank, et al., 1957; Wiltbank, et al., 1965; Clanton and Zimmerman, 1970; Maree and Harwin, 1971; Short and Bellows, 1971; and Holloway and Totusek, 1973). There is general agreement that low levels of energy intake delay the onset of puberty, regardless of whether these levels are fed from birth to eighty weeks of age (Sorenson, et al., 1959) or from seven to twelve months of age (Short and Bellows, 1971).

In a study of the factors affecting age and weight at puberty, Arije and Wiltbank (1971) stated that heifers which grew faster before weaning tended to reach puberty at an earlier age and heavier weight; that those which grew faster after weaning tended to be heavier, but not necessarily younger at puberty. This latter point may, in part, be explained by Wiltbank (1966) where weaned heifers were wintered to gain about 0.2 kg and 0.4 kg per day. It was found that when post-weaning gains are at a low level, small differences in gain have a major effect on age at puberty; but at high level post-weaning gains, differences in average daily gain do not have a major effect on age at puberty. It was concluded that after the animal reaches a certain critical weight, variation in average daily gain has little or no effect on age at puberty.

Data presented by Short and Bellows (1971) were in agreement with Wiltbank (1966), Clanton and Zimmerman (1970), and Arije and Wiltbank

(1971). Heifer calves with similar initial weights were wintered to gain 0.23, 0.45, and 0.68 kg per day for 153 days (from seven to twelve months of age) and then moved to pasture. Those fed the low level reached puberty at 433 days of age weighing 238 kg; medium level at 411 days, 248 kg; and high level at 388 days, 259 kg; even though the low level group had the highest weight gain on pasture and the high level group the lowest.

The dairy heifers studied by Sorenson, et al. (1959) consumed 60, 100, and 140% of recommended TDN levels (Morrison, 22nd edition) from one to eighty weeks of age. Here, the age and weight differences for the low and medium groups were similar to those of Short and Bellows (1971). However, animals in the high group reached puberty twelve weeks earlier, but at about the same weight as those in the medium group. Reid, et al. (1964) reported the same differences in age at puberty, however, there were small differences in weights and there was no trend towards lighter weight with delayed puberty.

Crichton, et al. (1959) completed a study of dairy heifers which were reared on four different nutritional regimes from birth until two months before first calving. Designated HH, HL, LH, and LL (L = low level, H = high level), the H level was 110%, and the L level was 70% for the first six months and 60% thereafter of the 1934 Ragsdale feed recommendations; the heifers were changed to their second feed level at 44 weeks of age. The ages and weights at puberty for the HH and HL groups were consistent with those given in the reports as described above. The LH group seemed to follow the trend described by Arije and Wiltbank (1971) - that high postweaning gains result in heavier weights, but not necessarily younger age at puberty. The HL group did not correspond to any other research data; it was the last group to reach puberty, yet weight at puberty was between that of the LL and HH groups.

The study by Wiltbank, et al. (1957) included not only three different levels of energy, but three different levels of protein within each level of energy as well. Here the energy levels were full-fed, two-thirds of full-fed, and maintenance; the protein levels were 0.23, 0.15, and 0.06 lb of digestible protein per hundredweight of body weight. The times from the begining of the experiment ot first estrus followed the patterns of other energy experiments and were 125, 159, and 203 days for the high, medium, and low energy groups respectively. There was, however, no consistent pattern of average daily gains for the protein groups; yet, the average times to first estrus were 152, 132, and 204 days for the high, medium, and low protein levels respectively. From this as well as the data of Bedrak, et al. (1964), Wiltbank, et al. (1965), and Clanton and Zimmerman (1970), it is evident that low levels of protein intake depress feed intake and thus lower the energy level consumed.

The source of protein in the diet can also be a factor in delayed puberty. Bond and Oltjen (1973) fed beef heifers, from 84 days until 3 years of age, three different diets where the protein sources were urea, isolated soy protein, and natural ingredients. Each diet contained similar crude protein and calorec analyses. Although the weights at puberty were similar, age at puberty for those on the urea diet was 300 days later than for those on the other diets. The delay in puberty was in part attributed to lower palatability and utilization of the urea diet which resulted in a lowered nutritional level.

All of the studies presented point to energy as the primary nutritional factor involved in delayed puberty in heifers; the role of protein remains less exacting. The physiological effects of underfeeding in calves is the continued growth of the skeleton and essential organs at the expense of muscular fat and tissue; ovaries remain underdeveloped and estrogens are not secreted in sufficient quantities such that accessory organs remain small. Whether or not the ovaries remain nonfunctional depends upon the severity and duration of underfeeding (Roubicek, et al., 1956; Wiltbank, et al., 1965; and Asdell, 1968).

The effects of nutrition level on subsequent reproductive ability have been examined. Holloway and Totusek (1973) studied three preweaning management systems for replacement heifers under range conditions; weaning at 140 days, 120 days, and creep-feeding and weaning at 120 days. Although there was no consistent delay in puberty for the early weaned group, they tended to have lower calving and weaning percentages. The calves from the creep-fed group had the heaviest birth weights but the lightest weaning weights due to the low milk yields of their dams. This suggests that the normal 240 day weaning is preferable for replacement heifers.

In the work by Short and Bellows (1971), described earlier, all heifers detected in estrus were artificially bred during a 60-day breeding season. Eighty-three versus 24 and 7% of high, medium, and low groups, respectively, reached puberty before the breeding season, and 100, 97, and 80% of the high, medium, and low groups reached puberty by the end of breeding. In the low group, fewer heifers became pregnant that were bred, and fewer were able to maintain pregnancy as compared to the other groups. Thus the final pregnancy rates were 87, 86, and 50% for the high, medium and low groups respectively.

Christenson, et al.(1967), Absher and Hobbs (1968), Bellows, et al. (1972), Corah, et al.(1975), and Falk, et al.(1975) have studied the effects of prepartum energy on reproduction of heifers. All of these studies showed that low levels of energy delay the return to estrus after calving;

this can lead to a reduced pregnancy rate as indicated by Bellows, et al. (1972). There is some indication that the percentage of live calves weaned may also be lowered (Falk, et al., 1975). Under more severe conditions, birth weights are reduced causing a slower rate of growth in calves (Christenson, et al., 1967) and lower weaning weights (Corah, et al., 1975).

Second-calf and older cows are similarly affected by low nutrition. Cattle fed very low levels of energy in the last three to four months of pregnancy gave birth to lighter-weight calves, produced less milk, and therefore weaned lighter calves than those fed higher levels (Hight, 1966; and Corah, et al., 1975). The effects of pre- and post-calving energy intake have been investigated by Wiltbank, et al.(1962), Dunn, et al.(1964), Wiltbank, et al.(1964), Wiltbank, et al.(1965), Hight (1968), Dunn, et al.(1969), and Bond and Wiltbank (1970). As before, birth and weaning weights of calves, and milk yields are affected by level of energy (and protein) intake (Wiltbank, et al.,1965; Hight, 1968; and Bond and Wiltbank, 1970).

Perhaps more important, in terms of new information, are the effects of energy level upon postpartum estrus and pregnancy rates. Prepartum energy level appears to have the greater influence upon time to first estrus (Wiltbank, et al., 1962; Dunn, et al., 1964; and Dunn, et al., 1969) although there is evidence that above and below normal energy levels may also exert significant influence as shown by Wiltbank, et al. (1964). That pre-calving energy level loses its influence upon postpartum estrus after about 100 days (Dunn, et al., 1969) is evidenced by comparing high-low (HL) groups with low-high (LH). As previously stated, the LH groups are delayed in returning to estrus, but then the numbers coming into estrus increase at a faster rate than those of the HL groups; in the end, the LH groups have as many as, or more than the HL group in estrus (Wiltbank, et al., 1962; and Dunn, et al., 1969). In contrast, data show that pregnancy rate is more greatly influenced by postpartum energy level than prepartum level; final pregnancy rates of LH groups were as high or higher than those of HH groups (Wiltbank, et al., 1962; Dunn, et al., 1964; and Dunn, et al., 1969). Conversely, Corah, et al. (1975) found no significant influence of prepartum energy level upon the interval to postpartum estrus; the animals were initially in "excellent" condition. Wiltbank, et al. (1962) stated that a lack of ovarian activity for cows on low levels of energy may be the result of a failure to release gonadotrophin and/or to produce gonadotrophic hormone. A theory is put forth, with supporting evidence, that: "perhaps both body condition and available energy are important factors affecting ovarian activity in the beef cow".

Many other studies have been concerned with the level of nutrition during winter and some of the results are similar to those previously discussed. Low winter energy levels can delay puberty and postpartum estrus (Joubert, 1954; Pinney, et al., 1962a; Wiltbank, et al., 1966; and Clanton and Zimmerman, 1970), and decrease birth weights and weaning weights (Pinney, et al., 1962a; and Pinney, et al., 1962b). Cattle that are wintered under range conditions and given protein supplement tend to have shorter intervals to postpartum estrus (Pinney, et al., 1972; and Kropp, et al., 1973) and higher milk yields (Kropp, et al., 1973). Similarly, drought or extreme range conditions may result in a conception rate of only 41% (Carroll and Hoerlein, 1966) or a calving rate of 48% (Speth, et al., 1962). But with energy supplementation, a conception rate of 77% (Barr and Barns, 1972) or a calving rate of 72% (Speth, et al., 1962) can be achieved.

As important as nutrition is to reproductive performance, to feed supplemental energy to improve conception rate when the level of nutrition is otherwise adequate is, at best, futile (Bellows, et al., 1968; and Loyacano, et al., 1974) and may prove detrimental in terms of calving difficulty and reduced milk yield (Pinney, et al., 1962a).

Computer programs

Since the invention of the digital computer, there has developed many new techniques for analyzing agricultural problems. Linear programs have been developed to formulate balanced rations for dairy (Howard and Shook, 1975) and beef cattle (Church, et al., 1963). Such programs have been expanded to include optimization. Booth (1975), for example, describes a program which formulates least-cost rations for the dairy herd and selects the optimum milk production level for maximizing income above feed costs.

Herd management has been aided with computerized record-keeping systems (Lineweaver and Spessard, 1975; and Premier Corporation, personal communication) and with genetic evaluation programs such as those used by the U.S.D.A.-D.H.I.A. (Dickenson, 1975).

Others have used linear programming to describe various beef production systems. Villareal (1966) has modeled the feedlot aspect of the California beef industry. Optimization techniques are used to determine the best geographical sources of feed and feeder calves, and to weigh the costs of internal beef production versus the importation of beef to meet consumer demands for beef.

Ely and Allison (1975) have modeled the individual feedlot operation. The program selects the ration to be fed, the rate of gain of the cattle, and the weights of cattle to be purchased, fed, and sold which maximize profit for beef cattle gain over feed, cattle, labor, and overhead costs.

Schwab (1974) has developed a beef/forage decision-making model which evaluates cow-calf and calf-yearling operations. The model considers specific forages, soil management groups, forage harvesting and storage, building and machine investment, and labor and machine hours. With user specified management policies, the model optimizes the allocation of farm resources required to maximize farm income.

Similarly, Wilton, et al. (1974) have modeled an on-farm integrated beef production enterprise which includes cropping, feeding and breeding activities with associated land, labor, animal housing, and crop storage requirements. Wilton and Morris (1975) use a similar model to determine the optimal production program given breeding system, i.e. straight-bred or cross-bred, reproductive rate, and cow size.

Although useful for systems that are linear and deterministic, many biological systems are too complex and contain non-linear and/or stochastic elements; such systems are not well suited to linear programming. Simulation techniques, however, permit the methodical study of such dynamic systems over a particular time period.

Smith (1973) and Vickery and Hedges (1974) have developed similar models to study sheep-grazing systems. Smith (1973) gave emphasis to pasture growth rate as affected by radiation, leaf area, soil moisture; and defoliation rate as affected by sheep stocking rate, herbage on offer, and pasture height. Total effects are measured in terms of sheep liveweight output.

Vickery and Hedges (1974) use the same type of pasture growth component but adjust for the age of plant parts as a function of frequency and intensity of grazing and season of the year. Herbage digestibility is accounted for in the green-dead herbage ratio with the assumption that digestibility declines with age. This model is more detailed in that it accounts for animal energy balance, weight change, wool growth, energy loss, and mortality.

A group of animal scientists at Texas A&M University have been modeling various aspects of beef production for a number of years. Long and Fitzhugh (1970), Long, et al.(1971a), Long, et al.(1971b), Cartwright, et al.(1975), Fitzhugh, et al.(1975), and Long, et al.(1975) have used both linear programming and simulation to evaluate the effects of various breeding systems, mature sizes, management, heterosis and complementarity upon efficiency of beef production. Simulation results indicate that heterosis and complementarity add to net efficiency, but which cow size is best may well depend upon the management system to be used.

Related to the above work is a model described by Joandet (1974) which simulates the female population and nutrition dynamics. A component of this is a female reproduction model developed by Sanders (1974) which simulates the occurrence of estrus and conception of cows and heifers during a specified time period.

Some rather detailed physiological functions have also been modeled. Blincoe (1975) has simulated iodine metabolism and applied it to lactating and non-lactating cattle and sheep. It was found that thyroid function was not affected by lactation in cattle, but that there were marked effects in sheep since they excrete high concentrations of iodine in their milk.

Rice, et al.(1974) used a modified version of the model by Smith (1973) as a component in a model which simulates growth and senescence of forage and its intake, assimilation, and utilization by the grazing ruminant. The rumen digestive process, which has two-directional causality with feed intake, is followed through to the allocation of digested energy and protein for body maintenance, pregnancy, lactation, and growth.

In contrast, the dairy enterprise model described by Smith and Ladue (1974) focuses on the entire herd and its management; land resources and cropping systems; buildings, machinery, and labor; financial and economic environment. It models both biological and economic systems. Most agricultural simulation models are of this form.

Halter and Dean (1965) used simulation towards improving managerial decisions on range-feedlot operations in California under the uncertainties of weather and prices. The decision points tested were (1) the purchasing rates of feeders for the range and the rate of transfer to the feedlot for finishing; and (2) the purchasing rates of feeders directly for the feedlot. With initial weights and feeding parameters held constant, the performance of the alternative decision policies were tested over a simulated distribution of price and range conditions. A policy was regarded as more successful if (1) it raised the mean income while variance in income was held constant or lowered; or (2) it lowered variance of income while it raised or held the mean level of income.

Simulation has also been used to study alternative policies towards improving beef production in developing countries. Husain (1970) used simulation to appraise a cattle breeding/fattening ranch in the Columbian Livestock Project. The model includes herd development, revenue and expenditure, income, cash flow, financial return, and economic return routines.

Lehker (1970) and Posada (1974) have developed models to study alternative methods of beef production and the transition from traditional to modern methods. They also included costs and revenue to the farmer and the government from such changes.

Manetsch, et al. (1971) have developed a global model to be used as a planning tool for developed and underdeveloped countries. Based upon the Nigerian agriculture and economy, the model is comprised of three submodels: (1) the Northern annual crop-beef model simulates the production of beef, subsistence food, and cash crops within four distinct crop regions; land allocation, modernization, population, and processing. (2) The Southern perennial-annual crop model simulates the production and marketing of several food and cash crops while reflecting the competition and interaction of these crops in four different regions representing different ecological and natural conditions. It also simulates land allocation-modernization decisions, population and processing. (3) The nonagricultural model calculates employment requirements, import-export balances, government revenues and the components of the national income accounts. It can interact with the agricultural models receiving data on agricultural inputs, exports and investments, and determine the quantity of food and other agricultural raw materials demanded by the nonagricultural sectors.

Jaske (1976) has modeled a beef cattle enterprise, primarily the land extensive cow/calf operation. It includes cattle demography, forage growth, feed stock accounting, nutrient impacts upon growth and reproduction, management decision-making, and financial routines. The model is designed to be a practical tool capable of investigating the effects of management decisions on the physical and financial variables of interest to decision makers.

II. MODEL DESCRIPTION

This model is oriented towards the cow/calf operation, although routines are included for feeder cattle. Such factors as variable genotypes and heterosis effects have already been explored and, therefore, are not included here (Long and Fitzhugh, 1970; Long, et al., 1971a; Sanders, 1974; Cartwright, et al., 1975; Fitzhugh, et al., 1975; and Long, et al., 1975). Direct environmental effects such as temperature and disease have also been excluded. At present, feed quality is measured only by total digestible nutrients (TDN) content. Monthly milk yields and mortality rates are fixed in the model, i.e. they do not change according to the nutrition level or body condition.

The beef cow typified by this model is a British breed of medium frame with a mature weight of 505 kilograms (kg). Upon entering the breeding herd at two years of age with her first calf, she may remain productive for as long as ten years.

General organization

The model uses a modified SIMEX1 format (Manetsch, 1975) which consists of a main program to set initial conditions, call subroutines, and control the printing of output; and numerous subroutines which perform the various mathematical operations. These subroutines can be classified into the following functional groups: (1) herd demographics, (2) nutrition dynamics, and (3) reproduction dynamics.

Herd demographics requires age, sex, and function disaggragation; birth and mortality rates, number of births within each class of reproducing females, and average body weights of each subpopulation.

Nutrition dynamics requires average daily dry matter intake of feeds according to the amount available, rumen capacity of the animal, and reproduction-lactation status; energy requirements for body maintenance, gain, and lactation; determination of average daily weight change after requirements for maintenance and lactation have been met, and after weight loss due to calving has been accounted for.

Reproduction dynamics requires determination of age and weight at first estrus (puberty) in heifers based upon time of birth, weaning weight, and average weight change since weaning; determination of first postpartum estrus and conception rates based upon body condition after calving and at breeding.

Each of the subroutines will be discussed according to the functional group in which it belongs. Since certain subroutines may fall into more than one of these groupings, they will be discussed according to their primary function.

Program BEEF

Program BEEF is the executive routine used for this model and is a modified version of the SIMEX1 routine described by Manetsch (1975). The routine permits NRUN consecutive simulation runs where for each run, model variables are assigned a predetermined set of initial conditions, values are assigned to the control parameters, and default values are assigned to the variable model parameters. This latter group are specially noted in the Glossary of Terms found in Appendix A.

The model requires certain exogenous inputs for each run. These include initial herd structure, size, and body weights; delay lengths, number of stages in each delay, and mortality rates; initial reproductive status variables; initial calving period, average time at which heifers reach one year of age, age at which calves are to be weaned, and time of weaning; and feed levels along with their respective TDN values.

Each simulation run has a duration of DUR years with NITER = DUR/DT simulation cycles, where DT is the time increment per cycle in years. Subroutines HDMOG4, WEIGHT, MGMT, and NUTRN are called in every cycle or as otherwise prescribed by some time parameter.

New values can be exogenously assigned to the variable model parameters whenever subroutine NAMLST is called. This is a relatively simple routine which checks the list of variable parameters for a name identical to one appearing on a data card. If they match, a new value is assigned to that parameter. The process is repeated until the end of the data string is encountered.

In contrast to SIMEX1, two parameters have been added to BEEF which add greater flexibility to the program. TMLST is the first time after initialization that subroutine NAMLST can be called, and TMINT is the time interval between consecutive callings of NAMLST. Since both of these terms are variable parameters, subroutine NAMLST can be called at any desired time within the run. This feature was added so that feed allocations might be changed according to the anticipated needs of the breeding herd during the course of a particular run. This also allows for changes in the timing of events such as weaning or the breeding season.

Unlike the model developed by Jaske (1976) where the simulation run is stopped at various decision points, this model runs continuously for NRUN*DUR simulation years. Thus if any changes are to be made via subroutine NAMLST, such changes must be carefully planned, particularly their timing, before the run is started.

Program BEEF also controls the printing of simulation results. Printing frequency is ordered by BEGPRT, the time at which printing begins; PRTVL1, the initial time interval between printouts; PRTCHG, the time at which the frequency of printing is to be changed; and PRTVL2, the subsequent time intervals between printouts as directed by PRTCHG. Two different levels of printout are also possible. The value assigned to SELPRT determines if the output is to be of selected variables, whereas DETPRT determines if there is to be a detailed output. All of the terms controlling the printout are variable parameters, thus the operator can have frequent detailed outputs at the begining and end of a run with less frequent selected outputs during the interim.

There are two small computational routines in BEEF. The first is a set of simple arithmetic equations which determine some reproductive status values. The second is a series of equations which determine the mean body weight and the standard deviation of the mature cow population.

Figure 1 illustrates the structure of program BEEF as well as the calling sequence of the primary subroutines.

Herd demographics

The set of subroutines which comprise herd demographics are HDMOG4, BIRTH2, BIRAT, and WEIGHT. Together these routines simulate the change in herd populations and body weights over time. HDMOG4 and WEIGHT were developed by Jaske (1976) to which the reader is referred for a detailed description of these subroutines and the delay routines.

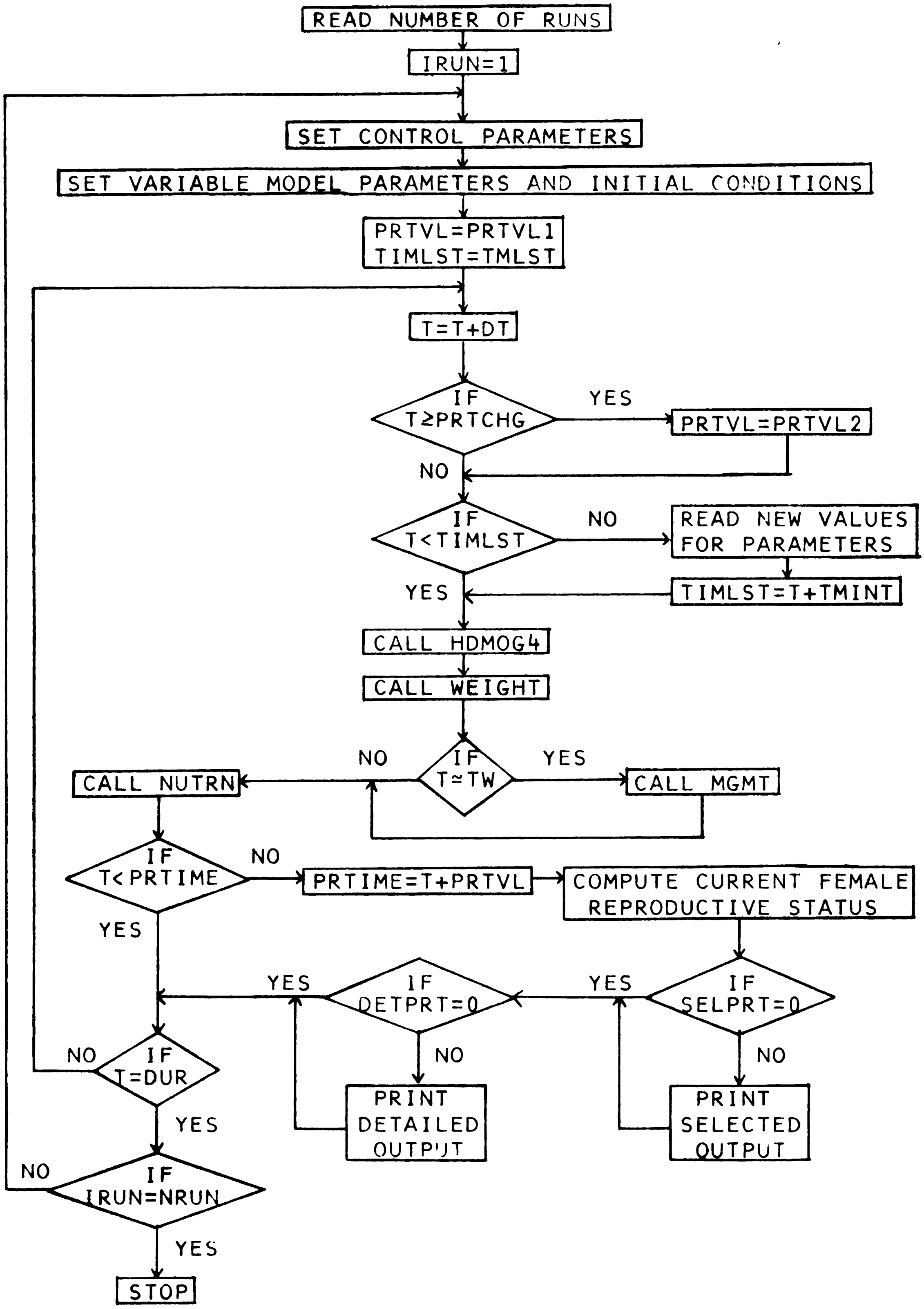

Figure 1. Flowchart of program BEEF

Subroutine HDMOG4 is designed to maintain herd populations on a disaggregated basis by sex, age, and function, thus resulting in the following nine herd cohorts:

POP1(t) = current number of mature cows,

POP2(t) = current number of replacement heifers,

POP3(t) = current number of bred heifers,

POP4(t) = current number of mature bulls,

POP5(t) = current number of young bulls,

POP6(t) = current number of steers,

POP7(t) = current number of male calves,

POP8(t) = current number of female calves,

POP9(t) = current number of market heifers.

Each population can be mathematically defined as

$$POP_i(t) = \sum_{j=1}^{KK_i} SUBPOP_{ij}(t) \tag{1}$$

where,

$$SUBPOP_{ij}(t) = \frac{DELAY_i(t) * RIN_{ij}(t)}{KK_i} \tag{2}$$

for distributed delays; or for discrete delays,

$$SUBPOP_{ij}(t) = DT * RIN_{ij}(t) \tag{3}$$

$RIN_{ij}(t)$ = intermediate delay rate corresponding to the $(KK_i + 1 - j)^{th}$ subpopulation of cohort i;

$KK_i(t)$ = the number of stages in the delay or subpopulations of cohort i;

$DELAY_i(t)$ = time required to pass through the aging or maturation interval for cohort i.

Cohorts 1,4,5,6, and 9 are modeled by distributed delays, whereas cohorts 2,3,7, and 8 are modeled by discrete delays.

All of the delay routines include the proportional loss rate

$$PLR_i(t) = DR_i(t) - \frac{ADDRT_i(t)}{POP_i(t)} \tag{4}$$

where $DR_i(t)$ = the annual mortality rate for cohort i,

$ADDRT_i(t)$ = the annual rate of additions to cohort i.

Since this model is designed to study the effects of low nutrient intake upon growth and reproduction, weight losses can and do occur. Unless some constraint is built into the model, negative gains over a long period of time can bring weight down to zero at which point a mode error occurs. However, little or no information is available concerning the degree of weight loss necessary for death to occur. Until such information is available, the following equations are used in HDMOG4 as a safety measure:

$$\text{if} \quad |DGAIN_{ij}(t-dt)| > W_{ij}(t-dt), \tag{5}$$

$$\text{then} \quad RIN_{iq}(t) = 0, \; q = KK_i + 1 - j$$

$$\text{and} \quad SUBPOP_{ij}(t) = \frac{DELAY_i(t)}{KK_i} * RIN_{iq}(t) = 0,$$

where $W_{ij}(t)$ = the average body weight of $SUBPOP_{ij}(t)$,

$DGAIN_{ij}(t)$ = average daily gain of $SUBPOP_{ij}(t)$.

The number of calves born per year to each of the three reproducing cohorts is computed,

$$B_i(t) = B_i(t-dt) + BR_i(t)*RPOP_i(t)*DT \tag{6}$$

where $B_i(t)$ is equivalent to BCOW(t), BREP(t), and BBRD(t) for cohorts 1,2, and 3 respectively; $BR_i(t)$ is the current annual birth rate for cohort i; and $RPOP_i(t)$ is the number of females in cohort i of breeding age. Both $RPOP_i(t)$ and $BR_i(t)$ are computed by subroutine BIRTH2 which is called each cycle by subroutine HDMOG4.

Because distributed delays simulate the maturation process rather than chronological aging, a special device is required to track the 2-year old heifer subpopulations as they enter cohort 1 until their first calving season is completed. Such tracking is necessary if the effects of nutrition upon reproduction are to be accurately recorded for the two heifer populations. This function is performed by subroutine BIRTH2 by saving the $KK_i{}^{th}$ subpopulation values in $COWNEW_{kj}(t)$ from the time BEGCAV(t) - DEL to time ENDCAV(t) where;

BEGCAV(t) = the time in the current year that the calving period begins,

ENDCAV(t) = the time in the current year that the calving period ends,

DEL = ENDCAV(t) - BEGCAV(t) + DT.

At time BEGCAV(t) the numbers of females that are of breeding age are summed for each of the first three cohorts. To summarize the number of heifers calving, any that have been tallied by $COWNEW_{kj}(t)$ are deducted from RPOP1(t) and added back to RPOP2(t) or RPOP3(t). $RPOP_i(t)$ is computed on every pass until time ENDCAV(t). Thus,

$$RPOP1(t) = \sum_{j=1}^{KK1} SUBPOP_{1j}(t) - \sum_{i=1}^{2} \sum_{\ell=1}^{KCNT_k} COWNEW_{k\ell}(t) \tag{7}$$

for mature cows; and

$$RPOP_i(t) = \sum_{k=1}^{KCNT_i} COWNEW_{ik}(t) + \sum_{j=NR_i}^{KK_i} SUBPOP_{ij}(t) \tag{8}$$

for heifers, where

$KCNT_i(t)$ = the number of heifer subpopulations which have passed into cohort 1,

$NR_i(t)$= the minimum delay stage separating young from old heifers in cohort i.

Subroutine BIRAT is called by BIRTH2 at time BEGCAV to compute $BFRAC_{in}(t)$, the accumulative percentage of females in each cohort calving over the entire calving period in D time increments, where D = 0.01923 years. For heifers;

if $A \leq CTIM_{ijk}(t) < B$,

$$BFRAC_{in}(t) = BFRAC_{i,n-1} + \frac{\sum_{j=NR_i}^{KK_i} \sum_{k=1}^{INB_{ij}} (CPAT_{ijk}(t) - CPAT_{ijk-1}(t))*SUBPOP_{ij}(t)}{RPOP_i(t)} \tag{9}$$

otherwise, $BFRAC_{in}(t) = BFRAC_{i,n-1}(t)$, n = 2, . . . , INTCAV.

where, A = BEGCAV(t), . . . , BEGCAV(t) + (INTCAV - 2)*D

B = BEGCAV + D, . . . , BEGCAV + (INTCAV - 1)*D

$$INTCAV = \text{int}\left(\frac{ENDCAV(t) - BEGCAV(t)}{D}\right) + 1.005$$

$CTIM_{ijk}(t)$ = the calving time of the j^{th} subpopulation in cohort i as a result of conception in the k^{th} estrus in the breeding season.

$CPAT_{ijk}(t)$ = fraction of the j^{th} subpopulation in cohort i to have calved by $CTIM_{ijk}(t)$.

This mechanism is illustrated in Figure 2.

The equations for mature cows operate similarly, but involve an additional weighting factor, $WF_j(t)$, which is used to estimate the fraction of $SUBPOP_{1j}(t)$ which was in $SUBPOP_{1,j-1}(t)$ at the previous breeding period. Again, this is necessary because of the use of a distributed delay for cohort 1.

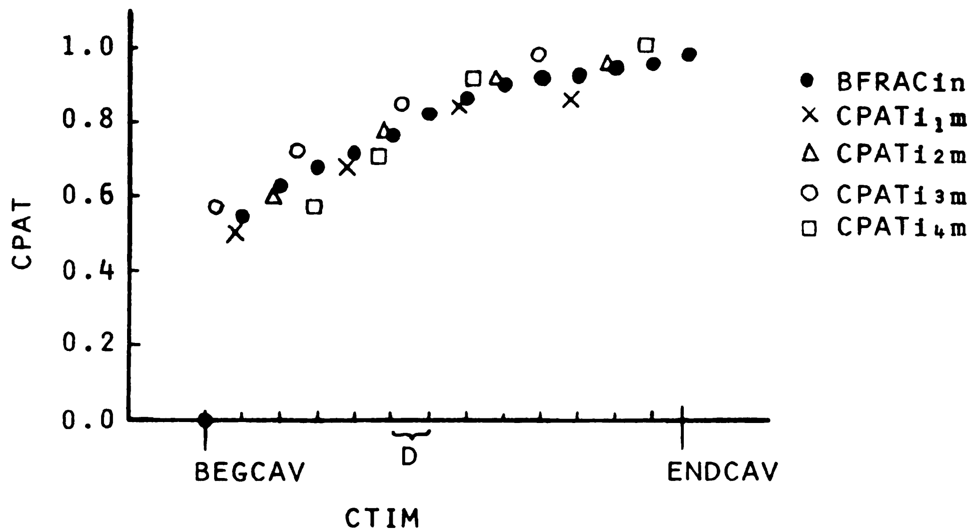

Figure 2. Illustration of $BFRAC_{in}(t)$ computation

The equations then become;

$$\text{if } A \leq CTIM_{1j-1,k} < B,$$

$$ALPHA = (CPAT_{1,j-1,k}(t) - CPAT_{1,j-1,k-1}(t))*WF_j(t)$$

otherwise, ALPHA = 0;

and if $A \leq CTIM_{1jk}(t) < B$,

$$BETA = (CPAT_{1jk}(t) - CPAT_{1j,k-1}(t))*(1 - WF_j(t))$$

otherwise, BETA = 0;

and

$$BFRAC_{1n}(t) = BFRAC_{1,n-1}(t) + \frac{\sum_{j=1}^{KK_1} (ALPHA + BETA)*SUBPOP_{1j}(t)}{RPOP_1(t)} \tag{10}$$

The values of $BFRAC_{in}(t)$ are then returned and used by subroutine BIRTH2 to compute the current annual birth rate, $BR_i(t)$, for each of the three cohorts during the calving season. This is accomplished by use of the linear interpolation function TABLIE (Llewellyn, 1965) and is

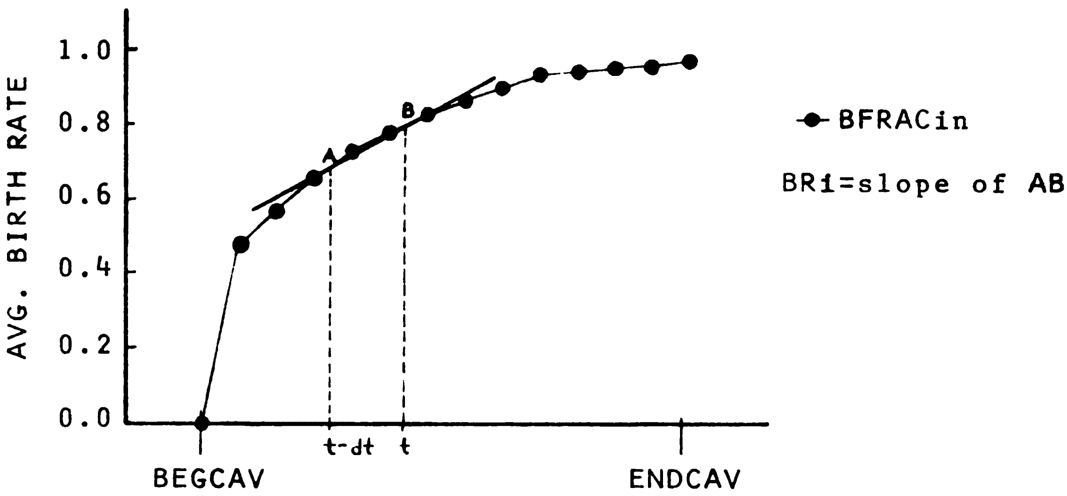

Figure 3. Illustration of $BR_i(t)$ computation

illustrated in Figure 3. Outside the calving season $COWNEW_{kj}(t)$, $RPOP_i(t)$, and $BR_i(t)$ are set to zero and the values of $BFRAC_{in}(t)$ are no longer used. The general structure of subroutine BIRTH2 is given in Figure 4.

The last subroutine in herd demographics is WEIGHT. It operates parallel to HDMOG4 by updating average body weights according to population shifts and average daily gains, $DGAIN_{ij}(t)$, in the corresponding subpopulations. Thus;

$$W_{ij}(t) = BETA_{ij}(t)*\{W_{ij}(t-dt) + \int_{t-dt}^{t} DGAIN_{ij}(\tau)d\tau\} +$$

$$(1 - BETA_{ij}(t))*\{W_{i,j-1}(t-dt) + \int_{t-dt}^{t} DGAIN_{i,j-1}(\tau)d\tau\} \qquad (11)$$

where $BETA_{ij}(t)$ is the fraction of animals remaining in the same subpopulation from the previous time period.

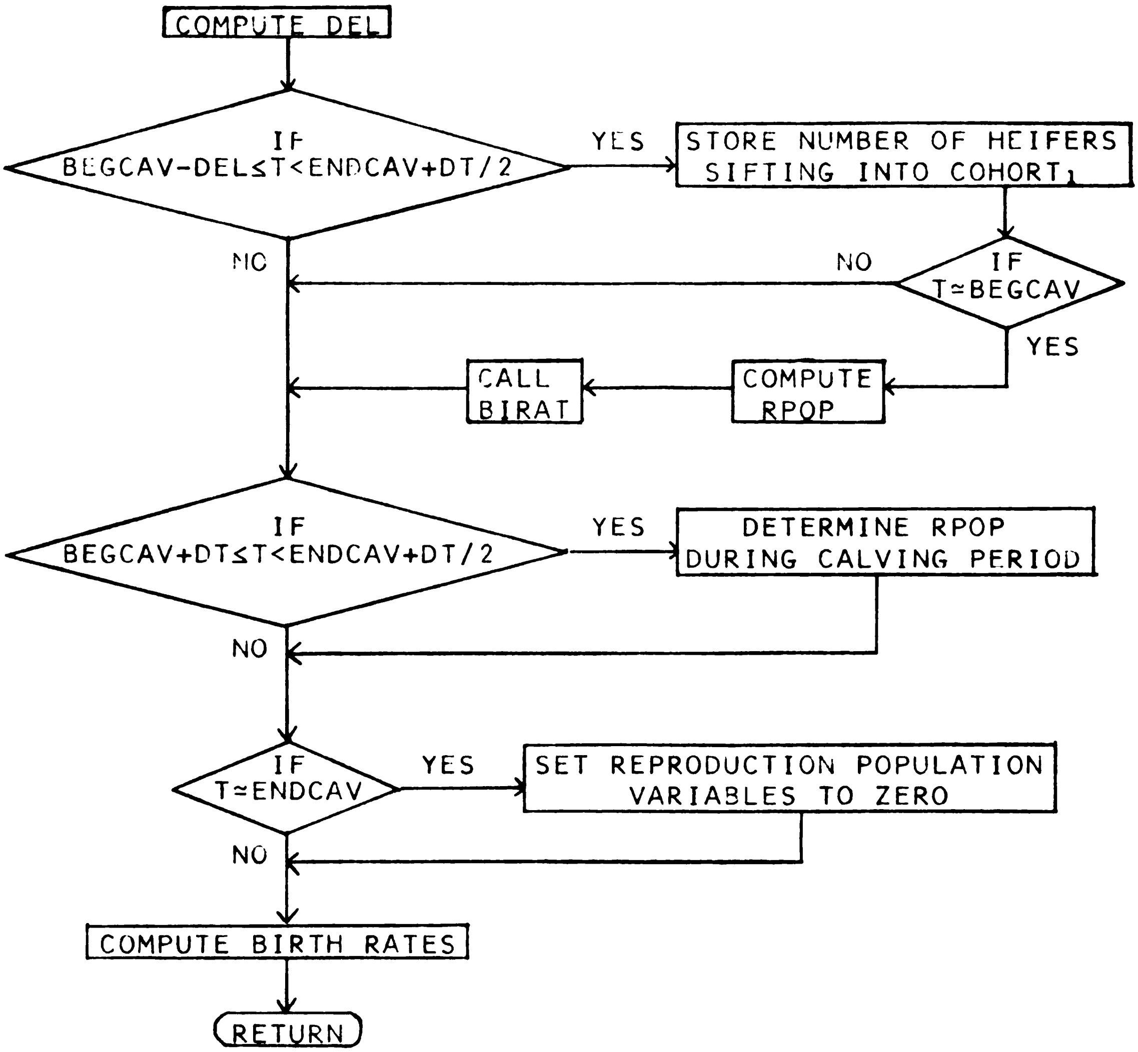

Figure 4. Flowchart of subroutine BIRTH2

Thus subroutines HDMOG4, BIRTH2, BIRAT, and WEIGHT simulate the births, deaths, aging, and weight changes of the herd populations over a given time period.

Nutrition dynamics

The nutrition dynamics component is comprised of subroutines NUTRN, COWCYC, GROFEM, GROMAL, and CNVRT. Called by program BEEF, subroutine NUTRN might be regarded as a herd status-checking and control routine.

The first major function of NUTRN is to determine the values of IPREG(t) and LAC(t), switches designating the current pregnancy and lactational status of the herd. IPREG(t) is determined by a complex series of IF statements. In essence, they ask (1) in what stage of the reproductive cycle is the herd, and (2) what is the sequence of events within the current cycle. For example, (a) is $\mathrm{BEGCAV}(t) \leq t \leq \mathrm{ENDCAV}(t)$, or is $\mathrm{ENDCAV}(t) \leq t \leq \mathrm{EBMX}(t)$, where EBMX(t) is the end of the breeding season; and (b) is $\mathrm{TBRD}_2(t) < \mathrm{ENDCAV}(t) < \mathrm{TBRD}_1(t)$, or is $\mathrm{ENDCAV}(t) < \mathrm{TBRD}_1(t) < \mathrm{TBRD}_2(t)$ where $\mathrm{TBRD}_1(t)$ and $\mathrm{TBRD}_2(t)$ are the times breeding begins for cows and heifers respectively. The statement series is divided into two sections (1) if $\mathrm{BEGCAV}(t) < t < \mathrm{ENDCAV}(t)$ and $t \leq \mathrm{EBMX}(t)$; and (2) if $\mathrm{BEGCAV}(t) < \mathrm{ENDCAV}(t) \leq t$ and $t \leq \mathrm{EBMX}(t)$. Within each of these sections it must be determined whether cows or heifers are bred first and whether breeding for one or both groups begins before or after ENDCAV(t). Also considered is whether or not one or both groups was bred the previous year and whether or not they are to be bred in the current year. Every possible rational combination in timing of reproduction events has been considered in order to provide a maximum of flexibility - a total of some thirty combinations. For this model, an example of an irrational combination of events is to begin breeding heifers and/or cows before the calving season begins, i.e., $TBRD_i(t)<BEGCAV(t)$. Therefore, if

IPREG(t) = 0, no cows or heifers are pregnant;

= 1, only heifers are pregnant;

= 2, only cows are pregnant;

= 3, both cows and heifers are pregnant.

LAC(t) is determined simply on the basis of whether or not any of the three groups of reproducing females have calved during the time interval (BEGCAV, TW) where TW is the time in the current year that weaning is to take place; that is, if BCOW(t), BREP(t), or BBRD(t) > 0 for cohorts 1,2, and 3 respectively. Thus, if

LAC(t) = 0, no cows or heifers are lactating;

= 1, both cows and heifers are lactating;

= 2, only cows are lactating.

No allowance has been made for "only heifers are lactating" since heifers have, or are at the point of, merging into cohort 1.

At time BEGCAV(t), the final subpopulation pregnancy rates for heifers, $HP_{kjm}(t)$, and cows, $PCP_n(t)$, are saved in the term $OLDCP_{ij}(t)$. This allows for the next breeding season to begin before the current calving season has ended, as both old and new values would be necessary for various computations until the calving season has ended.

As previously mentioned, the operator has the option of breeding or not breeding cows or heifers during a given year. If the decision is not to breed, subroutine NAMLST is used to set $TBRD_i(t) = -1$ and $DURB_i(t) = 0$, and subroutine NUTRN will then set the appropriate reproduction variables to zero or an initial value. Caution is advised in using this option as the various alternatives in the timing of the value changes for

$TBRD_i(t)$ and $DURB_i(t)$ have not been fully explored, where $DURB_i(t)$ is the duration of the breeding period for cohort i.

In order to compute milk yields during the lactation period, it is necessary to know the number of months in the calving period, ML(t), and the time elapsed since the begining of calving, TEBC(t). These values are computed;

$$ML(t) = \text{int}\left(\frac{ENDCAV(t) - BEGCAV(t)}{DM} + 1.005\right) \tag{12}$$

and $$TEBC(t) = t - BEGCAV(t) \tag{13}$$

where DM = 0.08333 years.

Because of the necessary delay length of 1.5 years for cohorts 2 and 3, there is a time period, from weaning until the end of the following calving period, where there may be two distinct groups of heifers within the same cohort. These are the heifers which have been recently weaned and heifers which have been bred and will be moving into cohort 1 as they reach two years of age. There are a number of instances where computations must be made with regard to one group but not the other. thus some variable term to demarcate these groups is required. The rationale for the computation of this term, $NR_i(t)$, is that the minimum age difference between the youngest subpopulation of weaned heifers and the youngest subpopulation of bred heifers is GEST, the length of the gestation period. The following computations are therefore made during each simulation cycle;

$$MXP = KZ + \text{int}\left(\frac{GEST}{DT}\right) + 0.5 \tag{14}$$

if $MXP > KK_i$, $NR_i(t) = KZ - 1$

otherwise, $NR_i(t) = MXP$

where KZ is the youngest subpopulation of cohort i.

In order to estimate the time of first postpartum estrus and conception rates, the average postpartum or yearling condition of the subpopulations of females to be bred in the coming season must be determined. This is done by subroutine NUTRN at time BEGCAV. In practice, condition is assessed according to the animal's apparent fatness or thinness. Since such a subjective measurement is most difficult to simulate, actual and expected body weights are used to estimate condition.

Brody (1945) describes growth as occurring in two phases (1) self-accelerating or increasing slope, and (2) self-inhibiting or decreasing slope. The self-accelerating phase is described by the equation;

$$W = Xe^{qt} \tag{15}$$

where W is weight at time t; X is theoretically the value of W at time t = 0; and q is the instantaneous relative rate of growth. The self-inhibiting phase, however, is described by the equation;

$$W = A - Be^{-kt} \tag{16}$$

where W is weight at time t; A is the mature weight; B is an age correction parameter; and k is the relative growth rate with respect to the growth yet to be made.

To compute expected weight (versus simulated actual weight) at a given age, these equations were adapted in a manner similar to that of Sanders (1974) where it is assumed that both equations adequately describe growth in weight at the time of puberty or about one year of age. This also assumes that, like dairy cows, beef cows reach about 86, 95, and 98% of their mature wither height at one, two, and three years of age respectively; and that $W = kH^{4.3}$ is true, where H is wither height. In contrast to Sanders (1974) where mature weight is 480 kg and the time unit is days, the equations were adapted to a mature cow weight of 505 kg and a time unit of years. Thus the equations used by this model are;

$$WMIN_{ij}(t) = THETA*COWMWT*e^{SIG*AGE(t)} \tag{17}$$

for heifers where, AGE(t) $\leq$ 1 year, is the age of the animal,

SIG = 0.80168832,

COWMWT = 505 kg,

THETA = 0.23460278,

and,

$$WMIN_{ij}(t) = COWMWT*(1 - 0.477*e^{-0.879*(AGE(t) - 1)}) \tag{18}$$

where AGE(t) > 1 year.

Condition is then estimated as;

$$PPW_{ij}(t) = \frac{W_{ij}(t)}{WMIN_{ij}(t)} \tag{19}$$

for non-pregnant cows or heifers in the j^{th} subpopulation of cohort i. Where there are pregnant animals, the weight that will be lost as a result of calving is deducted from the weight of the pregnant fraction to give the average postpartum weight of the subpopulation. In this case condition is estimated by;

$$PPW_{ij}(t) = \frac{W_{ij}(t) - OLDCP_{ij}(t)*GEST*GGEST*365}{WMIN_{ij}(t)} \tag{20}$$

where GGEST = 0.192 kg, the average daily gain due to gestation.

After all of the above computations have been made, subroutine NUTRN proceeds to call subroutine ALAC (to be discussed later) and subroutines COWCYC, GROFEM, AND GROMAL in the combination prescribed by KALLER. That is;

if KALLER = 0, no nutrition-growth subroutines are called,

= 1, only COWCYC is called,

= 2, only GROFEM is called,

= 3, only GROMAL is called,

= 4, COWCYC and GROFEM are called,

= 5, COWCYC and GROMAL are called,

= 6, GROFEM and GROMAL are called,

= 7, all nutrition-growth subroutines are called.

This mechanism allows the operator to study a particular group or groups of cattle - mature cows, growing heifers, and growing and mature steers and bulls - without the extra time and cost of superfluous computations.

The final set of computations performed by NUTRN are to update BEGCAV, ENDCAV, TYRLNG, and TWEAN at the appropriate times, where TYRLNG is the time in the year when the average age of the youngest group of heifers is one year; and TWEAN is the time in the year when calves are to be weaned. Thus, if t = TW(t),

$$\mathrm{BEGCAV}(t) = \min(\mathrm{TBRD}\ (t),\ \mathrm{TBRD}\ (t)) + \mathrm{GEST} + \mathrm{int}(t) \qquad (21)$$

$$\mathrm{ENDCAV}(t) = \mathrm{EBMX}(t) + \mathrm{GEST} + 0.01 \qquad (22)$$

$$\mathrm{TYRLNG}(t) = 1.0 + \mathrm{TW}(t) - \mathrm{TCVWN} \qquad (23)$$

where TCVWN is the average age at which calves are to be weaned;

and if t = BEGCAV(t),

$$\mathrm{TWEAN}(t) = \mathrm{BEGCAV}(t) + \frac{\mathrm{ENDCAV}(t) - \mathrm{BEGCAV}(t)}{2} + \mathrm{TCVWN} - \mathrm{int}(t) \qquad (24)$$

The general structure of subroutine NUTRN is given is Figure 5.

Subroutine COWCYC computes the estimated feed intake and weight changes for the lactating, non-lactating, pregnant, and non-pregnant mature cows in cohort 1. This population consists of ten subpopulations

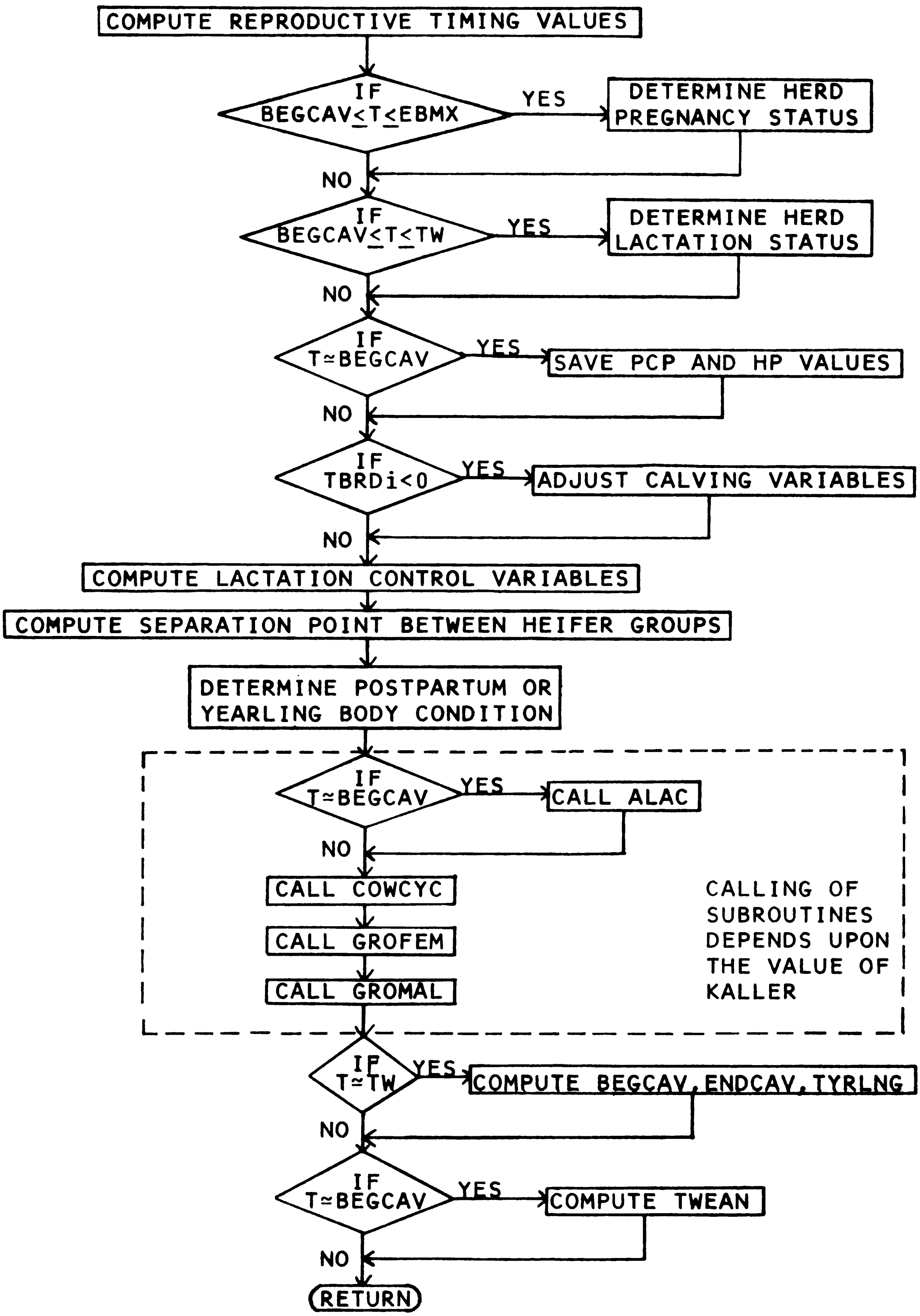

Figure 5. Flowchart of subroutine NUTRN

whose ages range from two to ten years. The reproduction variables for cows and heifers are computed by subroutine REPRO which will be discussed in a later section of this thesis.

Feed is allocated on a population or cohort basis where $RHGAL_i(t)$ is the roughage allocation for cohort i, and $CNCAL_i(t)$ is the concentrate allocation for cohort i. The TDN value of these feeds is then given by $TDNR_i(t)$ for roughages and $TDNC_i(t)$ for concentrates, these are inputted as kg TDN/kg feed on a 100% dry matter basis. Both types of feed can be allocated in two ways: (a) kilograms of dry matter per cohort per DT, or (b) as fractions of body weight per animal per day. For most practical purposes, method (a) would be used since feeds are harvested, stored, mixed, and fed in bulk. For research, however, it is desirable to specify more exacting feed levels thus method (b) would be used.

The operator directs the computer as to which method is being used by means of the switch KFEEDQ. For method (a), KFEEDQ must equal zero (0) so that the allocations per animal per day will be computed;

$$RHGPC(t) = \frac{RHGAL_i(t)}{POP_i(t)*DAYS} \tag{25}$$

for roughages, and

$$CNCPC(t) = \frac{CNCAL_i(t)}{POP_i(t)*DAYS} \tag{26}$$

for concentrates, where DAYS = DT*365. KFEEDQ must be set to one (1) for method (b), and the average daily individual allocations become;

$$RHGPC(t) = RHGAL_i(t)*W_{ij}(t) \tag{27}$$

$$CNCPC(t) = CNCAL_i(t)*W_{ij}(t) \tag{28}$$

for the j^{th} subpopulation of cohort i.

Since 2- and 3-year-old cows are still growing in body size and weight, their feed allocation by method (b) is increased by the multiplier CFY(t), where

$$CFY(t) = 2 - \frac{W_{ij}(t)}{COWMWT} \tag{29}$$

The average maximum feed intake per individual as a fraction of body weight, PD(t), is computed by means of the linear extrapolation function TABEXE (Llewellyn, 1965) from a table of dry matter intake values, PDI_k, versus body weights given by Fox (c. 1975b). This is illustrated in Figure 6. The maximum kilograms of dry matter intake, DDMI(t), is then;

$$DDMI(t) = PD(t)*W_{ij}(t) \tag{30}$$

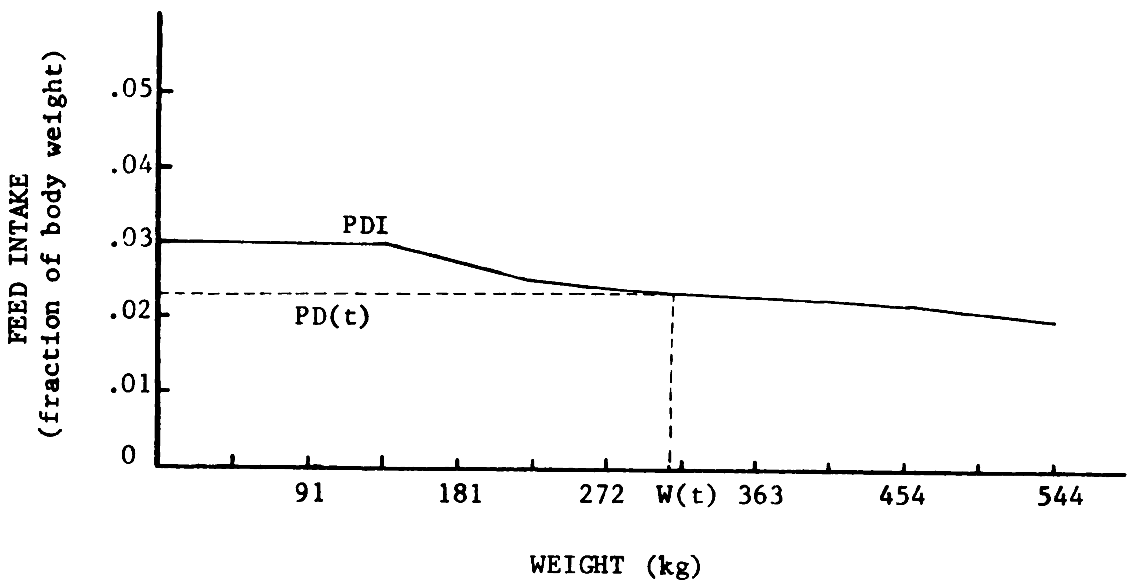

Figure 6. Computation of fractional feed intake PD(t)

If there are lactating cows, as specified by LAC(t), the next major operation of subroutine COWCYC is to determine the number of lactating cows, SCPOP(t), and their average milk yield, AVMLK(t), for the j^{th} subpopulation. SCPOP(t) is computed using function TABLIE and $PCC_{jk}(t)$ to find the fraction of cows which calved during the n^{th} month, or fraction thereof, in the calving season, $n = 1, \ldots, MOMX \leq TEBC(t)/DM$. $PCC_{jk}(t)$ is the fraction of cows calving in the k^{th} CDIF interval from time BEGCAV to ENDCAV, where CDIF = 0.03846. Thus,

$$SCPOP_{ij}(t) = \sum_{n=1}^{MOMX} CPOP_n(t) = \sum_{n=1}^{MOMX} (CW_n - CW_{n-1})*SUBPOP_{ij}(t) \tag{31}$$

where MOMX is the number of months which have passed within the calving season or the total number of months within the calving season. AVMLK(t) is computed using function TABEXE and $YMILK_k$ to find the average daily milk yields, AMLK(t), at DM intervals during the period TEBC(t) - DM* MOMX to TEBC(t), where $YMILK_k$ is the average daily milk yield for the k^{th} month of lactation. Thus,

$$AVMLK_j(t) = \frac{\sum_{k=1}^{MOMX} AMLK_k(t)*CPOP_k(t)}{SCPOP_j(t)} \tag{32}$$

If $BEGCAV(t) \leq t \leq ENDCAV(t)$, consideration must also be given for the 2-year-old heifers entering cohort 1. Since it is most difficult to determine the distribution of these heifers among the cohort 1 subpopulations, it is assumed that almost all of them are contained in subpopulations 1 and 2 during this time interval. Thus the number in $SUBPOP_{11}(t)$ is estimated as;

$$PROPHF_1(t) = \frac{HEIFC(t)*SUBPOP_{11}(t)}{SUBPOP_{11}(t) + SUBPOP_{12}(t)} \tag{33}$$

and in $SUBPOP_{12}(t)$ as,

$$PROPHF_2(t) = HEIFC(t) - PROPHF_1(t) \tag{34}$$

$$\text{where } HEIFC(t) = \sum_{n=1}^{2} \sum_{k=1}^{KCNT_n} COWNEW_{nk}(t) \tag{35}$$

In this instance, the fraction of heifers calving during the n^{th} month is determined from $PCC_{1k}(t)$, the average fraction of heifers calving in the k^{th} CDIF interval from time BEGCAV to ENDCAV. Thus,

$$SCPOP_j(t) = \sum_{n=1}^{MOMX} CCOW_n(t) + HC_n(t) = \sum_{n=1}^{MOMX} (CW_n - CW_{n-1}) * (SUBPOP_{1j}(t) - PROPHF_j(t)) + (HF_n - HF_{n-1}) * PROPHF_j(t) \tag{36}$$

and $$AVMLK_j(t) = \frac{\sum_{k=1}^{MOMX} AMLK_k(t)*(HC(t)*0.95 + CCOW(t))}{SCPOP_j(t)} \tag{37}$$

Since there is general agreement that lactation stimulates voluntary feed intake (Campling, 1966; Marsh, et al., 1971; Jordan, et al., 1973; and Church and Pond, 1974), a multiplier was derived from the NRC (1970) tables for lactating and dry pregnant cows. It was computed simply by finding the mean increase in dry matter consumption of lactating over dry pregnant cows of the same body weight. This multiplier was computed as 1.4425. Thus for lactating cows,

$$DDMI(t) = PD(t)*1.4425*W_{ij}(t) \tag{38}$$

The actual feed consumption then depends upon the total dry matter allocation per animal, RCPC(t); that is

$$RCPC(t) = CNCPC(t) + RHGPC(t) \tag{39}$$

Although lactating cows will have a higher DDMI(t) than non-lactating cows, the computations for actual intake are similar for the two groups;

if $DDMI(t) \leq RCPC(t)$,

$$DIC(t) = DDMI(t)*\left(\frac{CNCPC(t)}{RCPC(t)}\right) \tag{40}$$

$$DIR(t) = (DDMI(t) - DIC(t))*CFD \tag{41}$$

otherwise,

$$DIC(t) = CNCPC(t) \tag{42}$$

$$DIR(t) = RHGPC(t)*CFD \tag{43}$$

where DIC(t) and DIR(t) are the actual dry matter intakes of concentrates and roughages respectively, and CFD is a correction factor for digestibility of roughages.

The roughage and concentrate dry matter consumed by lactating cows is given by,

$$DIRL_j(t) = DIR(t)*SCPOP_j(t) \tag{44}$$

$$DICL_j(t) = DIC(t)*SCPOP_j(t) \tag{45}$$

and for non-lactating cows,

$$DIRNL_j(t) = DIR(t)*(SUBPOP_{ij}(t) - SCPOP_j(t)) \tag{46}$$

$$DICNL_j(t) = DIC(t)*(SUBPOP_{ij}(t) - SCPOP_j(t)) \tag{47}$$

The average dry matter intake of roughages, $DMIR_j(t)$, and concentrates, $DMIC_j(t)$, then become,

$$DMIR_j(t) = \frac{DIRL_j(t) + DIRNL_j(t)}{SUBPOP_{ij}(t)} \tag{48}$$

$$DMIC_j(t) = \frac{DICL_j(t) + DICNL_j(t)}{SUBPOP_{ij}(t)} \tag{49}$$

Neville and McCullough (1969) have determined the TDN and metabolizable energy (ME) requirements for maintenance, lactation, and gain of lactating and non-lactating beef cows. The results of their study are used in this model to simulate TDN utilization by the cows in cohort 1. Here again there are separate computations for lactating and non-lactating cows.

For lactating cows, the TDN requirements for maintenance, RTM, and lactation, RTL, are;

$$RTM(t) = W_{1j}(t)*0.0108 \tag{50}$$

$$RTL(t) = AVMLK_j(t)*0.3041 \tag{51}$$

The average daily weight change of lactating cows is then;

$$GL_j(t) = \left\{\frac{DIR(t)*TDNR_1(t) + DIC(t)*TDNC_1(t) - RTM(t) - RTL(t)}{2.30}\right\}*SCPOP_j(t) \tag{52}$$

However, for non-lactating cows,

$$RTM(t) = W_{1j}(t)*0.0081 \tag{53}$$

and the weight change becomes,

$$GNL_j(t) = \frac{DIR(t)*TDNR_1(t) + DIC(t)*TDNC_1(t) - RTM(t)}{1.80} * (SUBPOP1_j(t) - SCPOP_j(t)) \tag{54}$$

If $BEGCAV(t) \leq t \leq ENDCAV(t)$, the number of cows calving in the interval $(t,t+dt)$ and the number of cows currently pregnant must be computed. Function TABLIE is used to find the fraction of $SUBPOP_{1j}(t)$ that have calved by time t, CVB, and the fraction that will have calved by time t+dt, CVA, from the values given in $PCC_{jk}(t)$. The daily rate of weight loss due to calving, WLCV(t), for this group of cows is then computed;

$$WLCV_j(t) = \frac{(CVA - CVB)*SUBPOP_{1j}(t)*GGEST*GEST}{DT} \tag{55}$$

During the calving period, the current number of cows pregnant may consist of those which have not yet calved and those which have calved and have been rebred, i.e., where calving and breeding seasons over-lap. Thus, the number of mature cows pregnant, $COWP_j(t)$, is computed;

$$COWP_j(t) = CPNEW_j(t) + OCP_j(t) \tag{56}$$

where $OCP_j(t) = SUBPOP_{1j}(t)*OLDCP_{1j}(t) - SCLAC_j(t)$

$$CPNEW_j(t) = (SUBPOP_{1j}(t) - OCP_j(t))*PCP_{j+1}(t)$$

and SCLAC(t) is the number of mature cows less heifers which are lactating.

The daily gains due to gestation for this group are estimated as,

$$GP_j(t) = COWP_j(t)*GGEST \tag{57}$$

During this time period, separate computations are made for sub-populations 1 and 2 because of the heifers entering cohort 1. Thus the rate of weight loss due to calving becomes;

$$WLCV_j(t) = \frac{(PHCV_j(t) + PCCV_j(t))*GEST*GGEST}{DT} \tag{58}$$

where PHCV and PCCV are the number of heifers and cows in $SUBPOP_{1j}(t)$ that will be calving during the interval (t, t+dt).

The gains due to pregnancy then are;

$$GP_j(t) = (OCP_j(t) + OHP_j(t) + CPNEW_j(t))*GGEST \tag{59}$$

where $OCP_j(t) = \{(SUBPOP_{1j}(t) - PROPHF_j(t))*OLDCP_{1,j+1}(t)\} - SCLAC_j(t)$

$$OHP_j(t) = \{PROPHF_j(t)*OLDCP_{11}(t)\} + SCLAC_j(t) - SCPOP_j(t)$$

$$CPNEW_j(t) = \{SUBPOP_{1j}(t) - OHP_j(t) - OCP_j(t)\}*PCP_{j+1}(t)$$

Outside of the calving period, these computations are simply;

$$WLCV_j(t) = 0.0,$$

$$COWP_j(t) = PCP_{j+1}(t)*SUBPOP_{1j}(t), \tag{60}$$

$$GP_j(t) = GGEST*COWP_j(t) \tag{61}$$

The average daily weight change, $DGAIN_{1j}(t)$, over the time interval $(t, t+dt)$ for the j^{th} subpopulation of cohort 1 is then computed;

$$DGAIN_{1j}(t) = \frac{GL_j(t) + GNL_j(t) + GP_j(t) - WLCV_j(t)}{SUBPOP1_j(t)} \quad (62)$$

The final computations made by subroutine COWCYC are to summarize the feed consumed by the cohort and the current reproductive status. The total roughage and total concentrate dry matter consumed over the interval $(t, t+dt)$ are given by;

$$TDMIR_i(t) = \sum_{j=1}^{KK_i} DMIR_j(t)*DAYS*SUBPOP_{ij}(t) \quad (63)$$

and
$$TDMIC_i(t) = \sum_{j=1}^{KK_i} DMIC_j(t)*DAYS*SUBPOP_{ij}(t) \quad (64)$$

The roughage and concentrate TDN consumption are given by;

$$RTDN_i(t) = TDMIR_i(t)*TDNR_i(t) \quad (65)$$

and
$$CTDN_i(t) = TDMIC_i(t)*TDNC_i(t) \quad (66)$$

The current fractions of pregnant and lactating mature cows are computed;

$$CURPRG1(t) = \frac{\sum_{j=1}^{KK1} COWP_j(t)}{POP1(t) - HEIFC(t)} \quad (67)$$

$$CURLAC1(t) = \frac{\sum_{j=1}^{KK1} SCLAC_j(t)}{POP1(t) - HEIFC(t)} \quad (68)$$

Subroutine COWCYC thus describes the utilization of energy by mature cows of a given reproductive status; accounting for cows which are pregnant or open, lactating or non-lactating. The structure of this subroutine is illustrated by Figure 7.

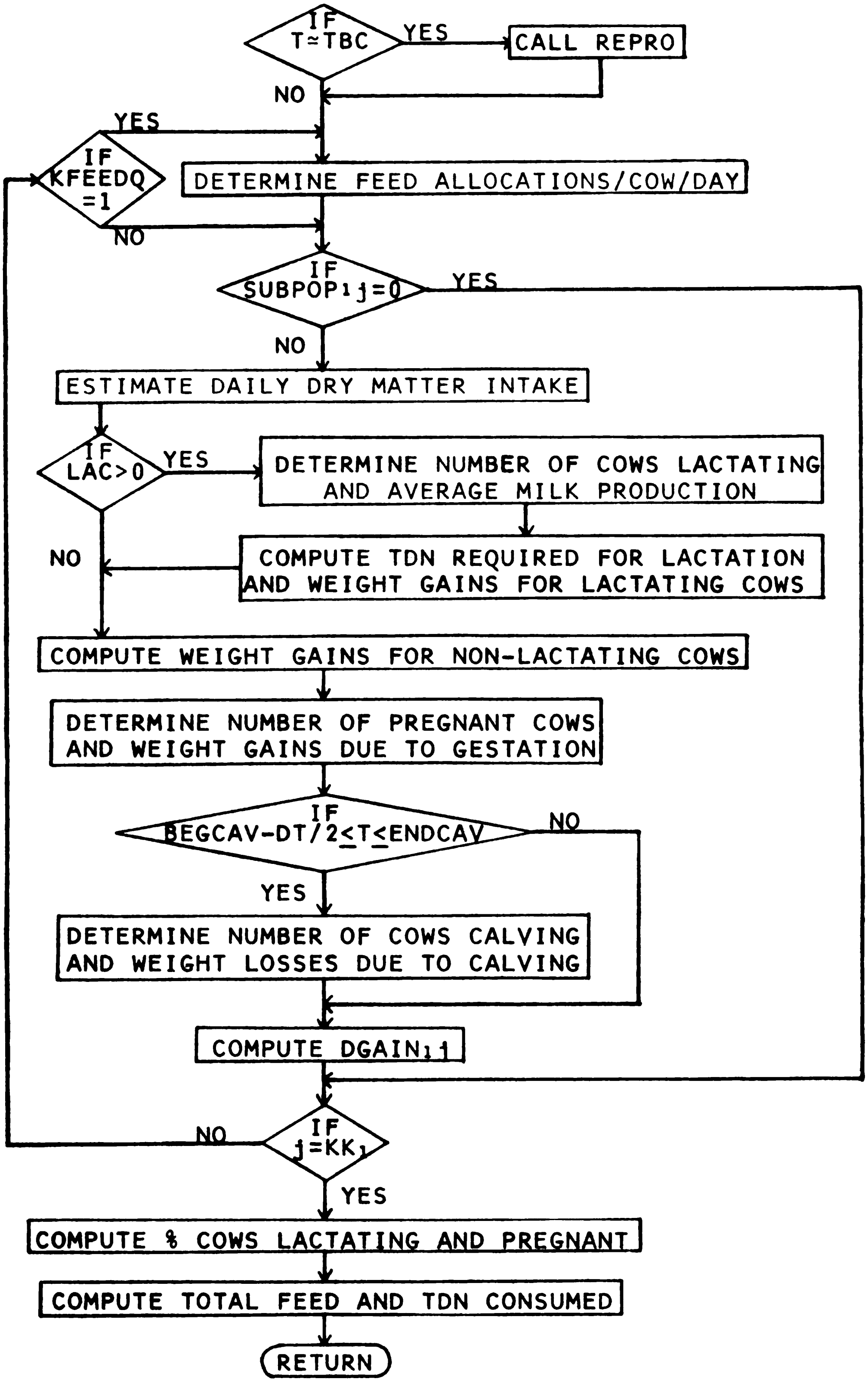

Figure 7. Flowchart of subroutine COWCYC

GROFEM is a subroutine which computes feed intake and energy utilization by heifers. It also computes age and weight at first estrus as well as the changes in feed intake and utilization, and weight changes resulting from changes in reproductive status. This subroutine considers the following heifer cohorts;

$POP_8(t)$ = female calves,

$POP_9(t)$ = market heifers,

$POP_2(t)$ = replacement heifers,

$POP_3(t)$ = bred heifers,

from the time of birth until two years of age.

The roughage and concentrate allocations per heifer per day, RHGPC(t) and CNCPC(t), are computed in the same manner as described for cows in subroutine COWCYC, equations (25) - (28). In contrast to subroutine COWCYC, where feed utilization and weight gains are based upon TDN intake, subroutine GROFEM uses the California net energy system developed by Lofgreen and Garrett (1968). Although this system may prove less accurate in estimating gains for bulls, light-weight cattle, or animals in a severe environment, it appears to be more desirable than the TDN and ME systems (Dickie, et al., 1973; Knox and Handley, 1973; and N.R.C., 1976).

Since the energy value of feeds is inputted in terms of TDN, subroutine CNVRT is called to convert it into net energy available for maintenance (NE_m^a), and net energy available for gain (NE_g^a) in terms of Mcal/kg dry matter of feed. This subroutine is a computerized version of the equations given by Lofgreen and Garrett (1968) and the N.R.C. (1976), and therefore become;

$$ME = TDN*3.6155 \tag{69}$$

$$FL = 2.2577 - 0.2213*ME$$

$$F = 10^{FL}$$

$$EM = 77/F$$

$$EG = 2.54 - 0.0314*F$$

where ME is the metabolizable energy in Mcal/kg dry matter; F is the grams of dry matter per unit of $W_{ij}(t)^{.75}$ required to maintain energy equilibrium; and EM and EG are NE_m^a and NE_g^a respectively. Thus, $TDNR_i(t)$ becomes $EMAR_i(t)$ and $EGAR_i(t)$ - net energy available for maintenance from roughages, and net energy available for gain from roughages - and similarly, $TDNC_i(t)$ becomes $EMAC_i(t)$ and $EGAC_i(t)$.

There is no information available regarding the voluntary intake of, and the preference for, milk, roughages, or concentrates by the beef calf prior to weaning. Crampton and Harris (1969) imply that the rumen of the very young dairy calf is not fully developed until about four months of age, although Sims, et al.(1975) have noted beef calves consuming forage during the second month after parturition. For this model, it has therefore been assumed that the calf will consume only its dam's milk until it is TAMD = 0.15 years of age, after which it will consume both milk and roughages and/or concentrates with a preference for milk until weaning.

Although young, rapidly growing cattle consume more feed per unit of size than adult cattle (Church and Pond, 1974), specific estimates of dry matter consumption by the unweaned calf are lacking in the literature. Fox (personal communication) has given a "rule of thumb" estimate of DMX = 0.095 kg dry matter/kg $W_{8j}(t)^{.75}$. From preliminary simulation trials and the dairy calf feeding schedule suggested by Crampton and Harris (1969), this figure overestimates intake for calves on the all-milk diet. This problem was solved by using the Beltsville growth standards for Holstein heifer calves (U.S.D.A., 1954) to derive an equation which computes the maximum dry matter intake of calves on an all-milk diet. The Beltsville standards contain estimated body weights and daily gains at ten-day intervals from birth to one year of age; only data up to 60 days of age was used for this equation. Fresh cow's milk contains 130% TDN on a 100% dry matter basis (Crampton and Harris, 1969) which converts to a NE_m^a value of 4.6659 Mcal/ kg dry matter and a NE_g^a value of 2.0218 Mcal/kg dry matter. The equations,

$$NE_m^r = 0.077*W^{.75}*0.93, \tag{70}$$

and $$NE_g^r = (0.05603*gain + 0.01265*gain^2)*W^{.75}*0.93 \tag{71}$$

give the daily net energy required for maintenance at a given weight, NE_m^r, and the net energy required to achieve a given rate of gain at a given weight, NE_g^r, for growing heifers (N.R.C., 1970). The multiplier 0.93 is used to adjust NE requirements when no growth stimulants are used (Fox and Black, unpublished report) as is the case throughout this model.

The estimated dry matter intake of milk required to achieve the gains of the Beltsville standards were thus computed;

$$DMM = \frac{NE_m^r}{NE_m^a} + \frac{NE_g^r}{NE_g^a} \tag{72}$$

Since the resulting DMM values were not proportional to $W^{.75}$, another factor TSC(t), age of the animal in years, is included to increase the accuracy of prediction. The equation for the expected milk intake, EMINT(t), is therefore of the form;

$$EMINT(t) = \alpha * W(t)^{.75} + TSC(t) * \beta .$$

The term α is solved by substituting the computed DMM value for the Holstein heifer, where the estimated birth weight is 42.5 kg and the estimated average daily gain is 0.27 kg. Thus,

$$0.376 \text{ kg DMM} = \alpha * 16.6 \tag{73}$$

and $$\alpha = 0.022603$$

And β is solved using all subsequent age groups, i.e., where TSC(t) > 0. Thus,

$$\beta = \frac{\sum_{i=1}^{n} \left(\frac{DMM_i - \alpha * W_i^{.75}}{TSC_i} \right)}{n} = 2.115 \tag{74}$$

where n is the number of age groups included. In computer form,the equation becomes;

$$EMINT_j(t) = 0.022603 * WM8_j(t) + 2.115 * TSC_j(t) \tag{75}$$

where $WM8_j(t) = W8_j(t)^{.75}$.

The average daily milk available to the calves in cohort 8, MLK, is computed with function TABEXE using the milk yields $YMILK_k$ and the value $TSC_j(t)$. The value of MLK on a 100% dry matter basis is,

$$DMMLK(t) = MLK * 0.12 \tag{76}$$

where 0.12 is the fraction of dry matter per kilogram of milk (Crampton and Harris, 1969). For calves where $TSC_j(t) \leq TAMD$, is true, $DMMLK(t) \leq EMINT(t)$ is also true.

However for calves where $TSC_j(t) > TAMD$, DMMLK(t) remains as computed in equation (76) and the maximum dry matter intake, DMI(t), is computed;

$$DMI_j(t) = DMX*WM_{ij}(t) \tag{77}$$

It follows that if $RCPC_j(t) > (DMI_j(t) - DMMLK_j(t))$,

then $$DMIR_j(t) = RHGPC_j(t)*CFD*\left(\frac{DMI_j(t) - DMMLK_j(t)}{RCPC_j(t)}\right) \tag{78}$$

and $$DMIC_j(t) = CNCPC_j(t)*\left(\frac{DMI_j(t) - DMMLK_j(t)}{RCPC_j(t)}\right) \tag{79}$$

Otherwise,

$$DMIR_j(t) = RHGPC_j(t)*CFD \tag{80}$$

and $$DMIC_j(t) = CNCPC_j(t) \tag{81}$$

There is a set of equations common to all of the cohorts in subroutine GROFEM which compute the total net energy available for gain. The amount of feed required for maintenance is computed;

$$FM_{ij}(t) = \frac{0.077*WM_{ij}(t)*DI_{ij}(t)}{(EMAR_{ij}(t)*DMIR_{ij}(t) + EMAC_{ij}(t)*DMIC_{ij}(t))*CFE} \tag{81}$$

and the total net energy available for gain is;

$$EG_{ij}(t) = \left(\frac{EGAR_{ij}(t)*DMIR_{ij}(t) + EGAC_{ij}(t)*DMIC_{ij}(t)}{DI_{ij}(t)}\right)* (DI_{ij}(t) - FM_{ij}(t))*CFE \tag{82}$$

where $DI_{ij}(t) = DMIR_{ij}(t) + DMIC_{ij}(t)$ (83)

CFE = 0.93, the adjustment factor for when no growth stimulants are used.

For cohort 8, these equations are adjusted to include the consumption of milk. Where calves consume roughages, concentrates and milk, equation

(81) has $EMAM_j(t)*DMMLK_j(t)$ added to the denominator, equation (82) has $EGAM_j(t)*DMMLK_j(t)$ added to the numerator, and equation (83) has $DMMLK_j(t)$ added to the right-hand side terms. However, where only milk is consumed the equations become;

$$FM8_j(t) = \frac{0.077*WM8_j(t)}{EMAM8_j(t)*CFE} \tag{84}$$

and

$$EG8_j(t) = EGAM8_j(t)*CFE*(DMMLK8_j(t) - FM8_j(t)) \tag{85}$$

where EMAM and EGAM are NE_m^a and NE_g^a for milk respectively.

In either case,

$$\text{if} \quad \left.\begin{matrix} DMMLK8_j(t) \\ DI8_j(t) \end{matrix}\right\} < FM8_j(t),$$

then $EG8_j(t) < 0$.

That is, if the total dry matter intake is less than that required for body maintenance, the animal will make-up the difference by drawing upon body reserves and therefore lose weight.

The equations which determine average daily gain, $DGAIN_{ij}(t)$, over the time interval (t, t+dt) for heifers are;

$$A = 0.003139 + \left(\frac{0.0506*EG_{ij}(t)}{WM_{ij}(t)}\right) \tag{86}$$

and

$$DGAIN_{ij}(t) = \frac{A^{.5} - 0.05603}{0.0253} \tag{87}$$

As such, these equations from N.R.C. (1970) assume that all weight gains will be positive. Since this model is as much concerned with weight losses as gains, a guided assumption has been made that the energetics of weight loss are the same as those of weight gain (Ullrey, personal communication).

Thus where $EG_{ij}(t)$ is negative, its absolute value must be used in equation (86), and the quotient of equation (87) must be multiplied by (-1) to prevent a computer mode error.

Total feed and TDN consumption of each heifer cohort for the time interval (t, t+dt) is computed as in equations (63) - (66) in subroutine COWCYC.

Cohort 9, market heifers, is physiologically a homogeneous group which simplifies the modeling of feed intake and utilization. As in subroutine COWCYC, maximum dry matter intake is linearly extrapolated from the PDI_k values and computed by equation (30) as;

$$DDMI_{ij}(t) = PD_{ij}(t) * W_{ij}(t) \tag{30}$$

Actual dry matter intake is then computed,

if $DDMI_{ij}(t) \leq RCPC_{ij}(t)$,

$$DMIC_{ij}(t) = DDMI_{ij}(t) * \frac{CNCPC_{ij}(t)}{RCPC_{ij}(t)} \tag{88}$$

$$DMIR_{ij}(t) = (DDMI_{ij}(t) - DMIC_{ij}(t)) * CFD \tag{89}$$

otherwise,

$$DMIC_{ij}(t) = CNCPC_{ij}(t) \tag{90}$$

$$DMIR_{ij}(t) = RHGPC_{ij}(t) * CFD \tag{91}$$

The remaining computations are described by equations (81) - (83), (86), (87), and (63) - (66).

The computations for replacement and bred heifers, cohorts 2 and 3, contain the same basic equations as described for cohort 9, but are complicated by reproductive functions. In this model, the only major difference between the two cohorts is age groupings. However, within each cohort, the population is potentially very heterogeneous in terms of physiological function. As previously mentioned, during the time interval from TW to ENDCAV, there are usually two distinct groups of heifers in each cohort, the recently weaned, rapidly growing heifers and the older pregnant heifers. In addition, during the period BEGCAV to ENDCAV there may be older heifers which are pregnant and non-lactating, non-pregnant and lactating, or non-pregnant and non-lactating. The subroutine must account for all of these groups when computing feed utilization and weight changes.

If there are any older heifers which are lactating, LAC(t) = 1, the number that are lactating, SCPOP(t), and the additional energy required for maintenance and milk production must be computed. As in subroutine COWCYC, the average daily milk yield, $AMLK_k(t)$, for the group of heifers, $CPOP_k(t)$, which calved during the k^{th} month of the calving season, k = 1, . . ., $MOMX \leq TEBC(t)/DM$, is linearly extrapolated by function TABEXE from $YMILK_n$. $SCPOP_j(t)$ and $CPOP_k(t)$ are determined as in equation (31) except that values are linearly interpolated from $PHC_{ijk}(t)$, the fraction of the j^{th} subpopulation of heifer cohort i calving during the k^{th} CDIF interval from BEGCAV to ENDCAV.

As with lactating mature cows, the maximum dry matter intake, DDMI(t), is increased by the multiplier 1.4425 - see equation (38). The actual dry matter intake of roughages and concentrates is then computed as in equations (40) - (45). The average net energy required for lactation is given by;

$$AEL_{ij}(t) = \frac{ELAC_{ij}(t) + EML_{ij}(t)}{SUBPOP_{ij}(t)} \tag{92}$$

where

$$ELAC_{ij}(t) = 0.690* \sum_{k=1}^{MOMX} AMLK_k(t)*CPOP_k(t)*0.95 \tag{93}$$

$$EML_{ij}(t) = WM_{ij}(t)*0.024*SCPOP_{ij}(t) \tag{94}$$

In equation (93), the value 0.690 is the amount of net energy in Mcal required to produce one kilogram of milk containing 3.5% fat. This value was taken from a table of nutrient requirements for milk production given by Foley, et al. (1972) and is approximately equal to the 0.3041 kg TDN/kg milk given by Neville and McCullough (1969).

The value 0.024 used in equation (94) is the additional Mcal per kilogram WM of net energy required for maintenance of lactating heifers. It was derived by computing the NE_m that would be required for a lactating heifer using the equations of Neville and McCullough (1969) given weight and TDN, and comparing it with the NE_m required by a non-lactating heifer using equation (70), given the same weight and TDN values. The resulting term is an average of several comparisons.

The maximum and actual feed intakes for non-lactating heifers are computed by equations (30), (40) - (43), (46), and (47). The average dry matter intakes of roughages and concentrates for the subpopulation are then given by equations (48) and (49).

If there are any pregnant heifers and if the calving season has begun, weight changes due to pregnancy and calving must be determined. The number of heifers pregnant within a given subpopulation at a given time is determined according to the current stage of the herd reproductive cycle and the age group of the subpopulation. During the heifer breeding season, the number of animals pregnant is determined by the average times that estrus periods occur during the breeding season, $PT_{ijk}(t)$, and the fraction of heifers, $HP_{ijk}(t)$, that are pregnant following the k^{th} estrus period. The underlying assumption is that with each successive estrus period that the cow is exposed to a bull or bred by artificial insemination (A.I.), the greater the probability that she will become pregnant. Thus on a group basis, this means an increasing percentage of pregnant cows as the number of exposures increases.

From the end of the breeding season until BEGCAV, the fraction of heifers pregnant in the j^{th} subpopulation is the last value entered in $HP_{ijk}(t)$ as designated by the counter $ICOUNT_{ij}(t)$. Thus the fractional gain due to pregnancy prior to calving is determined by;

$$GP_{ij}(t) = GGEST*HP_{ijk}(t) \tag{95}$$

During the calving period, the number of older heifers that are still pregnant and have not merged into cohort 1 is computed;

$$COWP_{ij}(t) = OLDCP_{ij}(t)*SUBPOP_{ij}(t) - SCPOP_{ij}(t) \tag{96}$$

and the fractional gain due to pregnancy is;

$$GP_{ij}(t) = \frac{GGEST*COWP_{ij}(t)}{SUBPOP_{ij}(t)} \tag{97}$$

The fraction of older heifers calving in the time interval (t, t+dt) is estimated by differencing the fractions HFB and HFA that will have calved by time t and t+dt as determined by function TABLIE from the values of $PHC_{ijk}(t)$. The fractional rate of weight loss due to calving is then

$$WLCV_{ij}(t) = \frac{(HFA_{ij}(t) - HFB_{ij}(t))*GGEST*GEST}{DT} \tag{98}$$

Because of these reproductive functions, the equations which determine energy utilization by the subpopulations in cohorts 2 and 3 vary somewhat from those previously described. The feed required for maintenance is computed;

$$FM_{ij}(t) = \frac{(0.077*WM_{ij}(t) + AEL_{ij}(t))*DI_{ij}(t)}{(EMAR_{ij}(t)*DMIR_{ij}(t) + EMAC_{ij}(t)*DMIC_{ij}(t))*CFE} \tag{99}$$

whereas the energy available for gain, $EG_{ij}(t)$, is determined as in equation (82). The average daily gain then becomes;

$$DGAIN_{ij}(t) = \frac{A^{.5} - 0.05603}{0.0253} + GP_{ij}(t) - WLCV_{ij}(t) \tag{100}$$

where the value of A is determined by equation (86).

As previously mentioned, the current reproductive status of heifers is tracked until they have completed their first calving season. The heifers which have reached 2 years of age and merged into cohort 1 are saved by subpopulation in $COWNEW_{ik}(t)$. When the number of subpopulations which have merged is known, $KCNT_i(t)$, the number of these heifers which are lactating can be computed;

$$SCPOP_{ik}(t) = \sum_{n=1}^{MOMX} (OHF_n - OHF_{n-1})*COWNEW_{ik}(t) \tag{101}$$

where the OHF values are linearly interpolated from $PHC_{ijk}(t)$ at DM intervals. The number of two-year old heifers pregnant prior to calving is;

$$COWP_{ik}(t) = HP_{ikn}(t)*COWNEW_{ik}(t) \tag{102}$$

and those still pregnant during calving are computed;

$$COWP_{ik}(t) = OLDCP_{ik}(t)*COWNEW_{ik}(t) - SCPOP_{ik}(t) \tag{103}$$

Thus for the entire cohort, the fractions of heifers that have been bred and are pregnant, $CURPRG_i(t)$, and lactating, $CURLAC_i(t)$, are computed;

$$CURPRG_i(t) = \frac{\sum_{j=1}^{KK_i}(COWP_{ij}(t) + HP_{ijk}(t)*SUBPOP_{ij}(t)) + \sum_{k=1}^{KCNT_i} COWP_{ik}(t)}{HSUM_i(t) + SCNEW_i(t)} \tag{104}$$

$$CURLAC_i(t) = \frac{\sum_{j=1}^{KK_i} SCPOP_{ij}(t) + \sum_{k=1}^{KCNT_i} SCPOP_{ik}(t)}{HSUM_i(t) + SCNEW_i(t)} \tag{105}$$

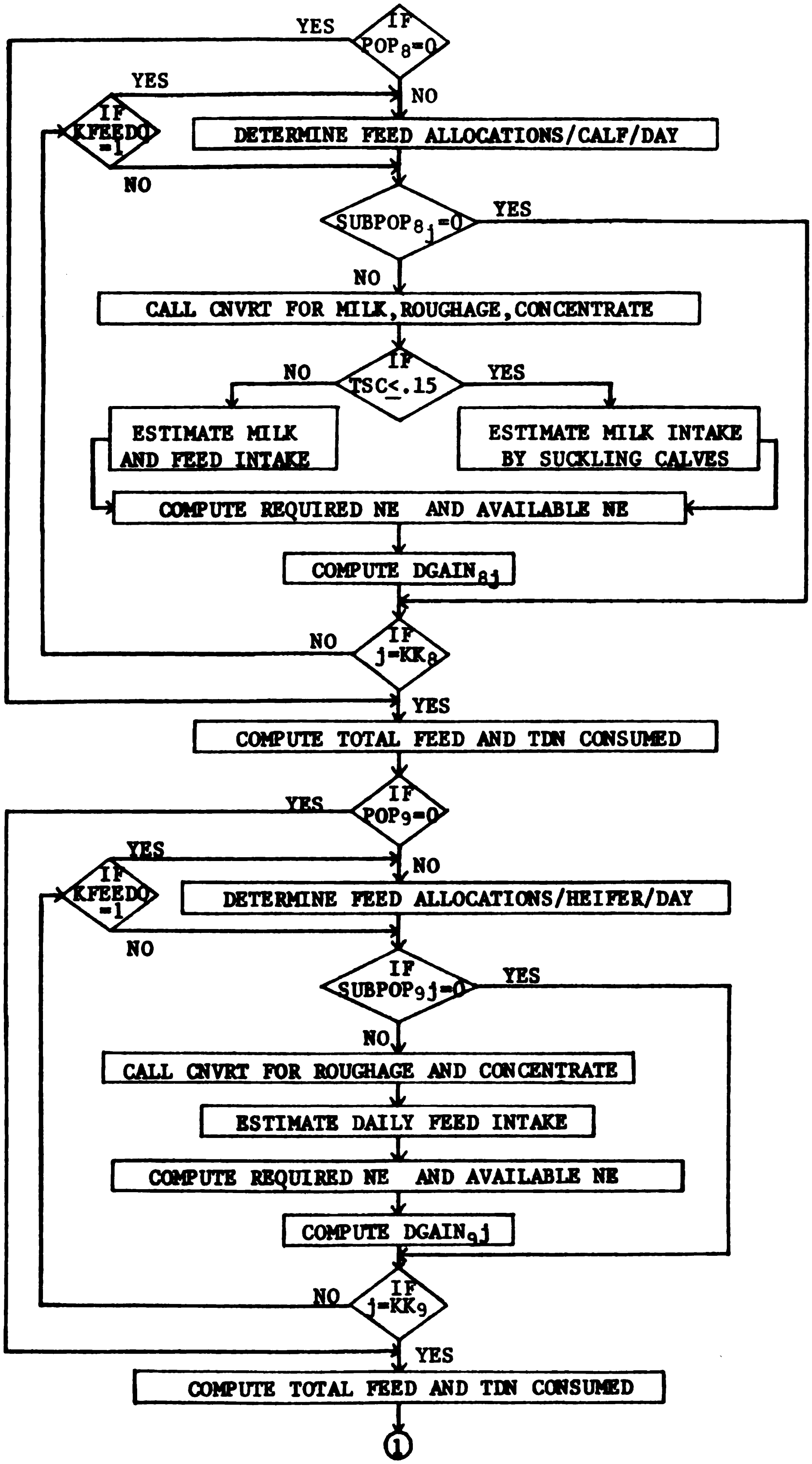

Figure 8. Flowchart of subroutine GROFEM

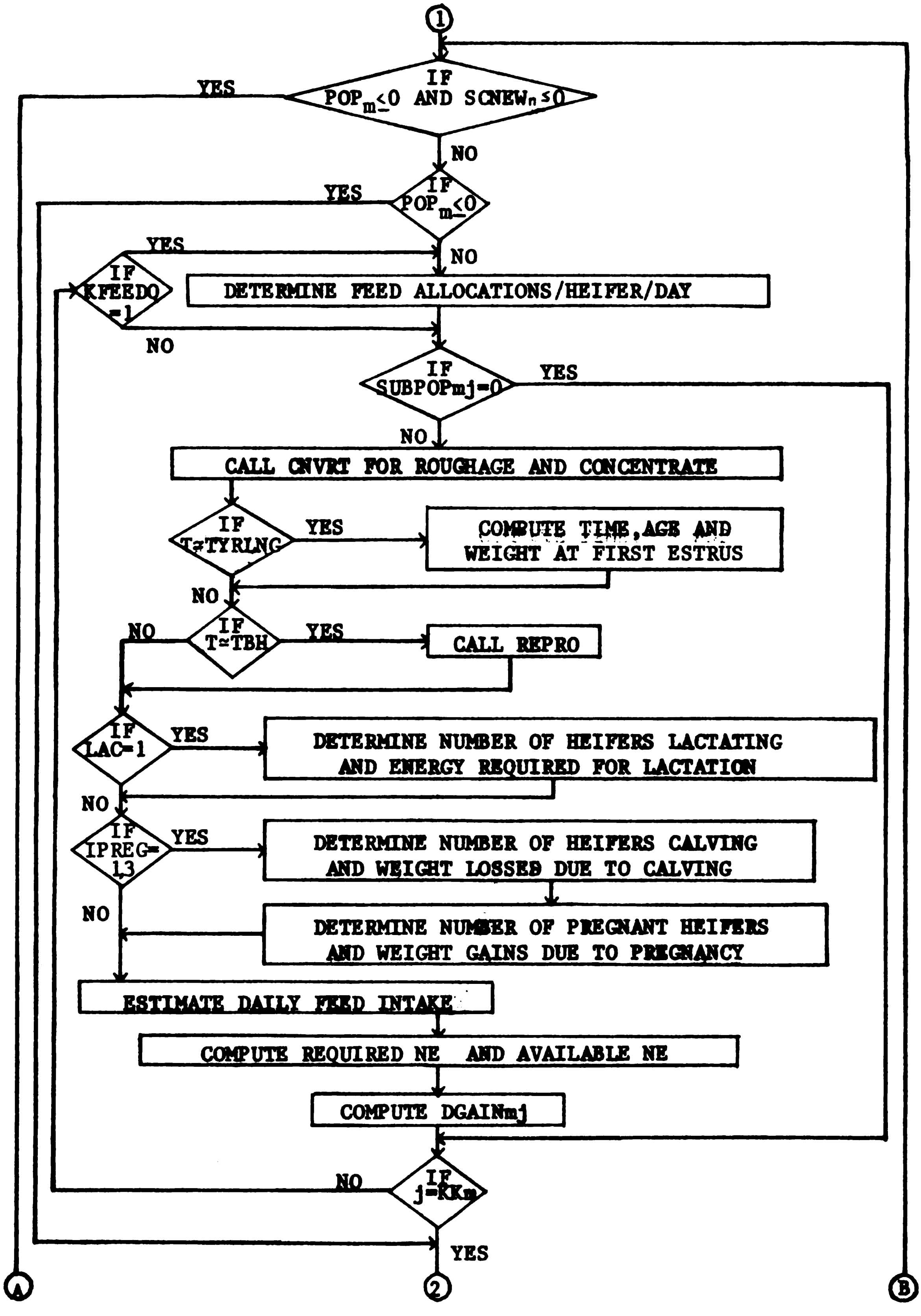

Figure 8 (cont'd.).

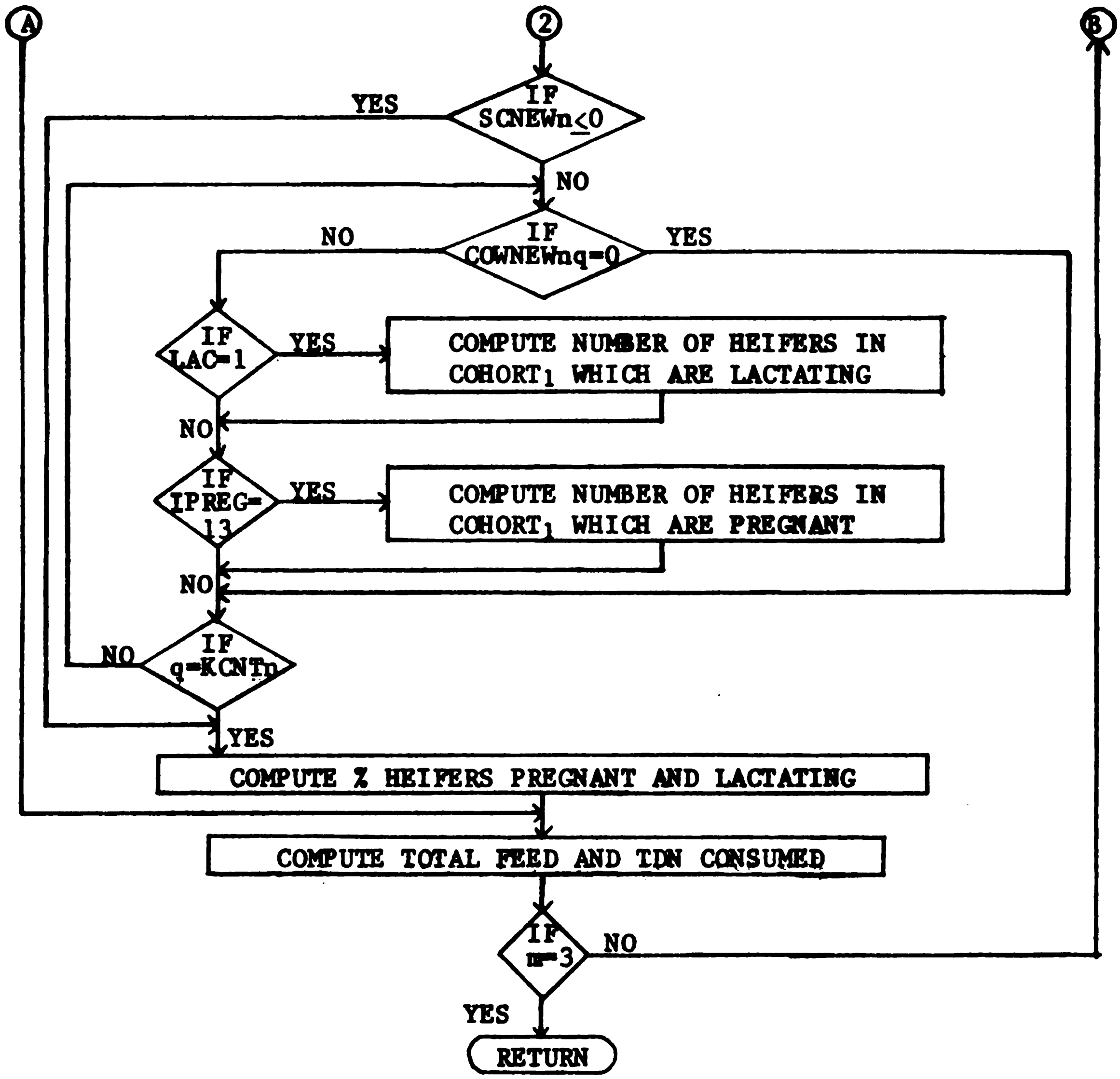

Figure 8 (cont'd.).

where, $HSUM_i(t)$ = total number of heifers currently in cohort i which have been bred;

$SCNEW_i(t)$ = the total number of 2-year old heifers from cohort i which have merged into cohort 1.

Subroutine GROFEM is, therefore, a relatively detailed subroutine, as illustrated in Figure 8, which describes feed intake and energy utilization, age and weight at puberty, and reproductive status where appropriate for heifer calves, market heifers, bred heifers, and replacement heifers.

Subroutine GROMAL simulates feed intake and utilization for the four male cohorts;

$POP4(t)$ = mature bulls,

$POP5(t)$ = young bulls,

$POP6(t)$ = steers,

$POP7(t)$ = male calves.

This subroutine is much like the first two sections of subroutine GROFEM which describe the nutrition of heifer calves, cohort 8, and market heifers, cohort 9. Because of this, only the aspects in which the two subroutines differ will be discussed in this section. The reader is referred to equations (69), (75) - (85), and (63) - (66) with regard to cohort 7, and to equations (69), (30), (81) - (83), (88) - (91), and (63) - (66) for cohorts 4, 5, and 6.

Because of differences in the growth rates and the utilization of NE_g^a, the equations which compute $DGAIN_{ij}(t)$ require a different set of constants. Taken from N.R.C. (1970) these become;

$$B = 0.002779 + \frac{0.02736*EG_{ij}(t)}{WM_{ij}(t)} \tag{106}$$

$$DGAIN_{ij}(t) = \frac{B^{.5} - 0.05272}{0.01368} \quad (107)$$

where $EG_{ij}(t)$ is the total net energy available for gain, and $WM_{ij}(t)$ is the metabolic weight or $W_{ij}(t)^{.75}$.

Since the California net energy system was developed from studies on growing heifers and steers (Lofgreen and Garrett, 1968), the use of this system for predicting weight gains of bulls without appropriate adjustments may well give inaccurate predictions. Indeed, since bulls make faster and more efficient gains than steers (Hedrick, 1968; and Dickie, et al., 1973), it was deemed necessary to develop a crude adjustment factor for use in this model.

This factor was developed by comparing predicted steer gains with those given by N.R.C. (1970) for bulls of the same weight and TDN intake. Considering the differences in net energy requirements and the probability that as a bull approaches mature weight his gains will contain an increasing proportion of fat, the following equations compute the correction factor for bulls, CFM(t);

$$CFF_{ij}(t) = \frac{2.25 * W_{ij}(t)}{WMAT} \leq 2.25 \quad (108)$$

$$CFM_{ij}(t) = \frac{CFB * CFF_{ij}(t)}{WM_{ij}(t)} \quad (109)$$

where CFF is the correction factor for fat deposition,

WMAT is the mature weight of bulls, and

CFB is the derived constant 77.348.

The term $CFM_{ij}(t)$ is then substituted for CFE in equations (81) and (82). the final value of $DGAIN_{ij}(t)$ is also adjusted by dividing by a factor of $CFF_{ij}(t)^{.5}$.

Since the male reproductive processes and requirements have been

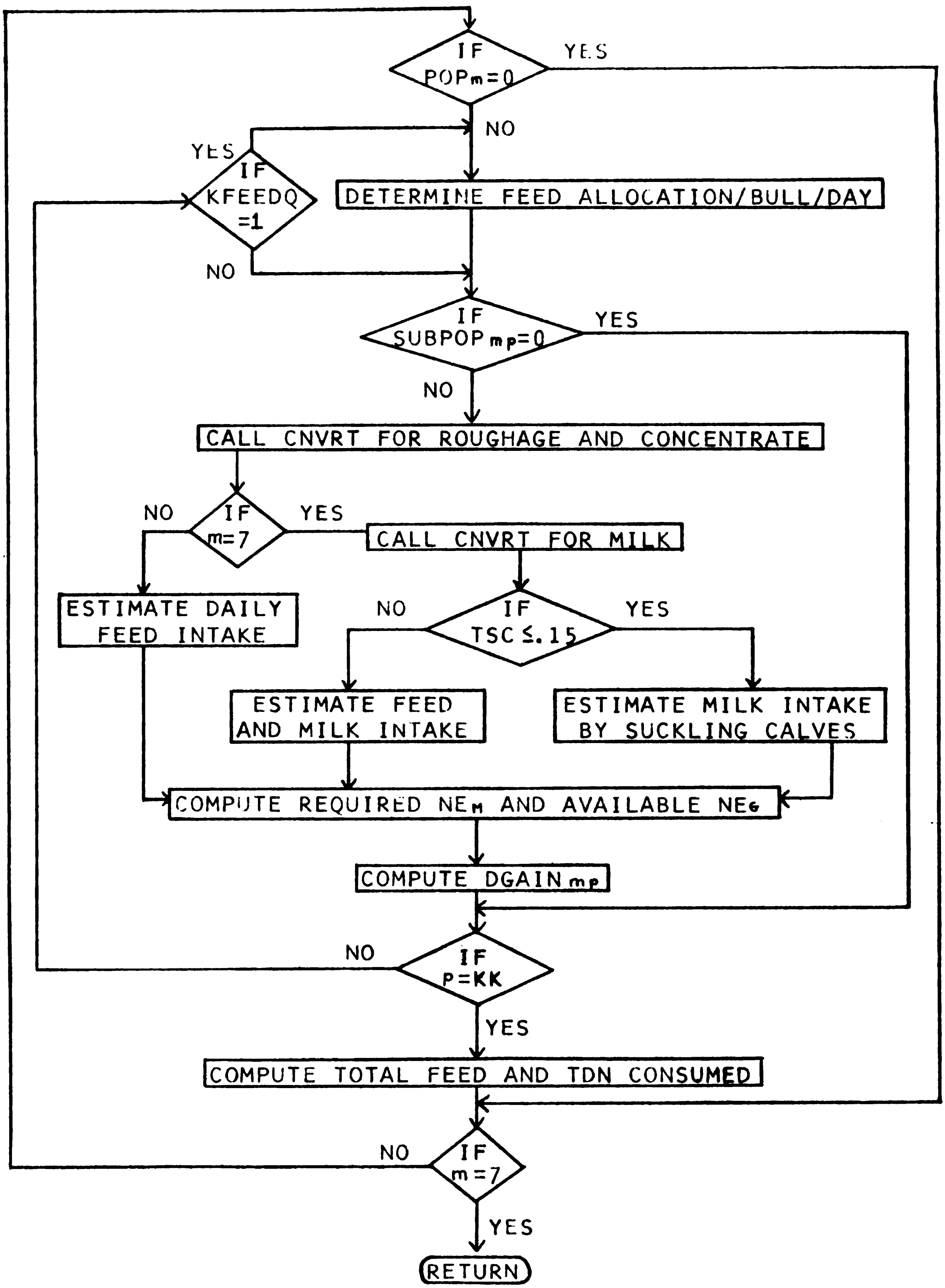

Figure 9. Flowchart of subroutine GROMAL

excluded from this model, the computations for feed intake and utilization have remained relatively simple for all of the male cohorts as shown in Figure 9.

This concludes the description of the nutrition dynamics component of the model. Although it is by far the largest component of the model, it is complete only in the sense that it considers the feed intake and energy requirements of all age groups and function classes of beef cattle.

Reproduction dynamics

Reproduction dynamics consists of four subroutines, AWPUB, REPRO, MGMT, and ALAC. Together they compute the age and weight of heifers at puberty, time of first postpartum estrus, pregnancy rates, calving rates, and time of calving for each female subpopulation as appropriate.

At time TW(t), a given fraction of heifer calves are weaned and are transferred to cohort 2 or 3 in such a way as to retain age and subpopulation groupings. When the average age of this group is one year, i.e. t = TYRLNG, the average age and weight at puberty for each subpopulation is computed by subroutine AWPUB.

Arije and Wiltbank (1974) developed a set of equations which predict age and weight at puberty for British-breed beef heifers. These equations were based upon spring calving and require birth date, weaning weight, and average daily gain from weaning until spring pasturing. Using the equations in this form would severely limit model usage in terms of herd management policies. Since the heifers would be about one year of age at the time of spring pasturing, the average daily gain from weaning until the calves are an average of one year of age was substituted into the equations. This allows for calving to take place at any desired time of the year.

Subroutine AWPUB is called by GROFEM at time TYRLNG(t) to compute age at first estrus, $AFEST_{ij}(t)$, and weight at first estrus, $WFEST_{ij}(t)$. It consists of the following equations;

$$AFEST_{ij}(t) = 631 + 0.12*BTH_{ij}(t) - 0.58*WEANWT_{ij}(t) + 724*|ADGWS_{ij}(t)|^2 - 717*ADGWS_{ij}(t) \quad (110)$$

$$WFEST_{ij}(t) = 111 + 0.60*BTH_{ij}(t) + 0.66*WEANWT_{ij}(t) + 331*|ADGWS_{ij}(t)|^2 - 202*ADGWS_{ij}(t) \quad (111)$$

where $BTH_{ij}(t) = \{TBRTH_{ij}(t) - int(TBRTH_{ij}(t))\}*365$;

$TBRTH_{ij}(t)$ = the average time (years) of birth of the j^{th} subpopulation of cohort i, i = 2,3;

$WEANWT_{ij}(t)$ = the average weaning weight of the j^{th} subpopulation of cohort i;

$ADGWS_{ij}(t)$ = the average daily gain from time TW(t) to TYRLNG(t) of the j^{th} subpopulation of cohort i.

Then $FEST_{ij}(t) = AFEST_{ij}(t) + TBRTH_{ij}(t)$ (112)

is the average time in the year that first estrus takes place for the j^{th} subpopulation of cohort 2 or 3.

Subroutine REPRO is called by subroutine COWCYC at time $TBRD_1(t)$, and by GROFEM at time $TBRD_2(t)$ in the current year to compute the time of first postpartum estrus, $TEST_{ij}(t)$; the fraction of females calving, $CPAT_{ijk}(t)$, by time $CTIM_{ijk}(t)$ as a result of conception in the k^{th} estrus of the breeding season; the fraction of heifers pregnant, $HP_{ijk}(t)$, following the k^{th} estrus at time $PT_{ijk}(t)$ in the breeding period; the fraction of mature cows, $PCP_j(t)$, becoming pregnant during the breeding season; and the weighting factors, $WF_j(t)$, to account for population shift in cohort 1 from the time of breeding until calving.

The subroutine must first estimate the average time of first postpartum estrus for each subpopulation of cohort 1. In studies of the effects of pre- and post-calving energy intake upon reproductive performance of mature cows and heifers, Wiltbank, et al. (1962) and Dunn, et al.(1969) found that the pre-calving level of energy had the greater influence upon postpartum estrus, especially in the early post-calving period. With this information and the data presented in the studies, a set of equations was derived to estimate $TEST_{1j}(t)$.

The data referred to above show that low energy levels delay the onset of postpartum estrus; the lower the energy level, the longer the delay with apparent decreasing predictability. Postpartum body condition, $PPW_{1j}(t)$, is used to indicate the pre-calving energy effects and is used in the linear interpolation function TABLI (Llewellyn, 1965) to determine the general time delay to estrus, DP(t). That is, if an animal is in good condition, $PPW_{1j}(t) \geq 0.95$, then DP(t) = 0.0959 years, whereas if an animal is in extremely poor condition, $PPW_{1j}(t) \leq 0.69$, then DP(t) = 0.548 years. The only stochastic element of the model is used here to simulate the decrease in predictability. A random number R(t) between zero (0) and one (1) is chosen by the computer and used as follows to compute the random factor, RANDF(t);

$$RANDF_{1j}(t) = 1 + R(t)*0.2*(1 - PPW_{1j}(t)) \qquad (113)$$

The average time of estrus is then estimated as;

$$TEST_{1j}(t) = (CTIM_{1,j-1,1}(t-dt) + DEST + DP_{1j}(t))*RANDF_{1j}(t) \qquad (114)$$

where $CTIM_{1,j-1,1}(t-dt)$ is the time at which the first fraction of cows in the j^{th} subpopulation calved in the recent calving season. Even though the majority of pregnant cows will have calved in the second time period, the equivalent time $CTIM_{1,j-1,1}(t-dt) + DEST$, where DEST is the duration of the estrous cycle, is used in the event that first postpartum estrus in the previous year was delayed such that only one estrus period occurred during the breeding period resulting in only one value for $CPAT_{ijk}(t-1)$ and $CTIM_{ijk}(t-1)$.

For the first-calf heifers which have recently entered cohort 1 it is necessary to average the old $CTIM_{ij1}(t-1)$ values from cohorts 2 and 3 and to substitute this average for $CTIM_{1,j-1,1}(t-dt)$ in equation (114).

The $TEST_{ij}(t)$ values for cohorts 2 and 3 are taken from the previously computed $FEST_{ij}(t)$ values.

After $TEST_{ij}(t)$ is determined, the time of first estrus, TFSRV(t), and the number of estrus periods, $INB_{ij}(t)$, within the breeding period $TBRD_k(t)$ to $TBRD_k(t) + DURB_k(t)$ must be computed for each subpopulation in cohorts 1, 2, and 3. Thus,

if $DIF = TBRD_k(t) - TEST_{ij}(t)$, and

$$\text{if } DIF \begin{cases} < 0, & TFSRV_{ij}(t) = TEST_{ij}(t) \\ \geq 0, & TFSRV_{ij}(t) = TEST_{ij}(t) + DEST*(\text{int}\frac{DIF}{DEST} + 1) \end{cases} \tag{115}$$

and therefore,

$$INB_{ij}(t) = \text{int}\left\{\frac{TBRD_k(t) + DURB_k(t) - TFSRV_{ij}(t)}{DEST}\right\} + 1 \tag{116}$$

The studies by Wiltbank, et al.(1962) and Dunn, et al.(1969) show that both pre- and post-calving energy level affect pregnancy rate, although the post-calving level exerts the greatest influence. Thus condition at calving (or about one year of age for heifers), $PPW_{ij}(t)$, and at breeding, $PBW_{ij}(t)$, as well as age (Rogers, 1972) are used to estimate pregnancy rates, and calving rates and times.

For heifers in cohorts 2 and 3, the same equations that were used to estimate condition at about one year of age, $PPW_{ij}(t)$ in subroutine NUTRN, are used to estimate $PBW_{ij}(t)$. That is,

if $AGE_{ij}(t) < 1$ year,

$$WMIN = BETA*COWMWT*e^{ALPHA*AGE_{ij}(t)} \tag{17}$$

otherwise,

$$WMIN = COWMWT*(1 - 0.477*e^{-0.879*(AGE_{ij}(t) - 1)}) \tag{18}$$

where $AGE_{ij}(t)$ is the average age of the j^{th} subpopulation of cohort i,

ALPHA = 0.80168832,

BETA = 0.23460278,

COWMWT = 505 kg.

$$\text{Thus, } PBW_{ij}(t) = \frac{W_{ij}(t)}{WMIN} \tag{117}$$

The pregnancy rates are then computed;

$$HP_{ijk}(t) = PRTG*FSVC*POPT_i*CONCP_k \leq 1.00 \tag{118}$$

where $CONCP_k$ = the optimum ratio of the accumulative fraction of females having conceived following the k^{th} estrus over the accumulative fraction having conceived following the $(k-1)^{th}$ estrus;

$POPT_i$ = the fraction of the optimum conception rate for heifers and cows because of age;

FSVC = 0.72, the optimum fraction of females which can conceive at first service.

$$PRTG = \{PPW_{ij}(t) + 3*PBW_{ij}(t) + 9*(PBW_{ij}(t) - PPW_{ij}(t)) + 3*(PBW_{ij}(t) - 1)\}/4 \leq 1.00 \tag{119}$$

and heifer pregnancy times are;

$$PT_{ijk}(t) = TFSRV_{ij}(t) + DEST*(ki - 1) \tag{120}$$

where DEST = the duration of the estrous cycle,

ki = the index number of the k^{th} estrus period, $k = 1,\ldots,INB_{ij}(t)$.

The calving rates and times then are;

$$CPAT_{ijk}(t) = HP_{ijk}(t)*CFC \tag{121}$$

$$CTIM_{ijk}(t) = PT_{ijk}(t) + GEST \tag{122}$$

where GEST is the duration of gestation.

Similar computations are made for the mature cows in cohort 1, where equations (18) and (117) compute $PBW_{\ j}(t)$. Thus,

$$PRECP_k(t) = CONCP_k*POPT_{j+1}*PRTG*FSVC \leq 1.00 \tag{123}$$

where PRTG is computed as in equation (119),

$$CPAT_{ijk}(t) = PRECP_k*CFC, \tag{124}$$

where CFC is the correction factor to account for fetal mortality;

$$CTIM_{ijk}(t) = TFSRV_{ij}(t) + DEST*(ki - 1) + GEST \tag{125}$$

and $$PCP_{j+i}(t) = PRECP_m(t),\ m = INB1_j(t). \tag{126}$$

The population shift weighting factor, $WF_j(t)$, for cohort 1 is;

$$WF_j(t) = \frac{SUBPOP_{1,j-1}(t)*GEST}{SUBPOP_{1,j-1}(t)*GEST + SUBPOP_{1j}(t)*(1 - GEST)} \tag{127}$$

except where j =1, WF (t) = 1.

Since the heifers in cohorts 2 and 3 may be merging into cohort 1 prior to, or during the next calving season, it is necessary to compute their mean pregnancy rate, $PCP_1(t)$.

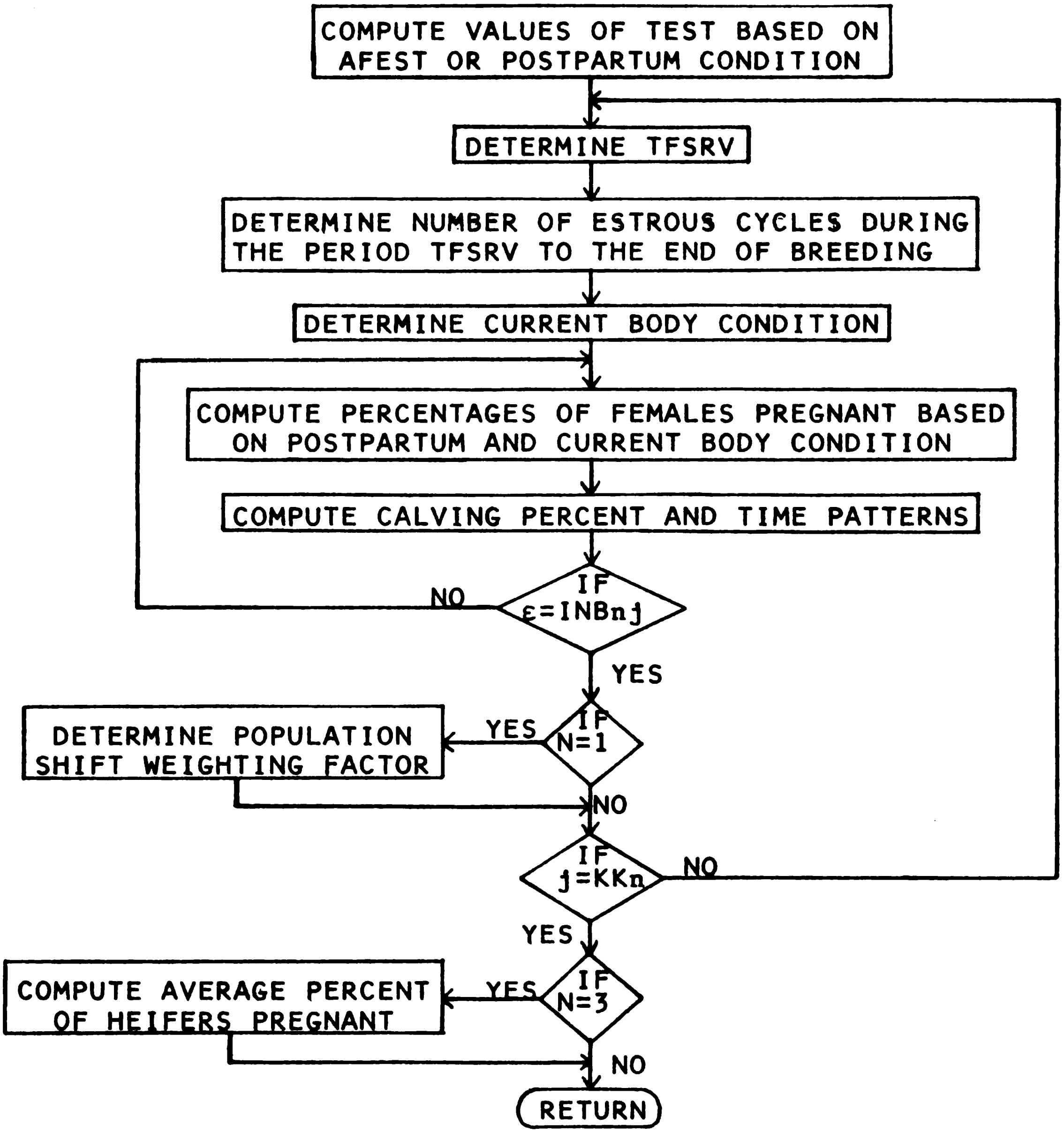

Figure 10. **Flowchart** of subroutine REPRO

$$PCP_1(t) = \frac{\sum_{i=1}^{2} \sum_{j=1}^{KK_i} CPAT_{ijk}(t)*SUBPOP_{ij}(t)}{\sum_{i=1}^{2} \sum_{j=1}^{KK_i} SUBPOP_{ij}(t)}, \quad k = INB_{ij}(t) \tag{128}$$

Subroutine REPRO is relatively detailed in its computations, but more research data is needed in order to develop good prediction equations for pregnancy rates based upon body condition or energy intake. The present form of this subroutine is given in Figure 10.

Subroutine MGMT, called by program BEEF at time TW(t), culls cows and heifers from the herd, weans calves into cohorts 2, 3, and 9, sells surplus cattle, and adjusts reproduction and population variables accordingly.

The cows in cohort 1 are culled according to the expected reproductive performance of the age group or subpopulation as illustrated in Figure 11. Thus the new population becomes;

$$SUBPOP_{1j}(t) = SUBPOP_{1j}(t-dt)*(1 - CULR_j) \tag{129}$$

where $CULR_j$ = the fraction culled from the j^{th} subpopulation.

The older heifers in cohorts 2 and 3 are saved according to the number required to bring the population of cohort 1 up to the desired level, COWMAX. Since the best calves are saved as replacement heifers, herd replacements are chosen from cohort 2 with the oldest and most mature heifers selected first. If the population of cohort 2 is insufficient to meet the required numbers, heifers are selected from cohort 3 in the same manner. All surplus heifers from these cohorts are sold as bred heifers. Because of the level of detail and the potential for large population changes, the reproduction variables for these two cohorts must be adjusted according to the population changes.

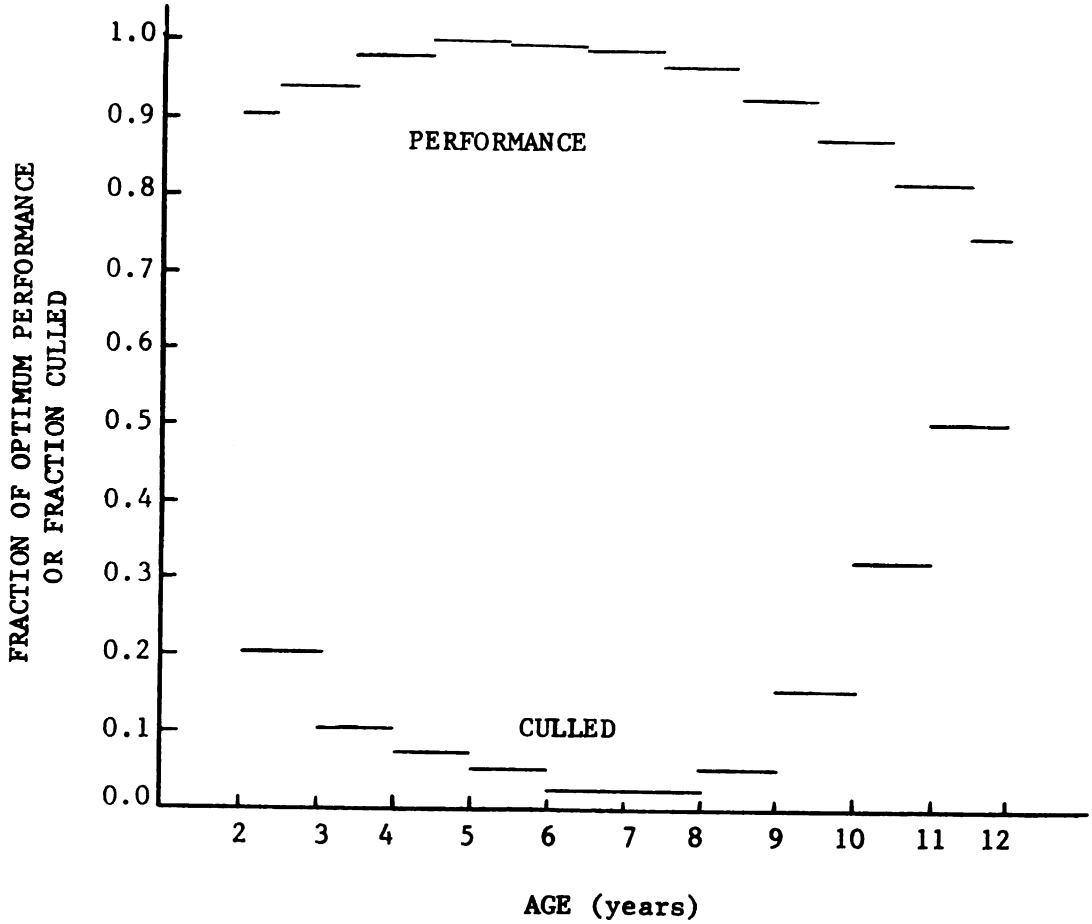

Figure 11. Relationship of performance to culling of cows

The weaning of heifer calves and their transfer into cohorts 2 and 3 is complicated by the necessary retention of age and subpopulation groupings; as though calves and heifers were in the same large cohort. The numbers of calves to be saved as replacement heifers, RHC(t), and bred heifers, BHC(t), are determined by;

$$RHC(t) = C5*POP_8(t) \tag{130}$$

and

$$BHC(t) = (1.00 - C3 - C5 - C9)*POP_8(t) \tag{131}$$

where C3 = the fraction of calves to be saved as market heifers,

C5 = the fraction of calves to be saved as replacement heifers,

C9 = the fraction of calves to be sold at weaning.

A DO loop routine sorts through cohort 8, in reverse order or from the oldest subpopulation to the youngest, to find and mark the subpopulations first required for RHC(t) followed by BHC(t). In this manner, the oldest, heaviest, and probably most mature heifers are saved as replacement heifers and in the following year they will be the first heifers selected to enter the breeding herd. Thus the first subpopulation to enter cohort 2 is marked by NRMAX(t); the number of subpopulations to enter is counted by NRHC(t); and the number of heifers required from the last subpopulation is saved in RHLAST(t) - this is usually only a part of the total number in the subpopulation. Similarly for those designated to enter cohort 3, NBMAX(t) marks the first subpopulation; NBHC(t) counts the number of subpopulations; and BHLAST(t) is the number of heifers required from the last subpopulation.

Prior to transferring subpopulations, weaning weights, $WEANWT_{i_k}(t)$, and time of birth, $TBRTH_{i_k}(t)$, are computed by;

$$\begin{aligned} WEANWT_{i_k}(t) &= W8_j(t) \\ TBRTH_{i_k}(t) &= t - j*DT \end{aligned} \tag{132}$$

where if $i = 2$,

$$j = (NRMAX(t) - NRHC(t) + 1),\ldots,NRMAX(t),$$

$$k = j - NRMAX(t) + NRHC(t);$$

and similarly for $i = 3$.

Although cohorts 2, 3, and 8 are modeled by discrete delays, that which is used for the heifers has a variable delay length and the number of stages in use, $KNOWS_i(t) \leq KK_i$, varies according to the amount of time space required. In order to retain the ages of the calf subpopulations, the following computations are necessary to determine the appropriate delay stages into which the calves are to be transferred. For replacement heifers, the stage number of the youngest subpopulation is

$$IRLO(t) = IDFRH(t) - NRHC(t) + 1 \tag{133}$$

and for the oldest subpopulation,

$$IRHI(t) = IDFRH(t) \tag{134}$$

where $IDFRH(t) = KK2 - \text{int}\left(\frac{AGEIN}{DT} + 0.5\right) + NRMAX(t)$ (135)

AGEIN = the age (years) at which heifers enter cohort 1.

Similarly for bred heifers, the stage number of the youngest subpopulation is computed;

$$KBLO(t) = IDFBH(t) - NRHC(t) - NBHC(t) + 1 \tag{136}$$

and for the oldest subpopulation;

$$KBHI(t) = IDFBH(t) - NRHC(t) \tag{137}$$

where $IDFBH(t) = KK_3 - \text{int}\left(\frac{AGEIN}{DT} + 0.5\right) + NBMAX(t) + NRHC(t)$ (138)

Using these values, the calf subpopulations are transferred into their appropriate positions in cohorts 2 and 3, and their body weights accordingly. If, however, $(NRHC(t) + NBHC(t)) > IDFRH(t)$ or $IDFBH(t)$, there are not enough delay stages in cohort 2 or 3 to retain population ages.

A default mechanism is then used where the youngest subpopulation is placed into $SUBPOP_{i1}(t)$, $i = 2,3$; the second youngest into $SUBPOP_{i2}(t)$, etc. until all of the desired subpopulations are transferred. This will lead to inaccurate estimates of expected yearling and breeding weights (computed by subroutines NUTRN and REPRO) as well as pregnancy and calving rates. Thus careful planning is required of the operator when deciding the delay lengths for these cohorts, the duration of the breeding season, and the fractions of calves to save.

After the calves have been moved into cohorts 2 and 3, the calves that are to be fed-out for market are retained in cohort 8 and are allowed to drift into cohort 9. Any surplus are sold as weaned calves, and the intermediate delay rates, $RIN_{ik}(t)$, for the four cohorts are recomputed to account for the population changes.

MGMT is, therefore, a culling and weaning subroutine which operates under the assumption that the oldest, and probably the heaviest and most mature, heifers of a given group will be the most desirable in terms of reproductive performance.

The last subroutine of reproduction dynamics, ALAC, is called by subroutine NUTRN at time BEGCAV(t). Its function is to determine the fractions of heifer and mature cow subpopulations calving during CDIF intervals from time BEGCAV(t) to ENDCAV(t). These fractions, $PHC_{ijk}(t)$ for heifers and $PCC_{jk}(t)$ for cows, are determined for the j^{th} subpopulation by searching all $CTIM_{ijn}(t)$, $n = 1, \ldots, INB_{ij}(t)$, for a time value which falls within some time interval $(\beta, \beta + CDIF)$ where

$$\beta = BEGCAV(t), \ldots, BEGCAV(t) + (k - 1)*CDIF,$$

$$k = 2, \ldots, \text{int}\left(\frac{ENDCAV(t) - BEGCAV(t)}{CDIF} + 2\right)$$

CDIF = 0.03846 years.

Thus if $\beta_k \leq CTIM_{ijn}(t) < (\beta + CDIF)_k$,

$$\text{for heifers, } PHC_{ijk}(t) = \begin{cases} CPAT_{ijn}(t), & \text{if greater than 0.} \\ PHC_{ij,k-1}(t), & \text{otherwise.} \end{cases}$$

$$\text{and for cows, } PCC_{jk}(t) = \begin{cases} CPAT_{1jn}(t), & \text{if greater than 0.} \\ PCC_{j,k-1}(t), & \text{otherwise.} \end{cases}$$

Since the heifers will be moving into cohort 1, the averages of their calving fractions are needed for computations in other subroutines. the term $PCC_{1k}(t)$ is reserved for these values which are computed;

$$PCC_{1k}(t) = \frac{\sum_{i=2}^{3} \left(\frac{\sum_{n=1}^{KNT_i} PHC_{ink}(t)}{KNT_i(t)} \right) * RPOP_i(t)}{\sum_{i=2}^{3} RPOP_i(t)} \tag{139}$$

Thus $PHC_{ijk}(t)$ and $PCC_{jk}(t)$ are the female calving fractions, the values of which are set at equal time increments over the calving season. Not only does this procedure facilitate the use of the calving fractions in the linear interpolation and extrapolation functions, but it also gives a common base from which to compare the reproductive performances of different subpopulations.

Subroutine ALAC might therefore be regarded as a simple data organizing routine, its structure is shown in Figure 12.

Subroutine calling .sequence and interrelationships

Although the subroutines of this model have been described according to their primary function, i.e. demographics, nutrition, and reproduction, the sequence in which they are called during a computer run is as follows;

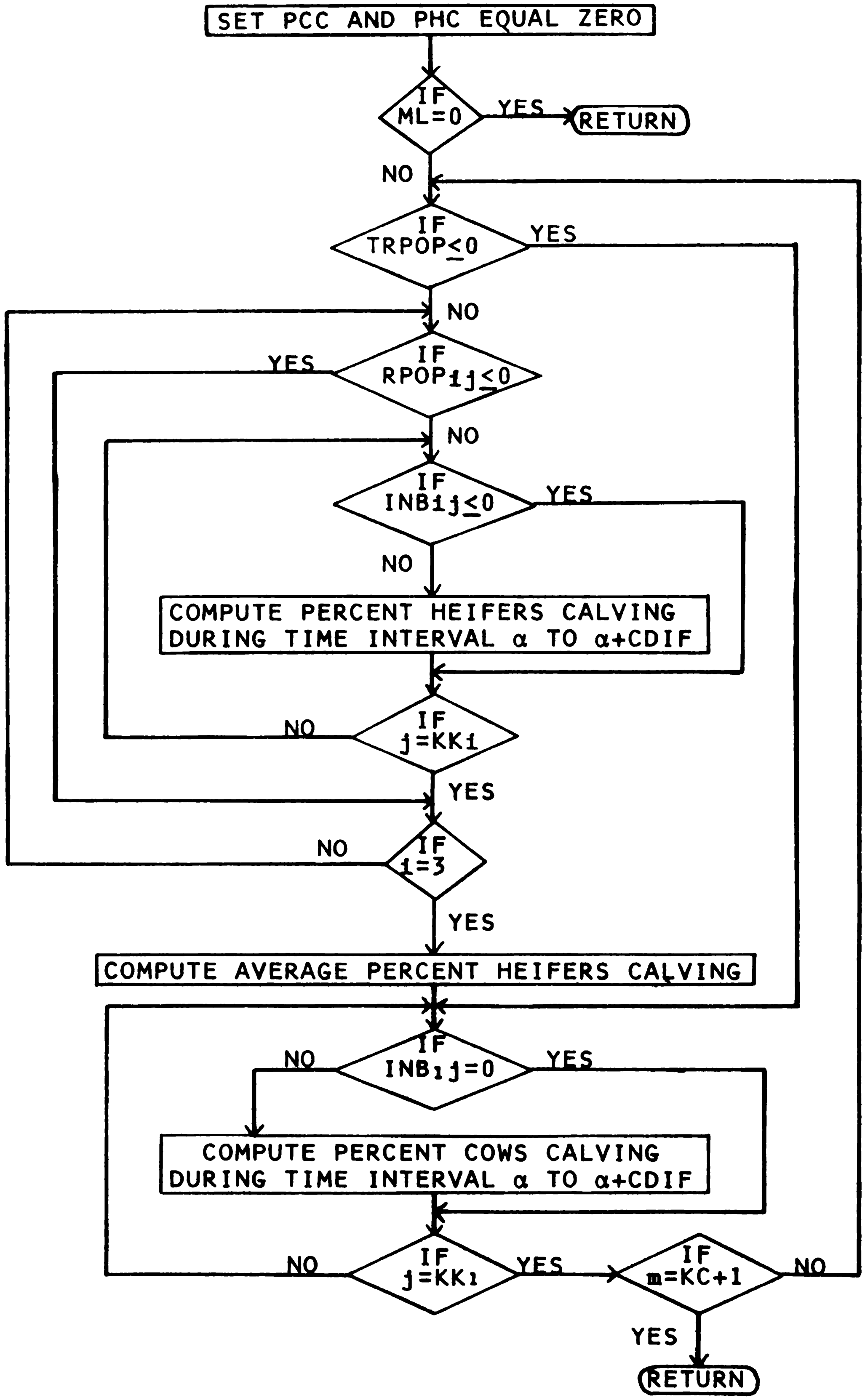

Figure 12. Flowchart of subroutine ALAC

```
PROGRAM BEEF
    ├─τ──→ NAMLST
    ├─────→ HDMOG4
    │          ├─────→ BIRTH2
    │          │          └─τ──→ BIRAT
    │          └─────→ DELAYS
    ├─────→ WEIGHT
    ├─τ──→ MGMT
    └─────→ NUTRN
               ├─τκ──→ ALAC
               ├─κ──→ COWCYC
               │          └─τ──→ REPRO
               ├─κ──→ GROFEM
               │          ├─────→ CNVRT
               │          ├─τ──→ AWPUB
               │          └─τ──→ REPRO
               └─κ──→ GROMAL
                          └─────→ CNVRT
```

where the symbol -τ- indicates the subroutine is called at a particular time; and the symbol -κ- means the subroutine is called if directed by the switch KALLER.

The block diagram of the female component, Figure 13, serves to illustrate the interrelationship of the various elements of the model. Because of the complex nature of this component, it was necessary to combine and abreviate terms. A special glossary, found in Appendix B, relates the terms of the diagram to those of the computer model.

The series across the top of the diagram shows the process by which changes in herd structure take place. It should be noted that the delay mechanisms, DEL, for the various cohorts are not identical. Cohort 8 is simulated by subroutine DDPLR and cohorts 2 and 3 by DVDPL, both of which are discrete time delays. Cohorts 1 and 9 are simulated by DLVDPL which is a distributed time delay.

The middle section of the diagram shows the relationship of the reproduction functions. The block AWP represents subroutine AWPUB, block REP represents REPRO, block BTH represents BIRTH2 and BIRAT, and

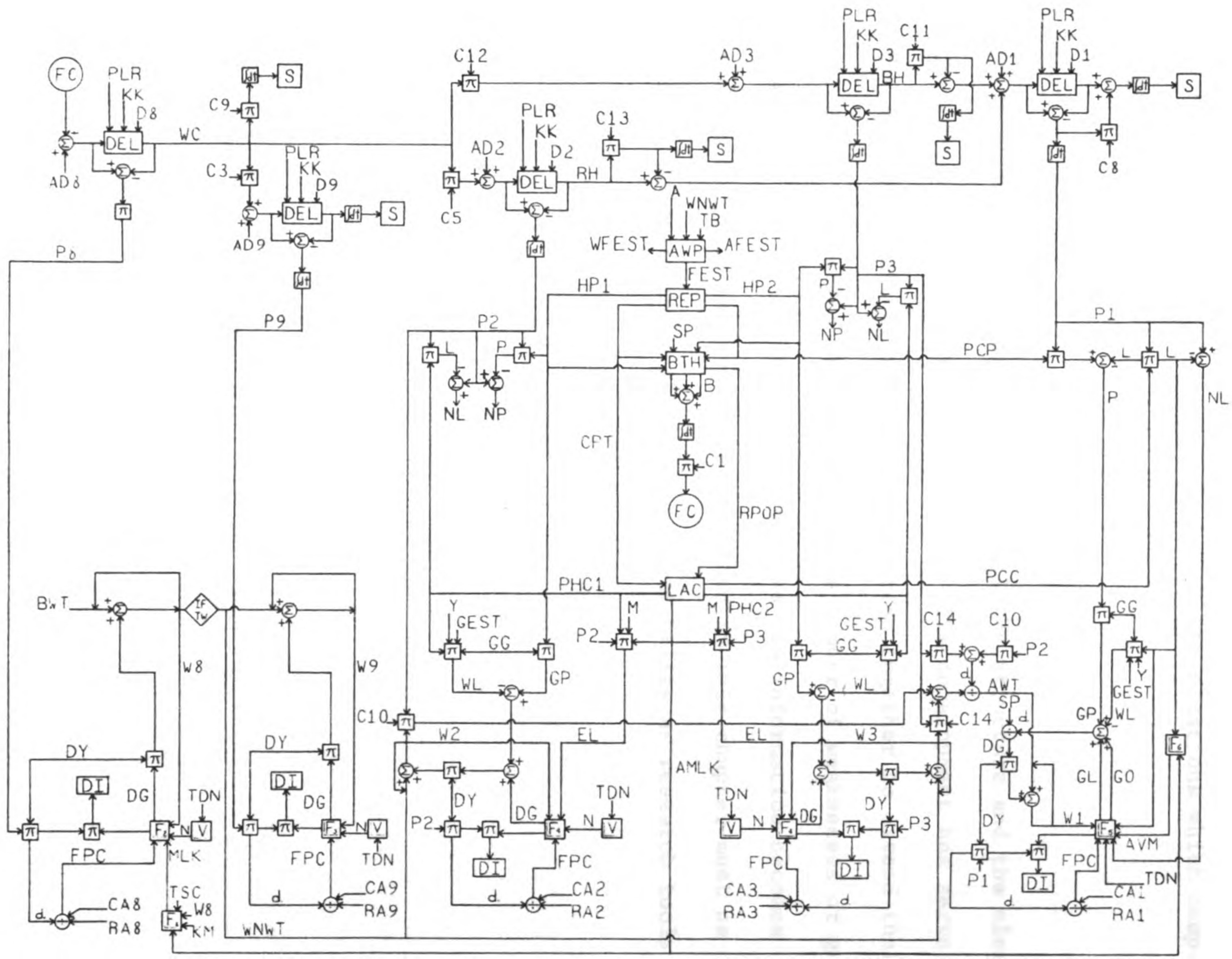

Figure 13. Block diagram of female component

block LAC represents subroutine ALAC.

The lower half of the diagram illustrates the nutrition section of the component where block V represents subroutine CNVRT. The functions F_i, defined in Appendix B, consist of the equations which compute average daily gain and feed intake.

Summary

This chapter has described in detail the structure and the elements which comprise the beef simulation model. Its development has served to tie several pieces of research information together to extend their usefulness. This study has also exposed a number of weaknesses or gaps in available beef research information. As new information becomes available, models such as the one described in this chapter must be rebuilt to increase their accuracy and reliability as research tools.

III. MODEL VALIDATION AND SIMULATION

Validation

For a simulation model to be truly useful for research, teaching, or decision-making, it first must be validated. Validation might be regarded as a two-step procedure. First, the computer model must be tested to see if it accurately describes the mathematical model. Second, the mathematical model must be checked to ascertain whether or not it represents reality. Should either of the steps fail, appropriate changes must be made and the validation procedures repeated. This process continues until the final version of the computer model is attained, after which it can be tested directly against real data. When there are gaps in the data available, expert opinion must be used in judging the validity of a particular section of the model.

Throughout its development, this model has undergone the iterative validation procedures. Here again, emphasis has been given to the female sector primarily because of the complexity of its model components. This section of the chapter will discuss three types of validation tests completed with this model; (1) a 5-year run to test the model's stability over time, (2) five 2.5-year runs to test stability over a range of different DT time intervals, and (3) a normal run to test simulation against available research data.

A number of preliminary 2.5-year runs were made to determine the feed levels, based upon Fox and Ritchie (1975c) and N.R.C. (1970), which give relatively normal rates of weight gain for the various cattle populations. The best values were further tested in a 5-year run to ensure that the values can maintain herd stability in terms of body weight. Table 1 lists these feed values for each cohort; they will be referred to as the control or normal values.

Table 1. Control feed values

COHORT	TDNR[a]	TDNC[a]	RHGAL[b]	CNCAL[b]	CODE[c]
1	0.50	0.0	0.015	0.0	A
	0.51	0.0	0.015	0.0	B
	0.58	0.0	0.028	0.0	C
	0.57	0.0	0.022	0.0	D
	0.54	0.0	0.0205	0.0	E
2	0.60	0.0	0.028	0.0	-
3	0.60	0.0	0.028	0.0	-
4	0.52	0.0	0.012	0.0	-
5	0.55	0.70	0.014	0.005	-
6	0.55	0.70	0.015	0.015	-
7	0.63	0.80	0.014	0.021	-
8	0.71	0.0	0.035	0.0	-
9	0.55	0.70	0.015	0.015	-

[a] Values are given in terms of kg TDN/kg dry matter.
[b] Values are given in terms of kg dry matter/kg body weight.
[c] A=gestation period; B=45 days pre-calving; C=calving period; D=early lactation and breeding; E=late lactation.

In the 5-year run using the control feed values, the initial herd structure consisted of 250 mature cows having a mean body weight of 491.6 kg, and 6 mature bulls having a mean weight of 673.3 kg. Because the remaining populations were generated endogenously by the model, the herd structure did not begin to stabilize until 2.2 years, when replacement heifers began merging into cohort 1.

Some difficulties were encountered in maintaining consistent body weights. The population of cohort 1 was initially larger than the desired 200 cows to compensate for death and culling losses in the first two years. This resulted in 30% of the initial population being made up of subpopulations 1 and 2, where extra feed is automatically allocated for growth. Because a distributed delay is used for this cohort, each subpopulation represents a stage of physiological maturity rather than a chronological age group. The result is that animals remain in subpopulations 1 and 2 much longer than desired and therefore attain unusually high body weights. These weights are averaged down once new animals enter the cohort. These faults were evident in the 5-year run where at 2 years the average cohort weight had increased to 530 kg, but after 2.5 years the weight stabilized at about 508 kg.

As previously indicated, subroutine GROMAL is less refined relative to the other subroutines. This was apparent in the 5-year run where the average body weights of the mature bulls of cohort 4 decreased to 617 kg and did not stabilize until after 4 years. The results indicate that higher TDN and/or allocations as well as a better equation to estimate energy utilization are necessary to achieve more desirable weight gains.

The body weights of all other cohorts as well as age and weight at first estrus, and pregnancy rates for cows and heifers remained consistent throughout the simulation run. Age of heifers at puberty averaged 0.978 years, weight at puberty was 272 kg, pregnancy rates were 75% for heifers and 96% for mature cows. These results have been found to be acceptable.

The second validation test consisted of five 2.5-year runs each having a different time increment. The DT values used ranged from 0.03846 to 0.125 years. Although the initial herd size remained the same for each DT trial, values for KK_i and $DELAY_i$ required adjustment because of the constraints of the delay routines. For the distributed delays, as used in this model,

$$DT < \frac{DELAY_i}{2*KK_i*\left(1 + \frac{DELAY_i*PLR_i}{KK_i}\right)}$$

and for discrete delays of non-variable length,

$$DT = \frac{DELAY_i}{KK_i}$$

Table 2 gives the $DELAY_i$ and KK_i values used for the DT trials. As DT increases, the number of delay stages must decrease to maintain approximately the same delay length for cohorts 5 through 9.

Table 2. Delay length (years) and stages for DT trials

COHORT		0.03846	0.040	0.050	0.0833	0.125
1	DELAY	10.0	10.0	10.0	10.0	10.0
	KK	(10)	(10)	(10)	(10)	(10)
2	DELAY	1.5	1.5	1.5	1.5	1.5
	KK	(40)	(40)	(40)	(40)	(40)
3	DELAY	1.5	1.5	1.5	1.5	1.5
	KK	(40)	(40)	(40)	(40)	(40)
4	DELAY	7.0	7.0	7.0	7.0	7.0
	KK	(7)	(7)	(7)	(7)	(7)
5	DELAY	2.25	2.25	2.25	2.25	2.25
	KK	(27)	(27)	(20)	(13)	(8)
6	DELAY	1.0	1.0	1.0	1.0	1.0
	KK	(13)	(12)	(9)	(5)	(3)
7	DELAY	0.7692	0.7501	0.750	0.750	0.750
	KK	(20)	(19)	(15)	(9)	(6)
8	DELAY	0.7692	0.7501	0.750	0.750	0.750
	KK	(20)	(19)	(15)	(9)	(6)
9	DELAY	1.0	1.0	1.0	1.0	1.0
	KK	(13)	(12)	(9)	(5)	(3)

Table 3 shows the resulting mean weights of mature cows at selected times. The reader should note that these weights are higher than those of the 5-year test because feed allocations and TDN level were held constant at 1.75% of body weight and 55% of dry matter respectively.

Table 3. Comparison of average cow weights at different DT increments

TIME	0.03846	0.040[a]	0.050	0.0833	0.125
0.0	491.6	491.6	491.6	491.6	491.6
0.5	510.0	508.0	520.2	502.6	498.8
1.0	518.6	530.4	523.1	508.6	494.7
1.5	561.2	541.8	573.1	530.7	512.8
2.0	568.6	578.3	573.4	533.6	505.9
2.5	554.3	-	548.0	515.0	-

[a] Actual printing of output was 0.04 per year later than indicated.

Were the feed levels changed according to the reproductive cycle, as was done in the 5-year run, the timing of these changes would be thrown off with the different DT values and thus render invalid results. Because of the delay length for cohort 1, population and weights change slowly relative to some of the other cohorts. Thus in the span of 2.5 years the weights are little affected by changing the DT value.

In contrast, the heifers that are modeled by discrete delays with short delay lengths are drastically affected by changes in DT; feed inputs remaining constant. The effects on the weight of the first heifer subpopulation born in simulation year one are shown in Table 4 at selected time intervals.

The instability of body weight is largely due to the fact that the feeding levels were determined at DT = 0.03846 which is in accordance with common practice; feed intake for the period t to t+dt is assumed constant

Table 4. Comparison of oldest heifer weights at different DT intervals

TIME	0.03846	0.040	0.050	0.0833	0.125
0.5	103.22	103.19	77.96	67.69	55.16
1.0	227.63	222.83	176.81	129.67	95.30
1.5	291.16	289.67	230.45	164.02	112.94
2.0	385.55	386.20	297.83	208.50	132.75

based upon body weight at time t. As DT is increased, the error in estimating feed intake increases, resulting in underestimated weight gains in the case of growing heifers.

The difficulties with changing DT are not restricted to weight changes. There are also differences in total herd population as shown in Table 5.

Table 5. Total herd population and DT interval

TIME	0.03846	0.040	0.050	0.0833	0.125
0.0	256	256	256	256	256
0.5	459	462	451	458	438
1.0	409	379	400	401	382
1.5	508	511	506	504	478
2.0	424	380	422	411	386
2.5	485	-	494	488	-

The differences here can be attributed to several factors. The lower weights, as described above, cause a delay in onset of estrus, lower pregnancy rates, and thus fewer calves born. With larger DT's, the timing of reproductive events can become crude and inaccurate. To a certain extent, larger DT values might safely be used if feed allocations and TDN values are increased. Another possibility would be to modify the method by which feed intake is computed, linking it to DT size. The simplest solution, however, is to avoid using large DT values.

DT values smaller than 0.03846 years cannot be used. The model design restricts KK_i to a maximum of 40. Herd demographics requires that cohorts 2 and 3 be allowed a maximum delay length of about 1.54 years with the constraint that $DELAY_i \leq KK_i*DT$. Thus a smaller value for DT can be used only after extensive modifications of the model are made.

Perhaps the most crucial test of a model is to compare the simulation results with actual research data. To accomplish this, a 2.5-year control run was made using the feed values given in Table 1. The results for heifers are shown along with data on Hereford heifers from Guilbert and Gregory (1952) and Brown, et al. (1956) in Figure 14. The heifers in these research studies reached mature weights of about 560 kg and 498 kg respectively. The desired mature weight for the simulated herd was 505 kg, however, the 5-year simulation run gave the average mature cow weight as 508.3 kg.

The shape of the curves in Figure 14 indicates that the growth rate of the simulated animals after weaning (36 weeks) is the inverse of what it should be. That is, the rate of gain immediately after weaning should remain high and then gradually decrease as age increases. This is the result of a necessary compromise in feeding levels. From the time of weaning until the end of the calving season there are two groups of heifers in cohorts 2 and 3, those just weaned and those pregnant with their first calf. In practice these two groups would receive different levels of feed, the younger group consuming a higher level of TDN. Because of the model's demographic structure, it would be most difficult to properly assign different feed levels for the two groups. Thus an

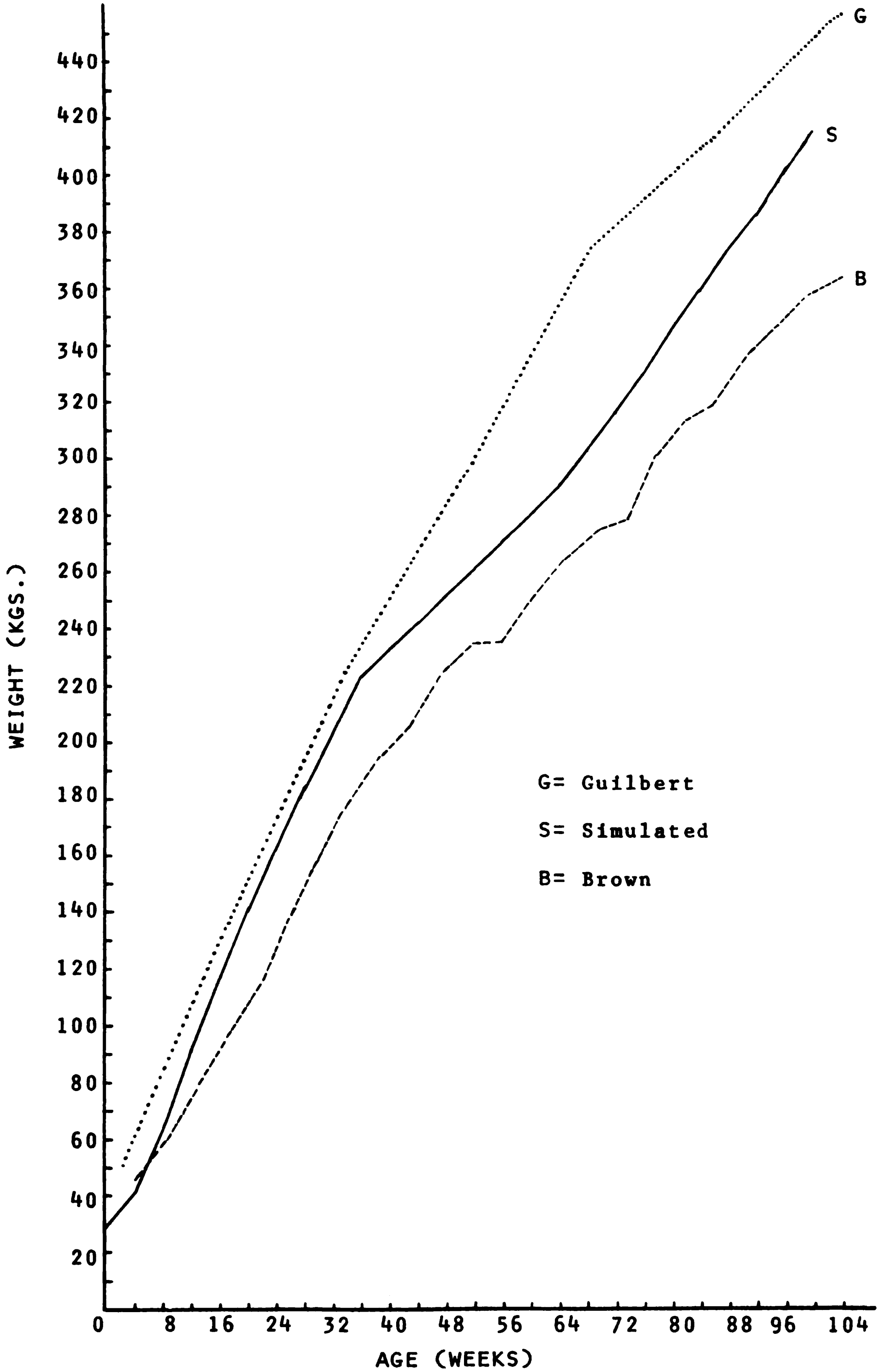

Figure 14. Simulated versus actual heifer growth curves

intermediate level was used which resulted in the lower rates of gain for the younger heifers. It should be noted that part of the increasing rate of gain of the older heifers (from 64 weeks) is due to pregnancy.

Thus when the DT value is small, the model remains quite stable and is capable of generating information which lies within the bounds of reality.

Simulation

There is a wide variety of problems which can be investigated with this simulation model. Among them are early versus late weaning, spring versus fall calving, and the time and duration of the breeding season in relation to the calving season. Of greater significance is the fact that the effects of low energy intake upon reproduction in females can be investigated.

To further study the energy-reproduction relationship, two sets of six 2.5-year simulation runs were made, each with a different quantity or quality of feed, and all deviating below the control levels of Table 1. In the first set, the TDN levels were 99, 95, 90, 85, 80, and 75% of the control values while the quantity of feed allocated remained constant at control levels. The second set was the reverse, TDN values remained constant at the control levels and the quantity of feed allocated deviated from control levels by the same percentages as above. All other factors such as initial herd size and weights, the time and duration of the breeding and calving seasons, and age at weaning remained the same for all twelve runs.

The results of the first set of computer runs are shown in Figure 15 for growth and Table 6 for reproduction. In all of the trials, calves received their normal milk levels, thus there were no differences in

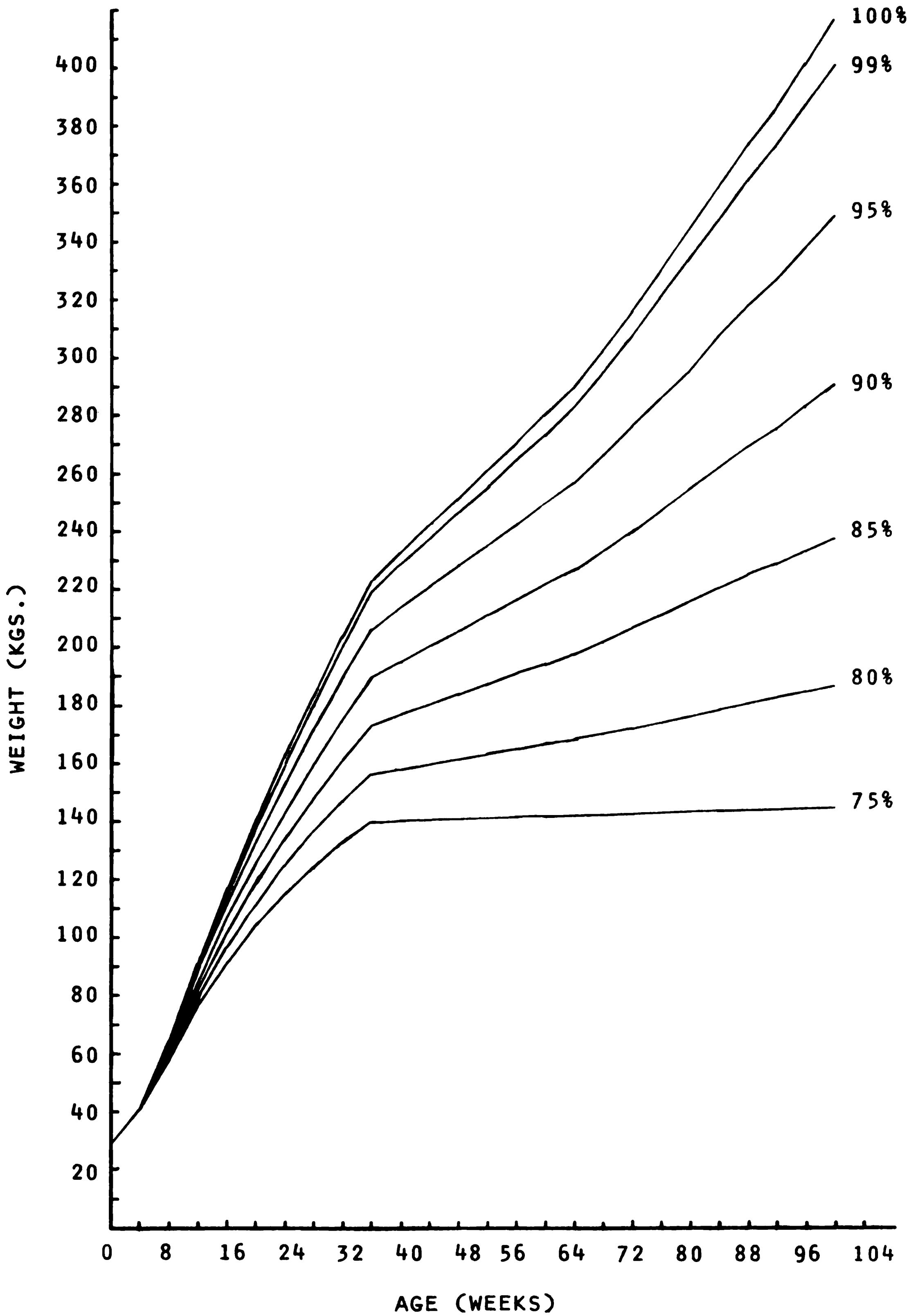

Figure 15. Simulated heifer growth at various TDN levels

Table 6. Effects of decreasing TDN levels on reproductive performance

	100%	99%	95%	90%	85%	80%	75%
HEIFERS (averages)							
Weaning weight, kg	213.1	210.1	197.8	182.4	167.0	151.5	136.2
Age at puberty, yr.	0.97	0.98	1.05	1.15	1.26	1.40	1.52
Weight at puberty	272.3	269.8	261.5	254.3	250.4	250.3	249.2
Percent pregnant	76.2	70.4	55.0	40.4	23.0	3.4	0.0
MATURE COWS (averages)							
Time of estrus in year 2	1.46	1.48	1.52	1.76	1.84	1.88	1.89
Breeding weight, kg	509.0	496.9	393.6	397.5	356.7	314.3	276.0
Percent pregnant	95.0	95.0	53.5	23.7	13.1	11.2	9.1

growth rates for the first few weeks. Once the calves started consuming roughages, the growth rates for the various treatment groups began to diverge. By weaning, (36 weeks) there was a 59% difference in weight between the 100 and 75% TDN groups. The final variation between the two groups was 187%.

The reproduction results were equally as dramatic. The difference in growth rate between the control and 99% TDN groups appears to be small in Figure 15, but it was sufficient to increase age at puberty, and decrease weight at puberty and pregnancy rate in heifers. These trends continue as TDN decreases. The results pertaining to puberty are consistent with those of Sorenson, et al. (1959) where dairy heifers fed 60% and 100% of recommended TDN reached puberty at 72 weeks, 241 kg; and 49 weeks, 270 kg respectively. Short and Bellows (1971) found similar results where eighty-nine beef heifers fed to gain 0.23, 0.45, and 0.68 kg per

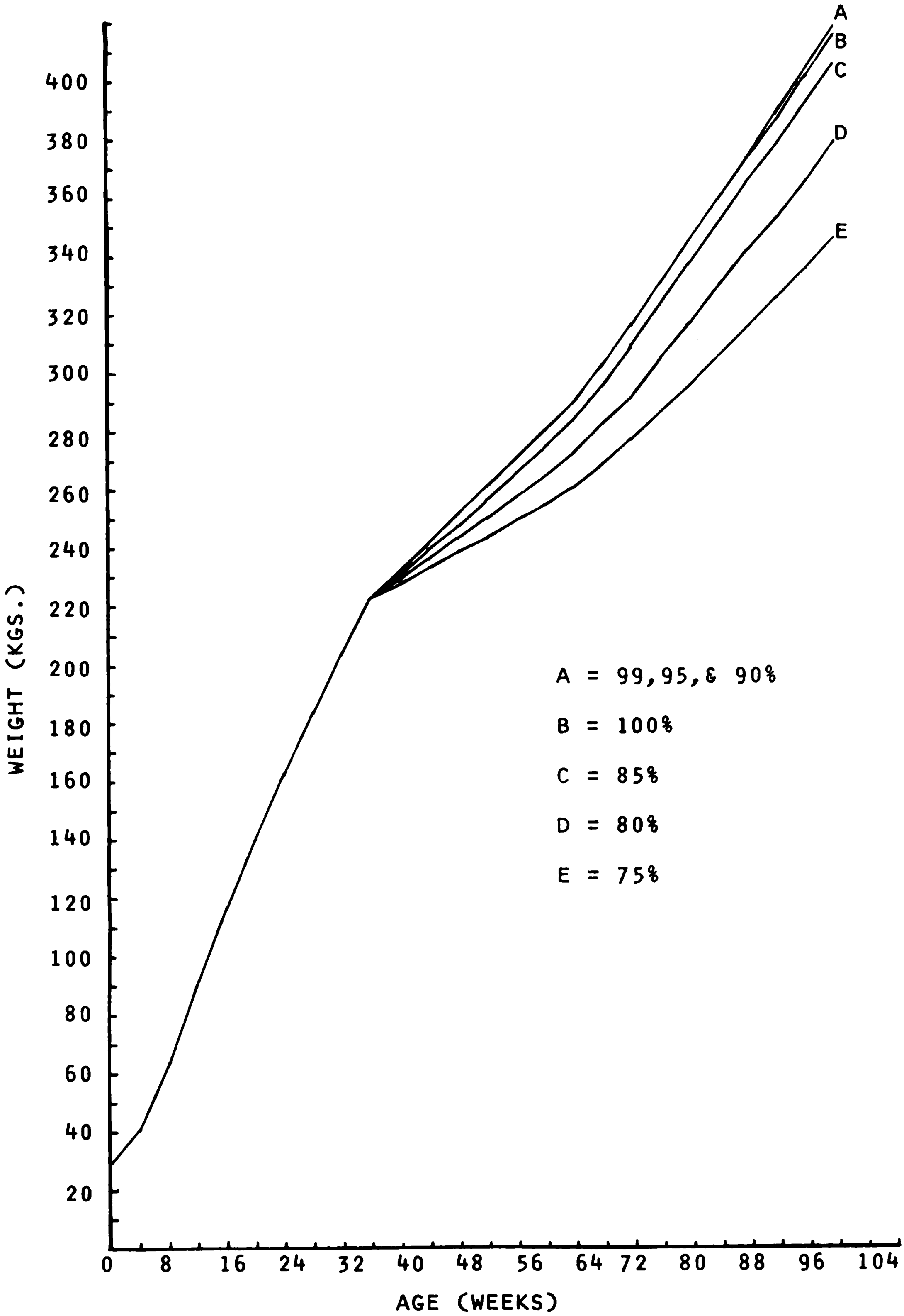

Figure 16. Simulated heifer growth at various allocation levels

day from age seven to twelve months reached puberty at 433 days, 238 kg; 411 days, 248 kg; and 338 days, 259 kg respectively.

The second set of computer runs, where feed allocations varied, gave much different results as shown in Figure 16 for growth and Table 7 for reproduction. No differences in growth rate are observed until the heifers are weaned, indicating that the control allocation for cohort 8 overestimated the quantity of feed required by calves when normal levels of milk are available. Thus 75% of the control allocation, or 0.0263 kg of dry matter (at 71% TDN) per kilogram of body weight, is adequate for notmal growth of nursing calves. After weaning, a 15% decrease in allocation was necessary to effect a change in growth rate; this is also due to an overestimation.

Table 7. Effects of decreasing feed quantity on reproductive performance

	100%[a]	95%	90%	85%	80%	75%
HEIFERS (averages)						
Weaning weight, kg	213.1	213.1	213.1	213.1	213.1	213.1
Age at puberty, yr.	0.97	0.97	0.97	1.00	1.05	1.12
Weight at puberty	272.3	272.3	272.2	271.4	272.4	275.9
Percent pregnant	76.2	76.2	75.9	68.1	61.0	52.0
MATURE COWS (averages)						
Time of estrus in year 2	1.46	1.52	1.70	1.84	1.88	1.90
Breeding weight, kg	509.0	457.5	409.9	367.2	323.5	283.4
Percent pregnant	95.0	90.0	30.6	13.1	12.6	11.3

[a]Values for the 99% test were invalid due to a timing error for making a parameter value change.

The constancy of the weaning weights across treatment groups yielded a strikingly different trend in the prediction of puberty. As allocation decreased from 90 to 75%, age at puberty increased, but weight at puberty remained about the same. Bond and Oltjen (1973) found similar results when beef heifers were fed balanced rations to study alternative sources of nitrogen. They attributed the delay in puberty to a low nutritional level caused by lowered palatability and utilization of the diet.

These and other preliminary trial results have shown cattle to be much more responsive to changes in TDN than to changes in allocation. Because the physical capacity of an animal limits voluntary feed intake, poor feed quality cannot always be compensated with higher feed quantity. It should also be noted that under actual conditions, animals suffering from severe nutritional stress will eventually die if the situation persists. This has yet to be accounted for in the simulation model since no information has been found giving the percentage of normal body weight which must be lost to cause the death of an animal. Because of this, the mortality rates remain constant except in the case of zero weight.

IV. SUMMARY AND RECOMMENDATIONS

Summary

The preceding pages have described the development of a computer model which simulates 1) the growth in body weight of beef cattle in response to a given set of feed levels; and 2) the reproductive performance of beef females as affected by age and body condition. The computer model is composed of a main program and a series of subroutines which are written in FORTRAN. The subroutines can be classified according to function by one of the following categories:

1. Herd demographics--where animals are aged and shifted from one cohort to another, and where changes in body weights are determined;
2. Nutrition dynamics--where feed intake and energy utilization are determined for animals of known weight and reproductive status;
3. Reproduction dynamics--where puberty, postpartum estrus, pregnancy rates, and calving rates and times are estimated for heifers and cows based upon age, weight, and body condition.

The model is designed so that it may be operated as an independent unit or as a component of a larger beef enterprise model developed by Jaske (1976). As an independent model, its main program, BEEF, serves as an executive routine where the parameter values and initial conditions are set, primary subroutines called, and output printed. This routine allows up to 99 consecutive simulation runs, and when coupled with subroutine NAMLST, where the values of the variable parameters can be changed at any time, innumerable combinations of conditions can be tested non-stop. In addition, any combination of three major herd components - mature cows, growing heifers, and growing and mature steers and bulls - can be selectively studied.

Although the cow/calf operation has been emphasized, the model was designed to include the complete breeding herd and/or feedlot operation. Given roughage and concentrate dry matter allocations and TDN levels, the utilization of energy for body maintenance, lactation, and weight gain is simulated based upon the California net energy system (Lofgreen and Garrett, 1968; and N.R.C., 1970) and the TDN system (Neville and McCullough, 1969). The reproductive performance of females is closely linked to body weight, rate of gain, and estimated condition. Thus as weaning weight and rate of gain decline, age at puberty increases for heifers; and as estimated body condition declines, the interval from calving to first postpartum estrus increases and pregnancy rates decline.

The model has been partially validated to the extent that research data and expert opinion permit. It was found to be most stable where $0.03846 \leq DT \leq 0.05$, as large values of DT result in an underestimation of voluntary feed intake for growing cattle. Large DT values were also found to be unsuitable because of the intricate timing of reproduction-related events. Except for some difficulties in determining energy utilization by bulls, the model is capable of generating realistic growth and reproduction data as proven by comparison with actual data.

The key feature of this model is its capacity to simulate the effects of low energy levels upon reproductive performance of females. In simulation runs where different TDN values were tested, the results showed that as energy intake decreased, age at puberty and interval to postpartum estrus increased, and weight at puberty and pregnancy rates decreased.

However, where allocation levels were reduced, weight at puberty remained constant whereas the remaining factors followed the same trends as in the TDN trials. This was due to constant weaning weights caused by an over-estimation of the quantity of feed required by nursing calves.

Another element unique to this and the model by Jaske (1976) is the inclusion of complete population dynamics. Until the development of these two models, only various segments of the herd had been considered in beef production models as noted by Joandet and Cartwright (1975).

To the extent that it has been tested, this model has been proven potentially useful as a research and decision-making tool. As with any first-generation model, it is imperfect and should be modified as improved methods and information become known.

Recommendations

One of the requirements of this model was that it be compatible with the model by Jaske (1976) in order to be used as a component. This has necessarily restricted the modifications that could be made, particularly during the final stages of model development. However, the following revisions are suggested if the model is to be used as an independent unit.

Several of the previously mentioned modeling problems could be alleviated by restructuring the demographic component. The difficulty of properly assigning feed levels to the two age groups of heifers in cohorts 2 and 3 may be solved by combining "replacement" heifers and "bred" heifers as cohort 2. Any precalving population changes would be handled by a modified MGMT subroutine. Cohort 3 would then be used for the recently weaned heifer population. The variable time delay mechanisms could then be used in such a way as to prevent the mixing of the two groups. With the maximum

KK_i still at 40, this new arrangement would allow $DELAY_i$, i = 2,3, to be shortened and DT to be as small as 0.01923 years. More flexibility would be added in terms of feed allocations, ages at weaning and calving, the number of subpopulations weaned while retaining age groupings, and the lengths of the breeding and calving seasons. This would also permit more thorough testing of the model for stability with the use of $0.01923 \leq DT \leq 0.03846$ years.

Another problem has been that of tracking animals and matching reproduction data with the appropriate subpopulation. Since it is more desirable to know chronological age than physiological maturity, a type of discrete delay could be substituted for the distributed delay used for cohort 1. The new delay system would consist of age cells with each representing a minimum three month period. With each DT interval, some population losses would be computed as before, but the populations would not be advanced until k*DT = cell time delay. Such a device could also be used for bull cohorts 4 and 5 to prevent the "spreading out" of populations and to increase computational accuracy.

The model could also be condensed and more efficiently operated with greater use of DO loops if the cohorts were renumbered. They would become:

POP_1 = mature cows,

POP_2 = replacement heifers,

POP_3 = market heifers,

POP_4 = weaned heifers,

POP_5 = heifer calves,

POP_6 = mature bulls,

POP_7 = young bulls,

POP_8 = steers,

POP_9 = male calves.

Further improvements could be made by devising better equations for determining energy utilization by bulls, voluntary feed intake by young calves, and return to postpartum estrus and pregnancy rates as related to body condition. Some function is also needed which depicts the non-linear growth in weight of the calf fetus; this would be used instead of the linear GGEST = 0.192 kg per day.

The model could be expanded to include the effects of various levels of protein. This is a particularly important element in the diets of young cattle and lactating cows. Low protein levels lead to depressed appetite, slow growth, and lowered milk production (N.R.C., 1976).

Finally, since this model is concerned with low nutrient levels, a most desirable addition would be a function which determines the compensatory growth of an animal. This too is an important factor as it occurs to some degree in cattle whenever their diet is changed from a low to a high plane of nutrition.

With these and perhaps additional revisions, this model could serve a number of purposes. It could be used for research studies or, with the addition of financial routines, for livestock investment projects both domestically and overseas. It might also be useful as a teaching aid where students choose a hypothetical beef operation, select management parameters, and formulate feed rations to test their knowledge and improve their skills in herd management.

As it exists, this model cannot be viewed as complete. Its development has served to blend various pieces of information into a form which extends their usefulness, as well as to expose several areas about which information is inadequate. Thus, only with continued research and much effort can this simulation model be improved and expanded into a truly useful instrument.

APPENDIX A

APPENDIX A

GLOSSARY OF TERMS

(terms with an * are variable model parameters)

$ACDMIC_i(t)$	accumulated dry matter intake of concentrates for cohort i . . . kg
$ACDMIR_i(t)$	accumulated dry matter intake of roughages for cohort i . . kg
$ADDRT_i(t)$	annual rate of additions to cohort i . . no./yr
$AFEST_{ij}(t)$	age at puberty of the j^{th} subpopulation of heifer cohort i . . . yrs
AGEIN	age at which heifers are to enter the breeding herd . . yr
BBRD(t)	number of calves born to the first-calf heifers of cohort 3
BCOW(t)	number of calves born to mature cows in cohort 1
BEGCAV(t)	time at which calving begins in the current year
*BEGPRT	time at which printing of model variables begins
BREP(t)	number of calves born to the first-calf heifers on cohort 2
CDIF	the time interval, equal to 0.03846 years, used in computing the number of females lactating and the number of females calving during the time interval t to t+dt
CFC	correction factor to account for fetal mortality
CFD	correction factor for roughage digestibility
CFE	correction factor for the effects of growth stimulants
$*CNCAL_i(t)$	concentrate allocation for cohort i . . . kg
$CONCP_k$	the optimum ratio of the accumulative fraction of females having conceived following the k^{th} estrus over the accumulative fraction having conceived following the $(k-1)^{th}$ estrus during the breeding period.
*COWMAX	maximum number of mature cows to be maintained
COWMWT	average mature weight of the cow herd . . . kg
$COWNEW_{ij}(t)$	heifer subpopulations which sift into cohort 1 prior to and during the calving period

$CPAT_{ijm}(t)$	fraction of the j^{th} female subpopulation in cohort i to have calved by $CTIM_{ijm}(t)$
CSM	a value equivalent to the time BEGCAV(t) which is used to compute the percentage of cows calving in the current time period t to t+dt
$CTDN_i(t)$	total number of kilograms of concentrate TDN consumed in the current time interval by cohort i
$CTIM_{ijm}(t)$	the calving time of the j^{th} subpopulation of cohort i as a result of conception in the m^{th} estrus of the breeding season . . . years
$CURLAC_i(t)$	the current percentage of POP_i lactating, i = 1,2,3
$CURPREG_i(t)$	the current percentage of POP_i pregnant, i = 1,2,3
*C1	fraction of female births
*C2	fraction of male calves saved as replacement bulls
*C3	fraction of female calves to be fed as market heifers
*C4	fraction of male calves sold at weaning
*C6	fraction of young bulls culled
C8	fraction of mature cows culled per year
*C9	fraction of female calves sold at weaning
*C10	fraction of replacement heifers entering the mature cow cohort 1
*C11	fraction of bred heifers sold
DAYS	the time increment in terms of days, DT*365
$*DELAY_i(t)$	length of time required to pass through the aging or maturation period for cohort i . . . yr
$DELAYP_i(t)$	length of time required to pass through the aging or maturation period for cohort i at time t-dt
DEST	duration of the estrous cycle . . . yr
*DETPRT	a switch that determines whether or not a detailed print-out of model variables is provided
$DGAIN_{ij}(t)$	the projected average daily gain of the j^{th} subpopulation of cohort i over time interval t to t+dt . . . kg

DIFM	the time interval equal to one month (0.0833 yr) used to compute the current milk yield
DM	the fraction of a year equal to one month
$DPPE_n$	time to first postpartum estrus for cows in the n^{th} percentage level of normal weight . . . yr
DR_i	the average annual mortality rate for cohort i
*DT	the time increment per simulation cycle . . . yr
*DUR	the duration of the simulation run . . . yrs
*$DURB_m$	the duration of the breeding period for female cohort i . . yr
ENDCAV(t)	time at which the calving season ends in the current year
$FEST_{in}(t)$	average time of first estrus (puberty) for the n^{th} subpopulation in heifer cohort i . . . yr
GEST	the average length of gestation for beef cattle . . yr
GGEST	average daily gain due to pregnency equal to 0.192 kg
$HP_{ijm}(t)$	fraction of the j^{th} subpopulation of heifer cohort i having conceived by time $PT_{ijm}(t)$
$ICOUNT_{kj}(t)$	number of estrus periods during the breeding season for the j^{th} reproducing subpopulation of the k^{th} heifer cohort
$INB_{ij}(t)$	number of estrus periods for the j^{th} subpopulation of cohort i during the breeding period
INTCAV(t)	number of D intervals in the calving season, D = 0.01923 yr
IPREG(t)	an endogenous switch that determines the pregnancy status of the cow herd
*KALLER	a switch that prescribes which combination of subroutines COWCYC, GROFEM, and GROMAL are to be called
KC	number of CDIF intervals in calving period BEGCAV(t) to ENDCAV(t)
$KCNT_i(t)$	a counter used to determine the number of subpopulations in heifer cohort i passing into the mature cow cohort 1 prior to and during the calving season
*KFEEDQ	a switch that prescribes the method of feed allocation being used
*KK_i	the number of delay stages of subpopulations for cohort i

KM	the number of K-1 points in the array of average monthly milk yields
$KNOWS_i(t)$	the current number of stages $\leq KK_i(t)$ in the discrete delay for cohort i
KPPD	number of K-1 points in the array of postpartum estrus times $PCTP_k$
KW	the number of K-1 points in the array of dry matter intake fractions PDI_k
LAC(t)	an endogenous switch that determines the current lactation status of the herd
$MAXHF_i(t)$	a counter used to determine the number of subpopulations having pregnant animals in heifer cohort i
ML(t)	the number of months in the calving season
MOMX(t)	the number of months which have passed within the calving season or the total number of months within the calving season; $0 \leq MOMX(t) \leq ML(t)$
$NR_i(t)$	minimum delay stage separating young heifers from older heifers in conort i
NRUN	number of required simulation runs
$OLDCP_{ij}(t)$	values of PCP_j and HP_{ij} computed in the previous year
$OROUT_i(t)$	delay output rate for cohort i computed at time t-dt
$PCC_{im}(t)$	fraction of the i^{th} subpopulation of cohort 1 calving during the m^{th} CDIF interval from time BEGCAV(t)
$PCP_i(t)$	fraction of the i^{th} subpopulation of cohort 1 pregant at the end of the breeding season
$PCTP_k$	the standard fractions of normal weights used to compute first postpartum estrus
PDI_k	daily dry matter intakes as a fraction of body weight
$PHC_{ikm}(t)$	fraction of the k^{th} subpopulation of heifer cohort i calving during the m^{th} CDIF interval from BEGCAV(t)
$PLR_i(t)$	current annual population loss rate in cohort i
$POP_i(t)$	total number of animals in cohort i
$POPT_n$	the fraction of optimum conception rate due to age for cohort i

$PPW_{ij}(t)$	postpartum or yearling weight as a fraction of expected weight for the j^{th} subpopulation of cohort i
*PRTCHG	time at which the frequency of printing is to be changed
*PRTVL1	initial time interval between printouts of model variables
*PRTVL2	subsequent time intervals between printouts of model variables as directed by PRTCHG
$PT_{ijm}(t)$	average time of service for the j^{th} subpopulation of heifer cohort i corresponding to the m^{th} estrus period of the breeding period
*$RHGAL_i(t)$	roughage allocation for cohort i . . . kg
$RIN_{ij}(t)$	intermediate delay rate corresponding to the $(KK_i+1-j)^{th}$ subpopulation of cohort i
$ROUT_i(t)$	current output rate of animals from cohort i
$RPOP_i(t)$	total number of females capable of reproducing, adjusted for heifers sifting into cohort 1
$RTDN_i(t)$	total number of kilograms of roughage TDN consumed in the current time interval by cohort i
$SCNEW_k(t)$	sum of heifers from cohort i sifting into cohort 1 prior to and during the calving period
*SELPRT	switch that determines whether or not a selected print-out of model variables is provided
SMM	smallest time unit corresponding to $YMILK_1$ and equal to 0.0 time since BEGCAV(t)
$SUBPOP_{ij}(t)$	current number of animals in the j^{th} subpopulation of cohort i and corresponding to the j^{th} stage in $DELAY_i$
T	the current time . . . yr
*$TBRD_i$	time in the year when breeding is to begin for female cohort i
$TBRTH_{km}(t)$	average birth time of the m^{th} subpopulation of heifer cohort k
*TCVWN	average age at which calves are to be weaned . . . yr
$TDMIC_i(t)$	total dry matter intake of concentrates for cohort i during the current DT time period
$TDMIR_i(t)$	total dry matter intake of roughages for cohort i during the current DT time period

*$TDNC_i(t)$	fraction of TDN in $CNCAL_i(t)$
TDNM	fraction of TDN in milk on a 100% dry matter basis
*$TDNR_i(t)$	fraction of TDN in $RHGAL_i(t)$
TEBC(t)	time elapsed since the begining of calving
$TEST_{ij}(t)$	the estimated time of first postpsrtum estrus in cohort 1; the estimated time of first estrus of heifers in cohort i
*TMINT	time interval between the calling of subroutine NAMLST by the main program BEEF
*TMLST	the first time after initialization within each run that NAMLST is called
TPOP(t)	the total herd population
TWEAN(t)	the time in the current year that weaning takes place
TYRLNG(t)	time in the year when the average age of younger heifers is one year
$W_{ij}(t)$	average current weight of animals in the j^{th} subpopulation of cohort i
WDIF	the weight increment between PDI_k points used in computing dry matter intake as a fraction of body weight
$WEANWT_{km}(t)$	weaning weight of the m^{th} subpopulation of younger heifers in cohort k
$WF_j(t)$	weighting factors for the j^{th} subpopulation of cohort 1 to account for population shift from the time of breeding to the time of calving
$WFEST_{ij}(t)$	weight at first estrus (puberty) of the j^{th} subpopulation of heifer cohort i
WSM	the smallest weight unit corresponding to PDI_1 equal to 0.0
$YMILK_n$	average milk yield for beef cows in the n^{th} lactation month

Reader's Note: Several functions are used in various equations in the text and are defined as follows:

int ( ) = the integer value of the enclosed value.
max ( ) = selects the term having the largest value of those enclosed.
min ( ) = selects the term having the smallest value of those enclosed.

APPENDIX B

APPENDIX B

GLOSSARY OF BLOCK DIAGRAM TERMS

TERM		
Diagram	Computer	
A	$ADGWS_{km}$	average daily gain from weaning to one year for heifers
AD_i	$ADDRT_i$	animals purchased and added to cohort i
AFEST	$AFEST_{km}$	age of heifers at puberty
AMLK	$YMILK_k$	average monthly milk yields
AVM	AVMLK	current average milk yield for the j^{th} subpopulation of cohort 1
AWP	AWPUB	subroutine which computes age and weight of heifers at puberty
AWT	---	average weights of 2-year-old subpopulations in cohorts 2 and 3
B	BCOW, BREP BBRD	number of calves born in current year to reproducing females in cohorts 1, 2, and 3
BH	ROUT3	annual rate of heifers leaving cohort 3
BTH	BIRTH2, BIRAT	subroutines where the current fraction of calves born to reproducing females in cohorts 1, 2, and 3 are determined
BWT	W_{81}	birth weight of female calves
C1	C1	fraction of calves which are female
C3	C3	fraction of female calves to be fed as market heifers
C5	C5	fraction of female calves saved as replacement heifers
C8	C8	culling rate of cows in cohort 1
C9	C9	fraction of female calves sold at weaning
C10	C10	fraction of replacement heifers to enter the breeding herd

C11	C11	fraction of bred heifers culled
C12	1-C9-C5-C3	fraction of female calves saved as bred heifers
C13	1-C10	fraction of replacement heifers culled
C14	1-C11	fraction of bred heifers to enter breeding herd
CA_i	$CNCAL_i$	concentrate allocation for cohort i
CPT	CPAT, CTIM	calving fractions and times for cohorts 1, 2, and 3
d.	---	denominator of a division function
D_i	$DELAY_i$	duration of time delay for cohort i
DEL	DLVDPL, DVDPLR, DLVDPL	delay function which advances populations through time
DG	$DGAIN_{ij}$	average daily gain for $SUBPOP_{ij}$
DI	$TDMIR_i$, $TDMIC_i$	total dry matter intake of roughages and concentrates by cohort i in the current time interval
EL	SMLK	total milk produced in the current time interval by $SUBPOP_{ij}$
FC	$SUBPOP_{81}$	current number of female calves born
FEST	$FEST_{km}$	time that puberty occurs in heifers
FPC	RHGPC, CNCPC	roughage and concentrate allocations per animal per day
GEST	GEST	duration of gestation
GG	GGEST	average daily gain due to pregnancy
GL	GL	total daily gain of lactating cows from cohort 1
GO	GNL	total daily gain of non-lactating cows of cohort 1
GP	GP	total daily gain of cows due to pregnancy
HP_k	HP_k	fraction of heifers pregnant in cohorts 2 and 3
KK	KK_i	number of stages in the delay for cohort i
KM	KM	k-1 months in the lactation period
L	PCCV, CPOP	fraction of cows currently calving; number of cows lactating

LAC	ALAC	subroutine which computes percentage of females which will calve in time interval CDIF
M	0.95	correction factor used to estimate milk yield of heifers
MLK	DMMLK	average daily milk consumed by calves on a 100% dry matter basis
N	EMAR, EMAC, EGAR, EGAC	net energy for maintenance and net energy for gain available from roughages and concentrates
NL	HFNL, COWNL	females currently not lactating
NP	---	females currently not pregnant
P	HPREG, COWP	females currently pregnant
P_i	POP_i	total current population in cohort i
PLR	PLR_i	population loss rate in cohort i
RA_i	$RHGAL_i$	roughage allocation for cohort i
REP	REPRO	subroutine which computes pregnancy fractions and times
RH	ROUT2	annual rate of heifers leaving cohort 2
RPOP	$RPOP_i$	number of females in cohorts 1, 2, and 3 capable of reproducing
S	$SALES_k$	number of animals sold from cohort k
SP	$SUBPOP_{ij}$	number of animals in stage j of $DELAY_i$
TB	$TBRTH_{km}$	time of birth of heifers
TDN	$TDNR_i$, $TDNC_i$	TDN value of roughage and concentrate for cohort i
TSC	TSC	time since calving
TW	TW	time of weaning in current year
V	CNVRT	subroutine which converts TDN to NE_m and NE_g
W_i	W_{ij}	average weight of $SUBPOP_{ij}$
WFEST	$WFEST_{km}$	weight at puberty for heifers
WL	WLCV	weight loss due to calving
WNWT	$WEANWT_{km}$	weaning weight of female calves
Y	1/DT	number of DT time intervals in one year

DEFINITION OF BLOCK DIAGRAM FUNCTIONS

NOTE: $DI_i(t) = \left\{\sum_{j=1}^{KK_i} DMIR_{ij}(t)*SUBPOP_{ij}(t)*DAYS\right\}, \left\{\sum_{j=1}^{KK_i} DMIC_{ij}(t)*SUBPOP_{ij}(t)*DAYS\right\}$

$FPC(t) = RHGPC(t), CNCPC(t)$

Terms used in the function definitions;

NE_{gm} = net energy available for gain from milk,

NE_{mm} = net energy available for maintenance from milk,

NE_{gr} = net energy available for gain from roughages,

NE_{mr} = net energy available for maintenance from roughages,

NE_{gc} = net energy available for gain from concentrates,

NE_{mc} = net energy available for maintenance from concentrates.

All of the above values are on a 100% dry matter basis.

$PD(t) = f(PDI_k, WSM, WDIF, KW, W_{ij}(t))$ = dry matter intake/kg body weight

$RCPC(t) = CNCPC(t) + RHGPC(t)$

$FI(t) = DMIR(t) + DMIC(t)$

$WM_{ij}(t) = W_{ij}(t)^{.75}$

Function F_1

A. If $(TSC(t) - TAMD) \leq 0$,

$MLK(t) = 0.12*\alpha$

B. Otherwise,

$MLK(t) \leq (0.022603*WM_{8j}(t) + 2.115*TSC(t))$

where,

$\alpha = f(AMLK, SMM, DIFM, KM, TSC(t))$ = average daily milk yield

$TAMD = 0.15$ years.

Function F2

$$DG_{8j}(t) = \frac{\left(0.003139 + \frac{0.0506*EG(t)}{WM_{j}(t)}\right)^{.5} - 0.05603}{0.0253}$$

where,

A. If $(TSC(t) - TAMD) \leq 0$,

$DMIR(t) = 0$,

$DMIC(t) = 0$,

$$EG(t) = NE_{gm}*CFE*\left(MLK(t) - \frac{0.077*WM_{8j}(t)}{NE_{mm}*CFE}\right)$$

B. Otherwise,

$$EG(t) = CFE*\frac{G(t)}{D(t)} * \left(D(t) - \frac{0.077*WM_{8j}(t)*D(t)}{M(t)*CFE}\right)$$

where,

$D(t) = DMIR(t) + DMIC(t) + MLK(t)$

$G(t) = NE_{gm}*MLK(t) + NE_{gr}*DMIR(t) + NE_{gc}*DMIC(t)$

$M(t) = NE_{mm}*MLK(t) + NE_{mr}*DMIR(t) + NE_{mc}*DMIC(t)$

and

1. If $RCPC(t) > (DMX*WM_{j}(t) - MLK(t))$,

$$DMIR(t) = \frac{CFD*RHGPC(t)*(DMX*WM_{8j}(t) - MLK(t))}{RCPC(t)}$$

$$DMIC(t) = \frac{CNCPC(t)*(DMX*WM_{8j}(t) - MLK(t))}{RCPC(t)}$$

2. Otherwise,

$DMIR(t) = RHGPC(t)*CFD$

$DMIC(t) = CNCPC(t)$

Function F3

$$DG_{9j}(t) = \frac{\left(0.003139 + \frac{0.0506*EG(t)}{WM_{9j}(t)}\right)^{.5} - 0.05603}{0.0253}$$

where,

$$EG(t) = CFE* \frac{G(t)}{FI(t)} * \left(FI(t) - \frac{0.077*WM9_j(t)*FI(t)}{M(t)*CFE} \right)$$

and

$$G(t) = NE_{gr}*DMIR(t) + NE_{gc}*DMIC(t)$$

$$M(t) = NE_{mr}*DMIR(t) + NE_{mc}*DMIC(t)$$

and where,

A. If $(W9_j(t)*PD(t)) \leq RCPC(t)$,

$$DMIC(t) = \frac{PD(t)*W9_j(t)*CNCPC(t)}{RCPC(t)}$$

$$DMIR(t) = (PD(t)*W9_j(t) - DMIC(t))*CFD$$

B. Otherwise,

$$DMIC(t) = CNCPC(t)$$

$$DMIR(t) = RHGPC(t)*CFD.$$

Function F_4

$$DG_{mj}(t) = \frac{\left(0.003139 + \frac{0.0506*EG(t)}{WM_{mj}(t)} \right) - 0.05603}{0.0253} + AWCH(t)$$

where,

$$AWCH(t) = GGEST*HP_{ikm}(t) - \frac{\beta*GGEST*GEST}{DT}$$

$$EG(t) = CFE*\frac{G(t)}{FI(t)}*\left(FI(t) - \frac{(0.077*WM_{mj}(t) + AEL(t))*FI(t)}{M(t)*CFE} \right)$$

and,

$$G(t) = NE_{gr}*DMIR(t) + NE_{gc}*DMIC(t)$$

$$M(t) = NE_{mr}*DMIR(t) + NE_{mc}*DMIC(t)$$

β = f(PHC, CSM, CDIF, KC, t) = fraction of heifers calving

$$AEL(t) = (WM_{mj}(t)*0.024*SCPOP_j(t)) + 0.690* \sum_{k=1}^{MOMX} (\gamma_k*SUBPOP_{mj}(t)*\delta_k*0.95)$$

γ = f(AMLK, SMM, DIFM, KM, k*DM) = average milk yield for the k^{th} month

δ = f(PHC, SMLL, CDIF, KC, k*DM) = fraction of heifers lactating in the k^{th} month

$$SCPOP_j(t) = \sum_{k=1}^{MOMX} (\delta_k * SUBPOP_{mj}(t))$$

$$DMIR(t) = DIRL(t) + DIRNL(t)$$

$$DMIC(t) = DICL(t) + DICNL(t)$$

A. For lactating heifers:

1. If $(PD(t)*W_{mj}(t)*1.4425) \leq RCPC(t)$,

$$DICL(t) = \frac{SCPOP_j(t)*PD(t)*W_{mj}(t)*1.4425*CNCPC(t)}{RCPC(t)}$$

$$DIRL(t) = CFD*(SCPOP(t)*PD(t)*W_{mj}(t)*1.4425 - DICL(t))$$

2. Otherwise,

$$DICL(t) = CNCPC(t)*SCPOP(t)$$

$$DIRL(t) = RHGPC(t)*SCPOP(t)*CFD$$

B. For non-lactating heifers:

1. If $(PD(t)*W_{mj}(t)) \leq RCPC(t)$,

$$DICNL(t) = \frac{(SUBPOP_{mj}(t) - SCPOP_j(t))*PD(t)*W_{mj}(t)*CNCPC(t)}{RCPC(t)}$$

$$DIRNL(t) = CFD*\{(SUBPOP_{mj}(t) - SCPOP(t))*PD(t)*W_{mj}(t) - DICNL(t)\}$$

2. Otherwise,

$$DICNL(t) = CNCPC(t)*(SUBPOP_{mj}(t) - SCPOP_j(t))$$

$$DIRNL(t) = CFD*RHGPC(t)*(SUBPOP_{mj}(t) - SCPOP_j(t))$$

<u>Function F_6</u>

$$AVM_j(t) = \frac{\sum_{k=1}^{MOMX} (\gamma_k * \phi_k * SUBPOP_{1j}(t))}{L_j(t)}$$

where,

γ_k = as in Function F_4

$\phi_k = f(PCC, SMLL, CDIF, KC, k*DM)$ = fraction of cows lactating

$$L_j(t) = \sum_{k=1}^{MOMX} (\phi_k * SUBPOP1_j(t))$$

Function F_5

$$DMIR_j(t) = \frac{DIRL_j(t) + DIRNL_j(t)}{SUBPOP1_j(t)}$$

$$DMIC_j(t) = \frac{DICL_j(t) + DICNL_j(t)}{SUBPOP1_j(t)}$$

I. For lactating cows:

A. If $qLAC(t) \leq 0$,

$GL(t) = 0$,

$DICL(t) = 0$,

$DIRL(t) = 0$

where $qLAC(t)$ = the endogenous switch that indicates lactating cows

B. Otherwise,

$$GL_j(t) = \frac{DIL_j(t) - L_j(t)*\{W1_j(t)*0.0108 + AVM_j(t)*0.3041\}}{2.30}$$

where,

$$DIL_j(t) = DIRL_j(t)*TDNR1 + DICL_j(t)*TDNC1$$

1. If $(PD(t)*1.4425*W1_j(t)) \leq RCPC_j(t)$,

$$DICL_j(t) = \frac{L_j(t)*PD(t)*1.4425*W1_j(t)*CNCPC(t)}{RCPC(t)}$$

$$DIRL_j(t) = CFD*(PD(t)*W1_j(t)*1.4425*L_j(t) - DICL_j(t))$$

2. Otherwise,

$$DICL_j(t) = CNCPC(t)*L_j(t)$$

$$DIRL_j(t) = RHGPC(t)*CFD*L_j(t)$$

II. For non-lactating cows:

$$NL_j(t) = SUBPOP_j(t) - L_j(t)$$

$$GNL_j(t) = \frac{(DICNL_j(t)*TDNC + DIRNL_j(t)*TDNR) - (NL_j(t)*W1_j(t)*0.0081)}{1.80}$$

where,

A. If $(PD(t)*W1_j(t)) \leq RCPC(t)$,

$$DICNL_j(t) = \frac{NL_j(t)*PD(t)*W1_j(t)*CNCPC(t)}{RCPC(t)}$$

$$DIRNL_j(t) = CFD*(NL_j(t)*PD(t)*W1_j(t) - DICNL_j(t))$$

B. Otherwise,

$$DICNL_j(t) = CNCPC(t)*NL_j(t)$$

$$DIRNL_j(t) = RHGPC(t)*CFD*NL_j(t)$$

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