A Microcomputer Simulation to Evaluate Management Strategies For Rearing Dairy Replacements.

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Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Animal Science (Dairy)

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April 18, 1997
Blacksburg, Virginia

Keywords: Dairy, Heifer, Growth, Modeling, Simulation

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ABSTRACT

A microcomputer simulation was developed as a tool for analyzing the dairy replacement enterprise. The simulation was constructed using a spreadsheet, and equations were developed using stepwise regression procedures. The simulation predicted BW, DMI, and fixed and variable costs for each week of a heifer's life from birth to calving. After calving, milk yield, feed costs, and fixed costs were predicted for first lactation. Variation was estimated for each predicted variable, thus enabling normal distribution of predicted values. The simulation was used to analyze profitability of various growth rate scenarios and marginal costs associated with changing feed costs, heat detection efficiency, death loss, and abortion rate. For the growth rate analysis, six scenarios were evaluated: 1) normal growth from 5 wk to calving, 2) accelerated growth from 5 wk to calving, 3) slow growth from 5 wk to calving, 4) normal growth from 5 wk to 14 mo and accelerated growth from 14 mo to calving, 5) accelerated growth from 5 wk to 14 mo and control growth from 14 mo to calving, and 6) slow growth from 5 wk to 14 mo and accelerated growth from 14 mo to calving. Average daily gain from birth to calving was 0.78, 0.90, 0.62, 0.78, 0.75, and 0.80 kg/d, and age at calving was 25.1, 23.1, 27.4, 23.1, 23.0, and 23.1 mo, respectively. Total rearing cost from birth to calving was 1246, 1220, 1275, 1148, 1148, and 1138 $/heifer, and net profit through first lactation was 399, 407, 319, 441, 432, and 463 $/heifer, respectively. Results suggest modest growth rates from birth to calving (0.75 to 0.80 kg/d) with reduced first calving age (<24 mo) is most desirable, and delayed calving (>24 mo) is costly and merits higher growth rates with earlier breeding. Increasing feed costs, death loss at birth through weaning, or abortion rate one percentage point increased rearing costs 7.33, 2.40, and 9.10 $/heifer. Improving heat detection efficiency one percentage point reduced rearing costs $2.80/heifer. For the heat detection analysis, the relationship between age at first calving and total rearing costs was -584.38 + 73.49 x calving age in mo (R-squared = 0.97), for ages at first calving from 24.4 to 26.6 mo. Results of this research agree with field observations that managers should strive for early calving (<24 mo) and modest growth rates (0.75 to 0.80 kg/d) to maximize profitability of the replacement enterprise. In addition, death loss, abortion rate, and heat detection efficiency are variables that a manager must control to minimize heifer rearing costs.

Acknowledgments

While at Virginia Tech, I have been fortunate to work with and learn from many individuals; it is impossible to properly thank all who have contributed to my education.

First, I would like to express gratitude to the John Lee Pratt Foundation for the Animal Nutrition Fellowship they provided, and to the Virginia State Dairymen's Association for financial contributions to this project.

I am sincerely grateful to Dr. R. E. James; I will never be able to repay the contribution he has made to my life. His guidance, patience, encouragement, and understanding have been invaluable in my training as a student and growth as a person. His demeanor and approach to life are qualities I hope to obtain some day.

I am also extremely grateful to Dr. M. L. McGilliard for his friendship and guidance. He has set a standard of excellence and dedication that will serve as an example to follow throughout my career. From his humor, to his thorough and logical approach to problem solving, I am grateful to have had the opportunity to learn from him. In addition, I would like to express gratitude for his tremendous impact and influence on this research.

Dr. C. E. Polan, my "academic grandfather", has also greatly contributed to my education at Virginia Tech. He always had time to answer my many questions, and continually challenged me to think and better understand dairy cattle nutrition. I also admire him for his approach to life.

I wish to extend gratitude to the other members of my committee, Dr. C. C. Stallings and Dr. T. L. Bailey. I am most grateful to Dr. Stallings for providing the opportunity to work with the Extension program in the Department of Dairy Science. It was a gratifying experience that contributed greatly to my career choice. I am grateful to Dr. Bailey for his significant contributions to this research. In addition, thanks to Dr. R. E. Pearson for his input and suggestions concerning this research.

This research would not have been possible without data sets contributed by Dr. Hugh Chester-Jones, University of Minnesota.

I also wish to thank all the graduate students at Virginia Tech who have provided cherished friendships and lively discussion. In particular, Amin Amadzadeh, Steve Ellis, Pat French, Luis Rodriguez, Miriam Weber, and David Winston have been good friends.

The Virginia Tech Dairy Center employees have been very gracious in ensuring research trials at the farm are conducted appropriately. Their dedication is appreciated.

Thanks to Wilson and Gail Bethard, as always, for their love and support. I am truly thankful to have such wonderful parents.

And finally, thanks most of all to my wife Rachel. Completion of this degree would not have been possible without the considerable sacrifices she made. She is the person I hold in highest esteem, and I dedicate this dissertation to her.

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Introduction

The replacement heifer enterprise is a critical component of a dairy farm. Although youngstock do not normally generate income for a dairy producer, the cost of rearing heifers is a substantial portion of operating expenses on a dairy farm. Typically, heifer rearing accounts for 15 to 20 percent of total costs of producing milk, ranking second only to feed costs for the milking herd (Heinrichs, 1996). Therefore, management schemes that optimize performance at minimum cost will have a large, positive impact on profitability of the farm.

The goal of a replacement program is to produce high quality replacements at a minimum cost that have potential for high production. Factors associated with achieving this goal include average age at first calving between 22 and 24 mo (Cady and Smith, 1996; Heinrichs, 1993; Keown and Everett, 1986; Gill and Allaire, 1976) and post calving BWs between 540 and 570 kg (Keown and Everett, 1986).

The purpose of this research is to evaluate the replacement program on modern dairy farms, identifying management practices that are most profitable and practical. Specifically, the objectives of this project are to:

1. develop a heifer simulation model which is an improvement on the simulations of Toro (1987) and Foster (1988);
2. determine optimal growth rates that minimize rearing costs and maximize profit through first lactation;
3. determine the cost of heifer rearing under various management schemes;
4. evaluate current BW and age recommendations at first calving;
5. develop an equation to predict growth of Holstein heifers;
6. develop an equation to predict first lactation milk yield of Holstein heifers from age and BW at calving;
7. evaluate reproductive management alternatives and their impact on profitability; and
8. evaluate the impact of varying feed costs on rearing costs and profitability through first lactation.

Review of Literature

This review of literature has two primary purposes. The first is to describe animal growth, specifically quantitative aspects that can be described mathematically. The second purpose is to define modeling and simulation and how they can be applied to modeling a biological system such as heifer growth. In particular, two simulations (Foster, 1988; Toro, 1987) concerning heifer management will be reviewed.

Growth

Webster's New World Dictionary (1986) defines growth as "the process of growing or developing, …a gradual development toward maturity". In reality, growth does not have such a simple and constant meaning. Gall (1969) states that growth is not even a scientific term, rather a label whose definition varies depending on the user. For example, even though adipose tissue of an aging man grows, the individual may not increase in total mass. From a physiological perspective, Beever et al. (1992) defined animal growth as the increase in size and the change in functional capabilities of the various tissues and organs within the animal. Beever also provided a simpler definition of growth: the net accretion of protein and fat in respective tissues, controlled by nutrition, environment and the genetic capacity to grow. Russel (1969) points out that growth does not have standard units, principally because it can be qualitative or quantitative. Quantitative characteristics include weight, height, and number of cells, and qualitative characteristics include prepuberty and puberty. In addition, Russel (1969) defined time associated with growth as qualitative (egg, larva, lymph, or adult stage) or quantitative (minutes, hours, days).

The biological process of growth involves hyperplasia (increase in cell number) and hypertrophy (increase in cell size). Tissue DNA content is an estimation of cell numbers, while the ratio of tissue protein to DNA is an estimation of cell size. In all farm animals, early prenatal growth is accomplished by hyperplasia. In pigs, sheep, and cattle, growth during the early post-weaning period involves hyperplasia and hypertrophy. Later growth is achieved mainly by hypertrophy. Postnatal growth (age versus BW) can be fitted to a sigmoid curve. All tissues exhibit sigmoidal growth patterns, but they do not all develop at the same time. Hence, all tissues in the body do not grow at a similar rate at a specific age. Vital organs are well developed at birth, but continue to grow until the later stages of growth. Skeletal and muscle growth slows dramatically after puberty, while fat growth increases at the same time. Laird (1965b) confirmed that growth of various body parts varies, but determined that the sum of growth of the parts was approximate to the growth of the whole animal.

The high prenatal and prepubertal growth rates of vital organs, skeleton, and muscle emphasize the importance of proper nutrition during these stages of growth. The order of development of these three body components is skeleton, muscle, and then fat. Nutrition has the most important influence on growth and development, implying that peak growth rates of tissues are dependent on plane of nutrition. A low plane of nutrition (low energy and protein) can delay maturity, which affects the development of adipose tissue, since adipose tissue growth occurs in late postnatal growth (Grant and Helferich, 1991).

Compensatory Growth

Cattle exhibit compensatory growth when a period of underfeeding and slow gain is followed by a period of overfeeding (energy and CP above NRC requirements). Hogg (1991) defined compensatory growth as the growth rate of an animal fed ad libitum after a period of nutritional stress. He defined nutritional stress as a limitation in the quantity and quality of food required by the animal which will not allow it to express its genetic potential for growth. Diets high in energy, protein, and minerals (15-40% greater than NRC) need to be fed to achieve compensatory growth (Head, 1992). Growth during the compensatory period is more efficient (kg BW gain per kg DM intake), and gains of 1.6 - 2.1 kg/d are possible for dairy heifers (Park et al., 1987).

Park et al. (1987) attempted to improve the growth efficiency of Holstein heifers by utilizing compensatory growth. They used a stair step nutrient regimen, meaning heifers were exposed to alternating periods of underfeeding and overfeeding. Beginning at 7.6 mo of age, a stair step nutrient regimen was used, with alternating 5, 2, 5, 2 mo periods. Treatment heifers were fed 15% below NRC (1978) requirements for energy and protein during the 5 mo (maintenance) periods, and 40% above NRC for the 2 mo (compensatory) periods. Control heifers were fed 100% of NRC throughout the trial. For the 14 mo test period, treatment heifers averaged 0.28 kg ADG and 6.89 kg DMI/d during the maintenance periods, and 1.91 kg/d gain and 9.12 kg DMI/d during the compensatory periods. This resulted in improved growth, energy, and protein efficiency during the compensatory periods compared to the maintenance periods. These workers used the following equations to define efficiency:

Growth Efficiency = kg gain x 100 / kg DMI;
Energy Efficiency = kg gain x 1,000 / (kg DMI x metabolizable energy)
Protein Efficiency = kg gain x 100 / kg protein intake

Compared to control heifers, treatment heifers consumed less DM (7.52 versus 9.36 kg/d, $P < 0.001$) and had greater gains (0.98 versus 0.68 kg/d, $P < 0.001$), resulting in improved growth, energy, and protein efficiency. In addition, treatment heifers had higher first lactation milk yields than the control heifers (23.4 versus 21.3 kg/d).

Park et al. (1989) used a similar stair step nutrient regimen to monitor mammary composition and milk yield. Holstein heifers, averaging 5.5 mo of age, began the first period (3 mo) on a restricted diet (15% below NRC), which was followed by 2 mo on a realignment diet (40% above NRC). The final four period lengths were 5, 2, 5 , and 2 mo respectively, and alternated from the restriction diet to the realignment diet. A control group was fed a diet to meet NRC (1978) recommendations. In two separate studies utilizing this stair step rearing method, Park et al. (1989) found increased ($P < 0.001$) milk yield for the test group (8715 kg versus 7913 kg for study I; 9251 versus 8533 kg for study II). Milk yields for studies I and II covered four and three lactation records, respectively, for each cow. In addition, the test group had 20% more mammary DNA and 200% more mammary RNA than the control group. The increase in mammary RNA could indicate increased concentration of mRNA, specifically casein mRNA. Park et al. (1988) postulated that increased concentration of mammary mRNA alters the expression of milk protein gene, thereby increasing milk protein secretion.

Garstens et al. (1991) reported beef steers exhibit compensatory growth similar to dairy heifers. They fed one group of steers a restricted diet to achieve 0.4 kg/d gain from 245 to 325 kg BW, followed by an ad libitum feeding period until 500 kg BW. The control group was fed ad libitum from 245 to 500 kg BW. Average daily gain from 325 to 500 kg was 1.54 and 1.16 kg/d for compensatory and control heifers, respectively. Gut fill was 10.8 kg less at 325 kg and 8.8 kg less at 500 kg for the compensatory steers. Final empty body fat was lower (24.2 vs 32.4%) and empty body protein (16.6 vs 14.8%) higher in compensatory steers. Net energy requirments for growth (NE_g) were calculated by multiplying energy coefficients for fat (9.39 kcal/g) and protein (5.64 kcal/g) by empty body contents. Consequently, net energy requirements for growth (NE_g) were 18% lower for compensatory steers. They concluded that reduced NE_g and changes in gut fill accounted for most of the compensatory response. In their study, compensatory growth altered nutrient partitioning, resulting in a higher protein, lower fat carcass.

Drouillard et al. (1991) also reported compensatory growth in beef steers, but did so by feeding either energy or protein-limiting diets restricted for either 77 or 154 days. They reported compensatory growth was enhanced by energy restriction more so than protein restriction, and severe energy restriction (.79 NE_g) enhanced compensatory growth more than mild energy restriction (.99 NE_g; control diet 1.26 NE_g). Duration of restriction had minor effects on compensatory growth. This is similar to the response Park et al. (1987) reported with short term restriction in dairy heifers.

Research has shown compensatory growth is substantial and worth consideration. It would be difficult under most practical conditions to rear dairy heifers utilizing several compensatory periods similar to Park et al. However, one or possibly two compensatory periods could be practical. The idea of compensatory growth also alleviates the need for excessive gains prepubertally, provided heifers reach breeding weight at the appropriate age. Slower gaining heifers can catch up during a compensatory period when gains are more efficient. Multiphasic growth curves may be necessary to mathematically describe growth of animals exhibiting compensatory growth.

Mathematical Models of Growth

Many mathematical equations representing growth have been developed (Brody, 1945; Guttman and Guttman, 1965; Fabens, 1965; Heinichs and Hargrove, 1987; Laird et al., 1965a; Laird, 1966; Richards, 1959). A growth curve is simply a mathematical relation between weight of an animal and time (Fabens, 1965). Growth curves relate the interrelationships of the genetic ability of an animal to grow and mature and the environment in which the animal grows (Fitzhugh, 1976). Many of the models are based on a linear relationship between age and weight, similar to: $weight = a + b(age)$; where a = intercept and b = slope (Russel, 1969). The models are generally empirical, static, and deterministic in form. Therefore, the application of each model across a population under varied environmental conditions is limited. Other models simply fit a polynomial equation to a data set (Heinrichs and Hargrove, 1987). Although this approach may be sound statistically, the coefficients obtained may not have biological meaning.

Ludwig von Bertalanffy (1957), in studies of growth functions across many species, attempted to relate growth to metabolic rate, thus providing a physiological basis for growth functions. One principle he followed was the “surface rule” of metabolism, which was discovered by Rubner in 1902 and explained by Bertalanffy in 1957. The surface rule implies that BW is in proportion to metabolic rate, regardless of age or species. Rubner discovered that metabolic rate (measured by oxygen consumption or calorie production per kilogram BW) decreased as body size increased, but remained approximately constant in proportion to body surface. This was based on Rubner's contention that mammals produce approximately 1000 calories/d per square meter of body surface. Warm blooded animals maintain a constant temperature with heat dissipation through the body surface. Therefore the same number of calories must be produced per unit of surface area to maintain constant body temperature. However, measuring the surface area of animals is difficult, therefore a mathematical calculation is applied: the surface area of a body can be expressed as 2/3 power of weight, since the cubic root of the volume or weight is a linear dimension, and therefore its square has the dimension of a surface. For example, a cube 3 x 3 x 3 meters has a volume of 27 cubic meters; the surface area for one side is 9 square meters (3 x 3), which is equal to $27^{2/3}$. A cube has six sides, so a constant of 6 would need to be multiplied by the surface area of one side (6 x 9). Accordingly, the surface area of a body can be estimated by $(BW)^{2/3}$ multiplied by a constant, following the allometric formula (Huxley, 1932) $M = bW^{\alpha}$, where M is the metabolic rate, W is BW, and b and α are constants. Therefore, the surface rule of metabolism implies that the basal metabolic rate is proportional to the 2/3 power of BW.

Bertalanffy (1957) further examined the metabolic rate and BW relationship and found that the surface rule unexpectedly applied best to cold blooded animals that were not thermoregulators. In addition, he found gill-breathing animals closely follow the surface rule. He also discovered that pulse rate in mammals is approximately in proportion to the ¾ power of BW. This was true for a wide range of species, from elephants to dwarf bats. Consequently, Bertalanffy described three theoretical metabolic rates. First is a metabolic rate of 2/3 power of BW following the surface rule. Second is a metabolic rate in proportion to BW, and a third is intermediate between the first two extremes. He determined the latter two by rewriting the allometric formula, as $\log M = \log b + \alpha \log W$. If metabolic rate is plotted against BW in this equation, a straight line with slope α results. If $\alpha = 2/3$, then the surface rule applies, if $\alpha = 1$, then the slope is 45^{o} and the metabolic rate is proportional to BW. If $1 > \alpha > 2/3$, then an intermediate rate of metabolism applies.

An accepted definition of growth is the difference between catabolic (breaking down of components) and anabolic (synthesis of components) processes in the animal. A simple formula describing this relationship was given by Bertalanffy in 1957:

$$\left(\frac{dw}{dt}\right) = pW^{m} - kW^{n}$$

where p and k are constants of anabolism and catabolism, respectively, and W is BW. The powers m and n indicate that catabolism and anabolism are in some proportion to BW. Bertalanffy (1951) found that the rate of catabolism was directly proportional to weight, implying that $n = 1$. Anabolism appears to be different, however. Substrate and energy availability are limiting factors to anabolism, therefore the rate of metabolism should influence the rate of anabolism. Bertalanffy (1957) theorized that anabolic rate and BW relationships are similar to metabolic rate and BW relationships, implying that metabolic rate can predict growth type. In other words, if metabolism in a particular species follows the surface rule (weight$^{2/3}$), then in the simple growth equation, $(\frac{dw}{dt}) = pW^m - kW^n$, n would equal 2/3 and m would equal 1. The n for bovines is often cited as 0.75 (Brody, 1945; National Research Council, 1996), also commonly referred to as metabolic BW (BW$^{.75}$). This simple growth equation can be transformed mathematically into the monomolecular function to the third power (Fabens, 1965).

Non-Linear Growth Equations

Other nonlinear equations of animal growth have been described that have a physiological basis similar to the approach of Bertalanffy, implying that the parameters have biological meaning. Richards (1959) and Perotto et al. (1992) described four such equations (Table 1). The defining relation in Table 1 defines how absolute growth rate changes with weight. In the equations for these curves, the parameters A, b, and k are constant throughout the growth curve of an individual animal, but vary depending on the animal in question. The mature weight (A) is the asymptotic or maximal size (asymptote being tangent to the curve at infinity). The parameter b is a constant of integration, determined by solving for b when W is initial weight. The paramater k establishes the rate at which a logarithmic function of W changes linearly with time. Biologically, k can be interpreted as a maturing index, relating how quickly W approaches A (Perotto et al., 1992). The parameter M determines the proportion of A at the inflection point, or the proportion of final size when growth rate slows. Therefore, M is responsible for the shape differences between the curves. For the monomolecular and logistic functions, M is fixed at 1 and -1, respectively. For the Gompertz function, M approaches infinity, and for the Richards function, M can be any positive value.

The monomolecular or Brody function (Brody, 1945) is of the decaying exponential type with no inflection point. Fabens (1965) described a similar function based on the work of Bertalanffy. For these functions, the highest growth rate occurs at birth and decreases continually (Figure 1). As an animal gets older, W becomes closer to A, but never passes A. For these functions, at age $\ln 2/k$ the animal is halfway between initial size and asymptotic size A. As age and W increase, growth rate declines linearly (Figure 1).

The autocatalytic or logistic curve is symmetrical around its inflection point. Growth rate increases with age and W until the inflection point, where it decreases until maximum age is reached. The Gompertz curve has an inflection point earlier than a logistic curve, precisely when $W = A/e$. In addition, the Gompertz curve is asymmetrical about its inflection point. The Richards function is essentially a modification of the monomolecular curve, with M added as an exponent to adjust the proportion of mature size at the inflection point. Richards (1959) adjusted the monomolecular curve with M to add flexibility, hence increasing its usefulness. Therefore, when $M = 1$, the monomolecular and Richards functions are identical.

Multiphasic Growth Curves

The previously described functions (monomolecular, logistic, Gompertz, Bertalanffy, and Richards) all assume growth is a continuous process resulting in a smooth shaped growth curve. A non-continuous growth curve was detected in mice by Gall and Kyle (1968) and Lang and

Legates (1969). The growth curve (Figure 2a) was in the form of two phases, corresponding to an average daily gain curve with two peaks (Figure 2b). It was therefore suggested by Eisen et al. (1969) that the growth curve of mice be analyzed in two parts. Brody and Ragsdale (1921) reported a two-phase postnatal growth curve in Jersey and Holstein cows, while Brody (1921) found a four phase growth curve in domestic fowl, two before hatching and two after. Koops and Grossman (1991) used a multiphasic function to describe growth of fat adjusted weight in pigs. Koops (1986) used human growth in height as a classical example of a multiphasic growth curve, with growth peaks for boys at age 7 and 14. From a practical standpoint, multiphasic growth curves may result from changes in environment.

Most early multiphasic growth curves were simply two logistic curves determined separately and combined. Koops (1989) devised a single function to mathematically describe two combined logistic curves, resulting in a curve resembling two overlapping sigmoidal curves. The formula was defined as:

$$Y_t = \frac{a_1}{1+e^{-km(t-b_1)}} + \frac{a_2}{1+e^{-km(t-b_2)}}$$

where Y_t = BW at age t, a_1 = asymptotic BW during the first phase, b_1 = age at first inflection point, km = maturation rate, a_2 = asymptotic BW during the second phase, and b_2 = age at second inflection point. Mature or asymptotic BW is estimated by (a_1 + a_2). Koenen and Groen (1996) used this function to describe growth of Dutch Black and White, Holstein, and crossbred cattle. They found this function superior to the Gompertz, Bertalanffy, logistic, and Richards functions. Koops and Grossman (1991) proposed another multiphasic growth function:

$$y^t = \sum_{i=1}^{n} [a_i\{1 + tanh(b_i(t-c_i))\}]$$

with a corresponding gain function (first derivative):

$$y\text{☠}^{t} = \sum_{i=1}^{n} [a_ib_i\{1 - tanh^2(b_i(t-c_i))\}]$$

where y^t is weight at age t, $y\text{☠}^{t}$ is gain, and n is number of growth phases. Each phase is determined by asymptotic value (2a), duration (4/b), and age at maximum gain (c). Units for asymptotic value are scale of measurement (for example, kg for BW), and time for duration. With either of these single mathematical functions (Koops, 1989; Koops and Grossman, 1991), multiphasic growth analysis is simplified.

Applications of Growth Curves

Fitting a growth curve to a group of animal weights assumes the actual growth curve is similar in shape to the curve being fit. With this assumption, parameters are estimated from field data. Fitting consists of estimating parameters such that the differences between observed and predicted values (residuals) are minimized. A “good fit” would be a situation where residuals are small. Graphical analysis is helpful in selecting a growth curve to fit.

Figure 3 displays growth curves representing the monomolecular, logistic, Gompertz, and Richards functions. These curves are intended to resemble growth of Holstein heifers, with a birth weight of 40 kg, and a mature weight of 726 kg. The parameter *k* (maturing index) is a large determinant of the growth rate or slope of the curves. For the monomolecular and Richards functions, at age ln2/*k* the animal is halfway between initial size and asymptotic size *A*. For the other functions, *k* was determined to match the growth pattern of the animals in question. For the Richards function, *M* was chosen to be 2. The Richards and monomolecular functions are identical when *M* = 1, providing *k* is constant.

The Gompertz growth curve has been used to desribe the growth of poultry (Barbato, 1991), and Doren et al. (1989) used the monomolecular function to describe growth of beef bulls. In analyzing growth curves of beef cows, Denise and Brinks (1985) found minor differences between the Richards and monomolecular functions. They argue, however, that the monomolecular function was faster and less costly to compute. The Richards function was slightly better due to smaller sums of squares (5429.1 versus 6054.0) and a better fit to actual data points. Perotto et al. (1992) compared the Gompertz, monomolecular, Richards, and logistic functions for describing growth of Canadian Holstein and Ayrshire dairy cattle. The monomolecular and logistic functions overestimated and underestimated mature weight, respectively. The Gompertz and logistic functions overestimated birth weight. They concluded the Richards function adequately described growth of dairy cattle. Brown et al. (1976) compared five nonlinear models (Bertalanffy, Gompertz, monomolecular, Richards, and logistic) to describe growth of beef heifers. Similar to Denise and Brinks (1985), they found the Richards function to be most suitable, although it was computationally most difficult.

Heinrichs and Hargrove (1987) did not fit their data to a particular growth curve, rather they computed a third order regression model. Their regression parameters for mean weight and height, mean plus one standard deviation, and mean minus one standard deviation are in Table 2. Using R-squared as a measure, the equations appear to explain the data accurately (R-squared > 0.99). However, a high R-squared is misleading in this situation because BW means for each month as opposed to actual data were used to compute regression coefficients. By using means the variation from animal to animal was removed, resulting in a regression line that closely fit each monthly data point. The R-squared would presumably be much lower if all data points were used in the regression. The three equations for weight are displayed graphically in Figure 4. Unlike the growth functions previously described, there does not appear to be an asymptote or inflection point. Figures 5a - 5d contain graphs comparing the monomolecular, logistic, Gompertz, and Richards functions to the Heinrichs and Hargrove mean BW equation. For each function, *b* was calculated such that birth weight prediction was 40 kg, and *k* was adjusted such that BW at 24 mo was similar to the Heinrichs and Hargrove equation. For the Richards function, *m* was adjusted until the curves appeared similar in shape. Based on these graphs, it appears the Richards and Gompertz functions crudely resemble the Heinrichs and Hargrove equation. Statistical analysis could verify this conclusion.

Growth Rates

Brody (1945) defined quantitative growth as the relatively irreversible change in measured size over time. Size can be measured in weight, height, length, etc. Growth in weight (gain) can be classified into absolute, relative, and cumulative gain. Absolute gain is the change in weight per unit time, described by the equation $R = (W_2 - W_1) / (t_2 - t_1)$; where $(W_2 - W_1)$ is the observed weight difference, $(t_2 - t_1)$ is the change in time, and R is growth rate. This equation represents average growth rate over a period of time, a constant daily rate. For example, a 100 day old heifer that gained 100 kg would have an absolute growth rate of 1 kg per day. This heifer probably did not gain exactly 1 kg each day, rather she gained more or less than 1 kg per day for 100 days to average 1 kg absolute gain. Therefore, relative growth rates defined over a considerable length of time may not provide useful information pertaining to the profile of growth of the animal. The shorter the time period, the closer absolute growth rate is to true growth rate. Brody states that when absolute growth rate is reduced to an interval, dt, sufficiently short to eliminate changes in growth rate, the true growth rate, $(\frac{dw}{dt})$ is obtained. Brody therefore defined true growth rate as the instantaneous growth, $(\frac{dw}{dt})$.

Relative growth rate is simply growth rate on a percentage basis, or $R = (W_2 - W_1) / W_1$; where W_1 is weight at the beginning of the time interval. Similar to absolute growth rate, the relative growth rate does not represent true growth rate. True growth rate would be approached when $(W_2 - W_1)$ is very small. Brody (1945) suggested using the average weight of the animal to calculate relative growth rates, or $(W_2-W_1)/[0.5(W_2-W_1)]$, is a more accurate method of computing relative growth. However, both equations are not physiologically based, as time is not considered. Using the concept of instantaneous growth, Brody suggested using the formula $(\frac{dw}{dt}) / W$ to compute instantaneous relative growth rate.

Although in theory instantaneous or true growth is desired in determining growth rates, calculation is impossible in a practical situation. However, Brody derived a method of determining absolute growth rate by using calculus. The derivation is as follows:

$$\frac{dw}{dt} = kW$$

$$\int_A^W \frac{dW}{W} = k\int_0^t dt$$

$$lnW = lnA + kt$$

$$W = Ae^{kt}$$

Instantaneous absolute growth rate is $\frac{dw}{dt}$ and k represents instantaneous relative growth rate. The instantaneous relative growth rate k can be computed by: $k = (lnW_2 - lnW_1)/(t_2-t_1)$, where (t_2-t_1) is the time interval. Percentage growth rate would be k*100. The constant A has the value of *W* when $t = 0$. Therefore, through mathematical manipulation, instantaneous growth for a given unit of time (*k*) rate can be determined.

Modeling

Brown et al. (1981) recognized modeling as part of the scientific method, as old as science itself. They cited regression equations, fat-corrected milk formulas, and total digestible nutrient equations as examples of simple models. Mertens (1977) broadly defined a model as a simplified, abstract, and idealized representation of reality based on an ordered set of assumptions. He further defined a mathematical model as a set of equations that when solved, predict changes that occur in the real world. The terms modeling or model building can be defined as the development of a mathematical model of a real situation or occurrence.

Brown et al. (1981) suggest the primary objective of modeling is to further understand input/output relationships of a system. In addition, they also cite the educational importance of modeling to help students better understand interactions in a given system. The flow chart dispayed in Figure 6 provides a guideline for modelers to use in model development. Brown et al. emphasize the importance of two often overlooked steps - model verification and publication.

France and Thornley (1984) classified models into the following categories: dynamic or static, deterministic or stochastic, and mechanistic or empirical. Baldwin et al. (1994) provided a description of these model classifications. Dynamic models must be integrated over time, and are based on differential equations (dx/dt); static models are algebraic and provide solutions for a specific time point. Deterministic models have solutions that generally apply to the average animal, while stochastic models include variation, typically as a mean plus or minus a SD. Solutions from a stochastic model for a group of individuals include variation normally found in the population. Therefore, stochastic models should represent nearly all animals in the population.

Empirical models are developed from a data set, thus they represent individuals in the data set, not necessarily the population. Although empirical models are often used to predict an animal response, they do not imply any understanding of mechanisms or underlying function. Mechanistic models, however, are based upon knowledge of mechanisms or underlying function. The knowledge of basic function enables prediction of a response similar to an empirical model. For example, an empirical growth model for growing heifers would be generated from actually measurements on a group of heifers. Variables in the mechanistic model would include factors that may influence growth rate such as diet, environment, intake, etc. Conversely, a mechanistic growth model would predict growth rate based on knowledge of tissue and skeletal growth of a heifer. Variables in the model may include protein intake, energy intake, body composition, age, and BW. The mechanistic model would have been based on previous research evaluating how each variable influences growth of body components. Loewer et al. (1983) proposed such a model that predicts growth of beef cattle based on body composition and nutrient intake.

It is apparent that mechanistic models are time consuming and costly to develop, but may be more useful to apply across a population of animals. The Cornell Net Carbohydrate and Protein System (Fox et al., 1992; O’Conner et al, 1993; Russell et al., 1992; Sniffen et al., 1992;) is an example of a current application of mechanistic and empirical modeling. The larger model incorporates mechanistic submodels that predict among other factors ruminal fermentation (Russell et al., 1992) and feedstuff degradation (Sniffen et al., 1992). Empirical models predict factors such as dry matter intake.

In agricultural applications, modeling (and simulation) is simply a mathematical representation of a biological system. Many ruminant systems have been modeled, including digestion (Baldwin et al., 1987; Fox et al., 1992; O'Conner et al., 1993; Russell et al., 1992; Sniffen et al., 1992), adipose tissue metabolism (Baldwin et al., 1994), liver metabolism (Baldwin et al., 1994; Freetly et al., 1993), mammary gland metabolism (Waghorn and Baldwin, 1984), the replacement heifer enterprise (Foster, 1988; Sorenson, 1988; Toro, 1987), dairy management practices (Foster, 1988), and dry matter intake (Brown et al.; Holter et al., 1996; Hubbert, 1991;, 1981; Kertz et al., 1991; National Research Council, 1987; Neal et al., 1984; Quigley et al., 1986a and 1986b). It is important to recognize, however, that no model can explain a biological system with 100% accuracy.

Simulation

Brown et al. (1981) suggest simulation should be the endpoint of modeling research. A simulation can be thought of as a collection of models that are used to simulate a real system, or an artificial representation of a real system, including variation that would likely occur. Mertens (1977) defined simulation as the numerical operation of a dynamic mathematical model to obtain a solution. Simulation is often used as a tool to research areas that are costly or time consuming to investigate in a real setting. For example, Toro (1987) simulated heifer rearing to research heifer management practices. The large number of animals and length of time preclude this research from being practical with live animals.

Toro Simulation

In 1987, Toro evaluated heifer rearing systems using computer simulation as a tool. The simulation contained 54 systems resulting from all combinations of two ages at weaning (6 or 12 wk), three breeding strategies (AI, natural service, or seasonal AI), three growth curves (slow, average, or fast), and three percentages of pasture (0, 20%, or 80%). Least expensive system ($793 from birth to calving, including fixed and random costs) was early weaning, AI, fast gain, and 80% pasture. Most expensive system ($1017) was late weaning, seasonal AI, slow gain, and no pasture. Average cost for each month calved after 24 mo was $19.98 for all heifers. Heifers in the slow rate of gain system were older (27.1 mo) and heavier (539 kg) at calving than heifers in the fast rate of gain system (24.8 mo and 521 kg). The results indicate dairy producers should strive for fast growing, early calving (24 mo) heifers, which parallels current recommendations (Hoffman and Funk, 1992). The results also indicate maximizing pasture utilization will decrease rearing costs.

A weakness of Toro's simulation involves the computer package, Q-GERT (Queing Graphical Evaluation and Review Technique), which is a network flow computer package. It is a simulation programming language that makes extensive use of Fortran subroutines. At the time of Toro's simulation, Q-GERT on the Virginia Tech mainframe was an ideal choice. Personal computers lacked speed and data storage capabilities necessary for a large simulation. Today, however, personal computers are faster and more powerful, enabling their use in simulation studies. Although Q-GERT is proficient at simulating, it is not widely used in other applications. Users unfamiliar with simulation studies may not know Q-GERT. Therefore, it's use by anyone other than the program developers is difficult, if not impossible. Spreadsheets, on the other hand, are familiar to many computer users. A simulation on a spreadsheet could be user friendly and allow for alterations by the user. A simulation program that is useable only by the developers will be of limited use other than for the specific project in which it was developed.

Aside from the computer package, another weakness of the Toro simulation was the growth equations used. Toro's growth equations were a modification of the Heinrichs and Hargrove (1987) equation developed from commercial herds in Pennsylvania. The equation predicts BW based on age as follows:

$$BW(kg) = 46.461 + 23.779(mo) + 0.237(mo^2) - 0.012\ (mo^3)$$

where:

mo = month of life.

Toro used the equation to predict weekly BW for average rate of gain heifers from weaning to calving. Weekly BW until breeding for slow and fast gain heifers were predicted from equations that were one standard deviation below and above the average gain equation. After breeding, Toro predicted BW of slow and fast gain heifers from the following equations:

slow rate of gain: $BW(kg) = 387.0348 + 3.2443(wk)$
fast rate of gain: $BW(kg) = 343.2143 + 4.3399(wk)$

where: wk = week of gestation.

The intercept in both equations is mean breeding BW. The coefficient is target calving BW (516.8 kg) minus breeding BW divided by gestation length (40 weeks), or kg of BW gain/wk.

From predicted BW, average daily gain was calculated using current predicted BW minus previous predicted BW plus a random deviate. All post breeding BW were predicted from equations that utilized a common desired calving weight (516.8 kg), resulting in similar lifetime average daily gain at calving for slow (0.61 kg/d), average (0.64 kg/d), and fast (0.65 kg/d) rate of gain heifers.

There are two weaknesses of the growth equations Toro used for his simulation. First, the prebreeding age curve is based on empirical data that was not fit to a growth curve, and the only variables in the model were time (age). The equations, therefore, lack physiological basis. The postbreeding age equation is simply a regression to allow heifers to calve at a predetermined desired BW. This again lacks physiological basis. Fitting the data to a growth curve would allow manipulation of parameters to alter growth rates. This approach is biologically and mathematically sound. Another biologically sound approach would be to include variables in the equation that might influence growth such as intake of protein and energy.

The second weakness was that the simulation did not account for differences due to diet, housing, DMI, or season. Age was essentially the only criteria considered for growth, although DMI was predicted from BW, TDN, and ADG. To illustrate effects environment can have on nutritional needs, Fox et al. (1988) developed a model to predict maintenance requirements of beef cattle for various combinations of temperature, wind, hide, hair coat, activity, and past and current plane of nutrition. They found cow-calf unit requirements were up to 70% higher than NRC recommendations under severe environmental conditions. If maintenance requirements are altered substantially by environment, then growth is to be similarly affected. Swanson (1970) found that ADG was linearly related to TDN per unit metabolic weight ($BW^{.6}$). The equation $TDN/BW^{.6} = 0.075 + 0.092*G$ described the relationship with a correlation coefficient of .79. Using this equation, Swanson found young heifers gained slightly more than older heifers, but concluded that the equation was suitable for heifers of all breeds from 4 to 24 mo of age. Contrary to Swanson, Hoffman et al. (1993) and Rayburn and Fox (1990) found energy to be a poor predictor of ADG. It is clear that factors in addition to age and energy influence ADG and BW, therefore quantifying some of these factors in an equation might predict growth more precisely. However, the difficulty in obtaining a data base with diet, DMI, weight, environmental and age parameters for heifers from birth to calving is recognized.

Lifetime profitability was another weakness of Toro's simulation. Costs were determined from birth until calving, but no estimate of lifetime profitability was made. The ultimate success of a heifer enterprise may be measured by the influence each heifer has on the profitability of the farm. In other words, successful replacement management schemes must optimize not only performance and cost relationships during the rearing period, but must also maximize returns a heifer will yield to the farm throughout her lifetime.

Foster Simulation

Foster (1988) used a microcomputer simulation to evaluate effects of all combinations of two levels of involuntary culling, heifer rearing (26 or 32 mo age at first calving), and sire selection against dystocia in heifers on timing and magnitude of net income in dairy cattle. The programs within the simulation were written in Turbo Pascal programming language. Two simulations were evaluated over a 20 y period, one for individual cows and one for herds. The herd simulation encompassed 20 herds, each with 80 cows and youngstock. The cow simulation encompassed 1000 cows. Eight models were needed to simulate all combinations of involuntary culling, heifer rearing, and dystocia.

Involuntary culling was either 12%, representing good management, or 24% representing poor management. In both cases total cull rate was 30%. Low involuntary culling allowed for animals to be culled for low net income and pregnancy status. Dystocia was evaluated by randomly mating heifers to bulls regardless of dystocia rating or mating heifers to bulls with a lower probability of difficult births.

Heifer rearing options were either 26 or 32 mo of age at first calving, corresponding to good or poor management. To achieve varying age at first calving, growth rates were varied from 6 mo of age until breeding. Growth from birth until 6 mo was identical for both groups. The breeding period began at 320 kg BW, with a similar time period from breeding until calving (280 d). The 32 mo heifers gained more after breeding to reflect an assumed heavier calving weight for older heifers. Feed costs per day were higher for the 26 mo group, but total feed costs and fixed costs were higher from birth to calving for the 32 mo group.

The main source of income for the study was milk production, estimated as the permanent herd effect for milk yield in the herd study, and by the sum of breeding value, permanent herd effect, and permanent cow effect for the cow study. Heifer fixed costs per day were constant ($0.40/d) from birth until calving and included facilities, taxes, insurance, bedding, labor, vaccinations, routine health exams. Variable heifer costs included feed, breeding fees, expenses for heat detection, and pregnancy determination. Fixed costs for first, second, and later lactations ($1.05, $1.18, and $1.26/d) were varied to account for labor differences. Feed costs were determined based on energy and protein requirements, with costs per nutrient increasing as nutrient density of the diet increased, reflecting higher ingredient costs of nutrient dense rations.

For the herd simulation, the combination of 26 mo age at first calving, low involuntary culling, and no selection for calving difficulty was associated with quickest cumulative payoff (54.0 mo) and highest net income ($0.485/d). The combination of thirty-two mo age at first calving, high involuntary calving, and no selection for calving difficulty was associated with slowest cumulative payoff (74.3 mo) and lowest net income ($0.246/d). Birth year, herd, and heifer rearing were statistically associated with cumulative payoff, while involuntary culling and selection for calving difficulty were not. Heifer rearing and involuntary culling were significantly associated with net income per day. Heifers calving at 26 mo had a cumulative payoff 15.4 mo sooner than 32 mo heifers (54.6 vs 70.0 mo), despite only a 6 mo difference in calving ages. The author concluded this difference was attributed solely to the 6 mo difference in calving age and the $170 difference in rearing costs ($1200 vs $1030 for 32 mo and 26 mo, respectively).

The results of the cow simulation were similar to the herd simulation. Heifer rearing had a large, significant influence on time to payoff. Involuntary culling and sire dystocia were statistically associated with time to payoff, but their influence was minor. The same combinations of main effects were associated with earliest and latest cumulative payoff and highest and lowest net income as the herd simulation. It appears the cow study proved that herd effects did not diminish the importance of heifer rearing to lifetime profitability of a cow.

Foster concluded from his simulation study that heifer rearing, specifically age at first calving, had the largest impact on profitability of a cow. This parallels other researchers recommendations to strive for early calving ages (Cady and Smith, 1996; Heinrichs, 1993; Keown and Everett, 1986; Gill and Allaire, 1976). Despite this important conclusion, the simulation had a few shortcomings concerning the heifer portion. First, relationships between first calving BW and milk production and profit were ignored. Keown and Everett (1986) have shown a strong relationship between first calving BW and first lactation milk yield. Second, the ages at first calving evaluated in the study may be dated considering current recommendations (Cady and Smith, 1996; Heinrichs, 1993). Most would consider 26 mo average, not early. Considering a wider range of ages, specifically lower ages, would provide useful information. Third, the equations used to predict growth of heifers may not have simulated a real life situation - they were determined mainly by the desired weight and age at first calving. It is recognized that Foster's simulation was not a heifer simulation, so considerable detail for the heifer portion may not have been possible due to time constraints. However, considering the results, a similar simulation with a more detailed and realistic heifer portion would provide valuable information concerning lifetime profitability of a cow.

Conclusions

It is evident that mathematical modeling and simulation have numerous applications in describing animal growth and biological systems. The field of modeling and simulation has expanded in the past decade, and should continue to do so, considering the costs involved with animal experimentation and the advancement of microcomputers.

Future modeling of dairy heifer growth may provide further insight into the biological and mathematical relationships that influence growth. The present study is an attempt to utilize a static, empirical, and stochastic model to describe growth. Mechanistic models, although time consuming and difficult to derive, may offer the optimal approach to biologically and mathematically describe growth. However, a mechanistic model that truly represents dairy heifer growth is not likely to be derived in the near future. Such a model would require considerable research effort on the part of many scientists from a variety of disciplines. Empirical models, however, may be the best current approach to quantify growth characteristics of dairy heifers. This approach will expand our knowledge of growth, provided future modelers attempt to incorporate variables into the model that have biological meaning. The only limitation of empirical modeling is obtaining a data set with all the desired variables (BW, wither height, hip height, body length, DMI, ration nutrient content, and environmental variables such as temperature, humidity, wind speed, moisture) measured on a routine basis (weekly, bi-weekly, or monthly) for groups of heifers under various management and environmental conditions. Once models are developed, simulation studies should be employed, utilizing the models to predict a biological system, which in this case is dairy heifer growth.

Current simulations of the dairy replacement enterprise are limited (Toro, 1987 and Foster, 1988). Although these simulations provided useful results, they could be improved in several areas. A primary objective of this project is to follow up and improve upon these simulations. There is a need for information concerning optimal management strategies for rearing dairy heifers. Live animal studies are expensive and time consuming, making them difficult to conduct during a student’s tenure. In addition, high costs limit the number of heifers possible in live animal studies, where large numbers are easily accommodated on the computer. The literature contains many live animal studies that were either short term, contained few animals, or evaluated a limited number of variables. Simulation allows for long term studies with large animal numbers and many variables. Toro and Foster have conducted two of the few heifer simulation projects that modeled heifer management from birth to calving. Results obtained from an improvement on their work should provide information regarding heifer management practices that is lacking in current literature.

Materials and Methods

Equations

The purpose of developing equations was to predict BW and DMI for Holstein heifers from birth until calving and first lactation milk yield for use in the simulation. Holstein heifer data sets from Virginia and Minnesota were obtained for three approximate age ranges: birth to weaning, 3 to 17 mo, and 17 mo until calving. Equations for DMI and BW were therefore developed for each age range. First lactation milk yield equation was developed from a data set containing DHIA records from Virginia.

Model Criteria and SAS Procedures

The SAS procedures PROC Stepwise (stepwise regression), PROC REG (regression) and PROC GLM (General Linear Model) were utilized to determine models that best fit the data (SAS, 1985). The SAS System for Windows release 6.11 (1996) was used for all analyses. Stepwise and REG procedures are regression analyses where only continuous variables are used. The GLM procedure allows for a mixture of continuous and discrete variables.

The Stepwise procedure is simply regression analysis in a stepwise fashion. The backward, forward, and MAXR (maximum R-squared improvement) options of Stepwise were used. The backward procedure builds a full model initially, then eliminates variables that contribute little to the model ($P > 0.15$). After a variable is eliminated, the regression is recalculated with previously insignificant terms eliminated. This is repeated until a model with all terms having $P < 0.15$ is obtained. Forward Stepwise regression is the opposite, with model terms that contribute most being added one at a time. A term is added to the model if $P < 0.50$. Unlike forward and backward options, MAXR does not choose the one best model, rather it chooses the best one-variable model, the best two-variable model, and so on. It initially finds the one variable model with the highest R-squared, then adds variables that improve R-squared the greatest. The Stepwise methods (backward, forward, MAXR) do not always select a model with the highest R-squared. Stepwise analysis calculates parameter estimates, F and *P* values for each model term, and R-squared and C(p) statistics as model criteria.

The C(p) statistic as proposed by Mallows (1964) expresses variance and bias, and is a useful criterion for discriminating between models (Myers, 1990). The C(p) statistic is determined by: $p + (s^2 - \sigma^2)(n-p) / \sigma^2$ where p is the number of model terms including the intercept, s^2 is the error mean square for the model in question, and σ^2 is the error mean square for the full model. A model with low C(p) is preferred: if C(p) is greater than p, the model may be under-specified. A C(p) less than or equal to p is ideal; Mallows (1964) recommended selecting the model where C(p) first approaches p. The weakness of the C(p) statistic is that the full model will always have C(p) equal to p. Therefore, C(p) is only useful when comparing subset models against the full model or other subset models. A subset model of the full model with a C(p) lower than *p* would be the preferred model.

Unlike Stepwise regression, the REG procedure (SAS, 1985) calculates a multiple regression as specified by the model. A standard REG analysis will calculate R-squared for each model and estimate a parameter for each variable. The all possible regression option of REG yields in addition the PRESS (Prediction Residual Sum of Squares) statistic. To determine PRESS, regression coefficients are calculated *n* times (*n* = number of observations), with one observation removed each time. The missing observation is predicted, and a prediction error or PRESS residual is calculated for each predicted value compared to the actual value. The sum of *n* squared PRESS residuals is the PRESS statistic. The PRESS statistic is ideal where data splitting is not utilized (Myers, 1990). A model with the smallest PRESS statistic is favored (Myers, 1990). The weakness of using the PRESS statistic is that there is no uniform scale. If data were in kilograms, then units for PRESS would be kilograms squared, implying the magnitude of PRESS is dependent on the data. An important advantage of PRESS is its sensitivity to collinearity (Myers, 1990).

The coefficient of determination, or R-squared statistic, was also used to evaluate models, but with caution. It is defined as (SS_{Model}/SS_{Total}), or the percentage of variation explained by the model. Using R-squared as the sole criteria for evaluating competing models is dangerous because adding model terms will always increase R-squared, as a new model term will always increase SS_{Model} some, while SS_{Total} does not change. Thus, R-squared can be artificially inflated by over-specifying the model. The R-squared statistic is most useful when comparing models with like number of variables, but possibly misleading otherwise. Adjusted R-squared, a method of adjusting R-squared for additional model terms (Darlington, 1968, Judge et al., 1980) is calculated by all possible regression analysis (SAS, 1985). Adjusted R-squared was manually calculated for GLM and Stepwise output as follows: $1 - [(SS_{Error}/\text{error df})/(SS_{Total}/\text{total df})]$. This criteria is preferred over R-squared because of the adjustment for error df.

The GLM procedure was used when class variables were included in the model. The solutions option of GLM allows for calculation of parameter estimates for class and continuous variables. A parameter estimate is calculated for each level of the class variable. For example, if heifer is included in the model and there are 100 heifers in the data set, then 100 parameter estimates are calculated. The estimates are used in the model by averaging all estimates (100 in the previous example) and adding to the intercept, assuming individual class constants are not desired. Therefore, utilizing class variables in the model results in a constant that adjusts the intercept for the class variable. The GLM procedure is the least acceptable method of evaluating models because it calculates only R-squared as criterion for discriminating between models. Therefore, GLM was only used to add class variables to models selected as best by Stepwise and REG analysis.

For equations to be useful in the simulation, a measure of variation is needed such that predicted values for a group of heifers are normally distributed with a particular mean and variance. An estimate of SD or SE would enable variation to be included by adding the SD multiplied by a Normal random deviate to the predicted value. Therefore, for each equation, SD was estimated.

Pre-Weaned Calf Equations

Equations were developed to predict weekly BW and daily DMI of pre-weaned dairy heifers. Four data sets were obtained from the University of Minnesota Southern Experiment Station (Chester-Jones et al., 1994, personal communication; Ziegler et al., 1995, 1996). Studies were conducted with female and male Holstein calves housed in individual hutches (Chester-Jones et al., 1994; Ziegler et al., 1995), indoor calf nursery or individual hutches (Chester-Jones, personal communication), or in individual hutches or in a controlled environment calf room (Ziegler et al., 1996). Males were excluded from data sets.

Calves received colostrum for four feedings, then milk at 9% BW in two equal feedings until 28 d and 4% BW in one feeding until 35 d (Chester-Jones et al., 1994, personal communication; Zielger et al., 1995) or 0.46 kg/d milk solids in two equal feedings until 28 d and 0.23 kg/d milk solids in one feeding until 35 d (Zeigler et al., 1996). Milk was either fortified waste milk, fortified non-medicated milk replacer, unfortified non-medicated milk replacer, or milk replacer medicated with decoquinate (Ziegler et al, 1995); fortified or unfortified waste milk (Chester-Jones et al., 1994); or medicated all milk protein milk replacer, medicated milk replacer with 55% of milk protein replaced by spray-dried red blood cells, medicated milk replacer with 55% of milk protein replaced by spray-dried red blood cells with decoquinate, or non-medicated milk replacer with 55% of milk protein replaced by spray-dried red blood cells with direct fed microbials (Ziegler et al., 1996). Fortified product contained animal plasma, sorbitol, citric acid, trace minerals, dried whey, sources of vitamin A, D, E, K, and B-complex. Calf starter containing 16% (Chester-Jones et al., 1994) or 18% crude protein (Ziegler et al., 1995,1996) was fed beginning at 3 d. Calves were weaned at 35 d.

Body Weight

The four Minnesota data sets were combined into one data set for development of an equation to predict BW. Statistics from this data set are in Table 3. Ages of heifers in this data set were between birth and 49 days, therefore BW prediction from equations from this data set are accurate only to 49 days of age.

For BW equation, the goal was to predict BW from age in days. Variables tested in the model included DATASET, CALF, AGE, AGE^2, and AGE^3. Non-continuous or class variables (DATASET, CALF) are not appropriate for regression analysis, thus only continuous variables (AGE, AGE^2, and AGE^3) were evaluated initially. All possible regression analysis was preferred over the General Linear Models procedure because of the additional model criteria calculated: C(p) statistic, PRESS statistic, and adjusted R-squared. Variables DATASET and CALF were included in a GLM analysis after Stepwise regression determined the best combination of continuous variables.

The Stepwise procedure of SAS (1985) was used initially to eliminate insignificant variables. The model BW = AGE + AGE^2 + AGE^3 + AGE^4 + AGE^5 was subjected to backward, forward, and MAXR Stepwise analysis. The backward procedure selected the model BW = AGE^2 and the forward procedure selected the model BW = AGE^2 + AGE^5 (Appendix Table A), although AGE^5 was not significant ($P = 0.48$). The MAXR procedure selected the best one, two, three, four, and five variable models (Appendix Tables B, C), although the only model with all significant variables ($P < 0.15$) was BW = AGE^2. Stepwise regression analysis provides evidence that BW = AGE^2 is the best model.

Two other sources of variation, CALF and DATASET, were also of interest. Differences between data sets may be significant because each data set was from a different feeding trial (Chester-Jones et al., 1994, personal communication; Ziegler et al., 1995, 1996). Even though all calves were female Holsteins, differences between calves may contribute to the variation in BW prediction. Therefore, GLM analysis was performed first on the model BW = CALF(DATASET) + AGE^2, followed by a model without calf (BW = DATASET + AGE^2). The results, in Table 4, demonstrate that CALF accounted for a substantial amount of variation, but DATASET alone did not. The model BW = AGE^2 had an adjusted R-squared of 0.53, while adding CALF improved adjusted R-squared to 0.91. Including DATASET alone in the model improved adjusted R-squared slightly (0.54). In addition, MSE from the model with CALF was dramatically lower (8.22) than the model with DATASET alone (38.31). Therefore, the best model to predict BW from the data sets analyzed is:

$$BW(kg) = 38.88 + 0.00808071 * AGE^2 \qquad \text{(Equation 1)}$$

Where:

BW = body weight (kg);
AGE^2 = square of age ($days^2$).

In this equation, the intercept (53.87) was adjusted for the average calf constant (-13.98).

The desired variance component for this equation is within heifer variation, not between heifer variation. In the simulation, BW is predicted for each week of life; therefore, the variation used should be an estimate of the variation of an individual heifer's BW for that given week. The combined data set utilized to generate the BW equation did not have BW for each week. The data set from Ziegler et al., 1996, contains BW at birth, 14 d, 28 d, 35 d, and 42 d. Therefore, only these data were used to estimate variance in BW for two week periods: birth to 14 d, 14 d to 28 d, and 28 d to 42 d of age. Appendix Table D lists MSE and root MSE from the model BW = CALF + AGE^2 for these age periods; the MSE is an estimate of the within-heifer variance of BW. For use in the simulation, root MSE is used as an estimate of SD used for BW prediction from previous week's BW on same calf.

Daily Starter Dry Matter Intake

Only the Ziegler et al. (1996) data set was used to develop an equation to predict DMI of starter diet. Remaining data sets (Chester-Jones et al., 1994, personal communication; Ziegler et al., 1995) had insufficient DMI data. Statistics for this data set are in Table 5. The objective of the equation was to predict DMI of starter diet for pre-weaned heifers from birth to 35 d, and for weaned heifers from 35 to 42 d.

Initially, a model was fit to predict total starter DMI from 0 to 42 days based on age and BW. The relationship was poor (R-squared < 0.09), however, so this approach was abandoned. Instead, one daily DMI for each period (3 to14, 14 to 28, 28 to 35, 35 to 42 d) was predicted from birth BW and BW gain from each period. Daily DMI was calculated by dividing total DMI by the number of days in the period. Birth weight may be important because the physical size of the heifer may influence DMI. Body weight gains for various periods were included to account for assumed higher DMI of faster growing heifers.

Tables 6 - 9 contain forward and backward Stepwise regression results from models predicting daily starter DMI from 3 to14, 14 to 28 , 28 to 35, and 35 to 42 d. For the 3 to 14 d period, the forward selected model was chosen by virtue of a lower PRESS and MSE, and a higher adjusted R-squared. Both forward and backward selected models for the 3 to 14 d period had $C(p) < p$. For 14 to 28 d and 35 to 42 d periods, the backward selected model was chosen by virtue of a lower PRESS statistic, a $C(p) < p$, and a non-significant variable in each forward selected model ($P > 0.10$).

The forward selected model had a lower PRESS than the backward selected model for the 28 to 35 d period, but the models were similar otherwise. Upon further inspection, it was revealed that both models may be over-specified. Figures 7 and 8 display C(p) against p plots for models selected by the MAXR Stepwise procedure for all age periods. The forward and backward selected models were also selected by MAXR in all cases except for the forward selected 35 to 42 d and 28 to 35 d models. The C(p) and p values in Figures 7 and 8 were obtained from MAXR analysis. Mallow (1964) suggested the best model is where C(p) first approaches p, beginning with a one variable model. From these plots, it appeared the models chosen for the 3 to 14 d, 14 to 28 d, and 35 to 42 d are appropriate. However, both the forward and backward selected models for the 28 to 35 d period had 10 variables ($p=11$), which is beyond where C(p) approaches p. The model where C(p) approached p had 6 variables ($p=7$). This model was subject to further regression analysis to determine PRESS (Table 8). From PRESS and C(p) statistics it appeared the 6 variable model for the 28 to 35 d period was superior to either forward or backward Stepwise selected 10 variable models, even though adjusted R-squared was higher and MSE lower for the 10 variable models. The PRESS and C(p) statistics were considered superior model criteria when the model is to be used for prediction purposes (Myers, 1990).

The chosen models to predict daily starter DMI were as follows:

Daily Starter DMI (kg), 3 to 14 d: (Equation 2)

$$-0.0184 - 0.1253*\mathrm{GAIN014} + 0.00004734*\mathrm{BWBIRTH}^2 + 0.00294086*\mathrm{GAIN014}^2 + 0.00324912*\mathrm{BWBIRTH}*\mathrm{GAIN014}$$

Daily Starter DMI (kg), 14 to 28 d: (Equation 3)

$$2.0967 - 0.1128*\mathrm{BWBIRTH} - 0.0497*\mathrm{GAIN014} + 0.00163432*\mathrm{BWBIRTH}^2 - 0.00633109*\mathrm{GAIN014}^2 + 0.00408185*\mathrm{GAIN1428}^2 + 0.00991946*\mathrm{GAIN014}*\mathrm{GAIN1428}$$

Daily Starter DMI (kg), 28 to 35 d: (Equation 4)

$$4.5127 - 0.2276*\mathrm{BWBIRTH} + 0.0889*\mathrm{GAIN1428} + 0.00317912*\mathrm{BWBIRTH}^2 - 0.01853156*\mathrm{GAIN014}^2 - 0.00319008*\mathrm{BWBIRTH}*\mathrm{GAIN014} + 0.02717998*\mathrm{GAIN014}*\mathrm{GAIN1428}.$$

Daily Starter DMI (kg), 35 to 42 d: (Equation 5)

$$
\begin{aligned}
&0.2719 - 0.1137*\mathrm{GAIN014} - 1.0669*\mathrm{GAIN1428} + 1.9984*\mathrm{GAIN2835} - \\
&0.01073528*\mathrm{GAIN014}^2 + 0.00827101*\mathrm{GAIN1428}^2 + 0.02519841*\mathrm{GAIN2835}^2 - \\
&0.02686572*\mathrm{GAIN3542}^2 + 0.00940889*\mathrm{BWBIRTH}*\mathrm{GAIN014} + \\
&0.01272710*\mathrm{BWBIRTH}*\mathrm{GAIN1428} - 0.03143912*\mathrm{BWBIRTH}*\mathrm{GAIN2835} + \\
&0.00738574*\mathrm{BWBIRTH}*\mathrm{GAIN3542} + 0.01265885*\mathrm{GAIN014}*\mathrm{GAIN1428} - \\
&0.04418419*\mathrm{GAIN014}*\mathrm{GAIN3542} - 0.02460145*\mathrm{GAIN1428}*\mathrm{GAIN2835} + \\
&0.11857928*\mathrm{GAIN1428}*\mathrm{GAIN3542} - 0.14991667*\mathrm{GAIN2835}*\mathrm{GAIN3542}.
\end{aligned}
$$

Where:

BWBIRTH = birth BW, kg;
GAIN014 = BW gain 0 to 14 days, kg;
GAIN1428 = BW gain 14 to 28 days, kg;
GAIN2835 = BW gain 28 to 35 days, kg;
GAIN3542 = BW gain 35 to 42 days, kg.

Degrees of freedom were lacking to add CALF in any of the DMI models.

Similar to the BW equation for pre-weaned heifers, the desired variance component for these equations was within-heifer variation, not between-heifer variation. In the simulation, starter DMI is predicted for each week of life; therefore the variation used should be an estimate of the variation of an individual heifer's starter DMI for that given week. The root MSE from Equations 2 - 5 provides these estimates (Appendix Table E).

After the best models were chosen, variables were examined to determine their worth or impact on prediction of starter DMI. Two methods were used to evaluate the impact of changing a variable (x) on starter DMI (y). The first method involved determining the derivative equation for each variable. The value of the derivative equation is the slope (change in DMI for a one-unit change in x). The derivative equations and slopes for each x variable when others are at their mean are presented in Table 10. A slope, by definition, is the change in Y for each unit change in X. Using this criterion, it appeared none of the variables elicit a large change in starter DMI, although the means for *y* are small. The second method determined the effect of changing each main effect variable by one, two, or three SD units. Tables 11 and 12 list these calculations, and it appeared that BWBIRTH has little impact on starter DMI prediction for 35 to 42 d old heifers. All other variables for all models had some impact: changing the variable ± 3 SD changed starter DMI at least 1 SD. Considering the minor impact of BWBIRTH on 35 to 42 d daily starter DMI, the model was re-calculated with BWBIRTH removed. The results, Model A in Table 13, show the change in MSE, PRESS and R-squared from the original models, suggesting this model does not predict as accurately as the original model. In addition, many of the model terms were no longer significant in the new model. For these reasons, the model without BWBIRTH was subject to backward Stepwise regression to select a new best model without BWBIRTH. This new model (Model B, Table 13) had an improved PRESS and MSE, therefore it was considered superior. The variables in this new model were then analyzed to determine their impact on prediction. From Tables 14 and 15 (Model A), it is clear that GAIN014 had little impact on prediction of starter DMI. Therefore, the model was subject once again to backward Stepwise regression analysis with GAIN014 removed. This new model (Model C, Table 13), has a higher

PRESS and MSE and lower adjusted R-squared than the other models. However, all variables in this model had a reasonable impact on prediction of starter DMI (Tables 14 and 15, Model B). Therefore, this new equation was selected to replace Equation 5 as the best model to predict 35 to 42 d daily starter DMI for Holstein heifers:

Daily Starter DMI (kg), 35 to 42 d: (Equation 6)

$$0.32920826 + 0.27863287*GAIN2835 + 0.02061021*GAIN3542^2 + 0.01048293*GAIN1428*GAIN3542 - 0.04158731*GAIN2835*GAIN3542;$$

Where:

BWBIRTH = birth BW, kg;
GAIN1428 = BW gain 14 to 28 days, kg;
GAIN2835 = BW gain 28 to 35 days, kg;
GAIN3542 = BW gain 35 to 42 days, kg.

Equations for Heifers from Weaning to 17 Months

The objective of equations for heifers in this age group is to predict BW and DMI for each week of life for use in the simulation. This group was considered separately because data in this age group did not overlap with any younger or older groups.

BW Equation

Four data sets from feeding trials conducted at Virginia Tech were combined and used to develop BW equations (Bethard et al., 1994, 1995, 1996a, 1996b). Statistics for this data set are in Table 16. All data were obtained from Holstein heifers housed in a confinement facility of counter-slope design. Heifers were fed a TMR through a Pinpointer 4000B computerized feeder (UIS, Inc. Cookeville, TN) which recorded daily intakes. The facility had four 3.6 m x 9.1 m pens with one feeder per pen. Heifers had 24 h access to the feeder, but only one animal could use the feeder at a time. Trials had either 4 treatments with 8 heifers per treatment (Bethard et al., 1994, 1995, 1996a) or 3 treatments with 6 heifers per treatment (Bethard et al., 1996b), and each treatment was administered to all heifers housed in one pen.

The feeding trials evaluated various protein sources (Bethard et al., 1994, 1995, 1996a), various energy levels (Bethard et al., 1994, 1995), whole cottonseed supplementation (Bethard et al., 1996a) and monensin supplementation (Bethard et al., 1996b). All diets within each trial were isonitrogenous; protein percent varied from 13.2 to 14.4% of DM. Crude protein percent and intakes were not included as possible variables due to the uniformity of dietary CP and varied protein sources. Diets varied from 52 to 90% DM, 59 to 67.8% TDN, 24.4 to 36.2% ADF, and 26.6 to 51.9% RUP (estimated using NRC, 1989 values). Diets were combinations of corn silage, alfalfa haylage, chopped orchardgrass hay, soybean meal, dry shelled corn, barley, blood meal, fish meal, corn gluten meal, whole cottonseed, urea, monensin, and minerals. Observations included weekly averages of daily DMI and weekly or bi-weekly BW and wither height measurements. Ages represented in the data were from 4 to 17 mo. Trials ranged from 90 to 335 d in length.

The equation developed to predict BW is for use in the simulation, therefore it must utilize variables predicted in the simulation that correspond to each week of a heifer’s life. The DMI equation by Quigley et al. (1986b) contains BW as a variable, indicating that BW must be predicted prior to DMI. Thus, the BW equation cannot use feed intake from the current week. For this reason, the previous week feed intake was used as a variable. Intake of ADF was used instead of TDN because TDN is predicted from ADF rather than measured directly. As previously mentioned, CP intake was not used due to experimental design of trials.

An initial backward and forward Stepwise regression was run on a model with the variables PBW (previous week BW), PBW75 (previous week metabolic BW, or $BW^{.75}$), PDMI (previous week DMI), PADFI (previous week ADF intake), and AGEW (age in weeks). In addition, the square of these terms and all two way interactions were included. Statistics for both models are in Table 17. The backward selected model is preferred due to a lower MSE and PRESS and a C(p) less than *p*:

(Equation 7)

$$BW = -89.57738148 -1.26555571*PBW + 36.23378851*PDMI + 11.39152110*AGEW - 0.01550936*PBW^2 + 0.38860628*PBW75^2 - 1.26778628*PDMI^2 - 0.03345607*AGEW^2 + 9.38254120*PADFI^2 + 0.47671446*PBW*PDMI + 0.14543368*PBW*AGEW + 0.37894857*PDMI*AGEW - 1.06706224*AGEW*PADFI - 2.41920128*PBW75*PDMI - 0.70679780*PBW75*AGEW.$$

Where: PBW = previous BW, kg; PBW75 = $PBW^{.75}$, kg; PDMI = previous DMI, kg/d; PADFI = previous ADF intake, kg/d; AGEW = age in weeks.

The full model was then subject to MAXR Stepwise regression analysis to determine C(p) for the best one through 19 variable models. Mallows (1964) suggested the best model is the subset model where C(p) first approaches *p*. Figure 8 contains a plot of C(p) against *p*, and it demonstrates that the best model, using Mallows suggestion, is the 14 variable model identical to Equation 7. The C(p) for this model (12.5) is the first model where C(p) is lower than *p* (15). This supports the conclusion that Equation 7 is the best among the candidate models.

The class variable HEIFER was added to Equation 7 using the GLM procedure of SAS. Table 17 lists the model coefficients, R-squared, adjusted R-squared, and MSE. Adding HEIFER slightly improved R-squared, adjusted R-squared, and MSE, therefore Equation 7 was retained as the best model.

Similar to Equations 1-5, the desired variance component for Equation 7 is within heifer variation, not between heifer variation. In the simulation, BW is predicted for each week of life; therefore the variation used should be an estimate of the variation of an individual heifer's BW for a given age period. Twelve age ranges were selected: less than 6 mo of age, greater than or equal to 16 mo, and monthly ranges from 6 to 16 mo. Equation 7 and two other models, BW = HEIFER + AGEW + PBW or BW = HEIFER + AGEW were fitted to 12 data sets, each composed of heifers within the desired age range. It was theorized that the simpler models with HEIFER in the model would provide a more realistic estimate of within heifer BW variation. The root MSE for each regression (Appendix Table F) provides an estimate of within-heifer variation for BW for the given age periods. The results suggest that the simpler models were more realistic as expected. The root MSE for Equation 7 was considered too high and unrealistic for most age ranges. The simpler models resulted in reasonable root MSE for all age ranges except < 6 mo and 10 to 11 mo.

An estimate of variation was further investigated by running the simple models from above on only one data set (Bethard et al., 1995), the only data set that contained weekly measurements of BW. The hypothesis was that within heifer variation in weekly BW measurements as used in the simulation might be represented more accurately this way. The results, presented in Appendix Table G, demonstrate the root MSE was further reduced for each range by using this approach. The two models used were very similar in MSE, but the model BW = HEIFER + AGEW (model B in Appendix Table G) was chosen because MSE were slightly lower for most age periods. The MSE for each age period were then regressed on age, using age in months that were halfway between the age range values. Models were run with all combinations of linear, quadratic, cubic, and quartic terms for age. The linear model:

$$\text{MSE for BW} = 6.443 - 0.08535*\text{AGEM}, \qquad \text{(Equation 8)}$$

Where AGE = age in mo,

was chosen by virtue of a lower PRESS and MSE. Although R-squared was poor (0.05), the equation does minimize variation in MSE from month to month.

After the best model was chosen, variables were examined to determine their worth or impact on prediction of BW. The derivative equations and slopes are presented in Table 18. Using these criteria, it appears a unit change in any of the variables will reasonably impact BW prediction. The second criteria involved determining the effect of changing each main effect variable by one, two, or three SD units. Table 19 lists these calculations, and it appears that all variables have a reasonable impact on BW prediction, although PDMI, AGEW, and PADFI impacts were small.

A histogram and a normal probability plot provide evidence that BW is normally distributed (Figures 9 and 10). The histograms appear bell shaped similar to a normal curve. The normal probability plots are considered normal if the data points tend to be near the line connecting the "+"'s, which they do (SAS, 1990). Therefore, variation can be added to the prediction of BW by multiplying the SD estimate by a normal random deviate and adding to the prediction.

DMI Equation

For heifers one week after weaning until 100 kg BW, DMI was predicted using the equation of Toro (1987) developed from NRC requirements (R-squared = 0.997):

$$\text{DMI, kg/d} = -0.4590 + 0.0341*\text{BW} + 0.99*\text{ADG} - 0.0132*\text{BW}*\text{ADG}$$

Where:
BW = Body weight, kg;
ADG = Average daily gain, kg/d.

For heifers >100 kg BW, DMI was predicted using the equation of Quigley et al. (1986) as follows:

$$\text{DMI} = -29.86 - (1.54\text{E-}5)*\text{BW}^2 + 0.157*\text{BW}^{.75} + 2.09*\text{ADG} - 0.118*\text{ADG}^2 + 0.73*\text{TDN} - 0.005*\text{TDN}^2 - 0.001*\text{BW}*\text{ADG} - .019*\text{TDN}*\text{ADG}$$

Where:

DMI = kg/d dry matter intake
BW = kg body weight
ADG = kg/d average daily gain
TDN = total digestible nutrient concentration in the diet

The equation of Quigley et al. (1986) is appropriate because it was developed from data obtained from Holstein heifers in the same facility as the data used to generate Equation 7. Dry matter intake predictions for each heifer will occur after BW has been predicted, thus ADG will be calculated from current and previous week BW. For a variance component, the root MSE for this model (1.18 kg) could be used to estimate SD. However, variation likely is not constant across ages represented in the data set, therefore an estimate of DMI variation by age period was desired. Lacking the original data set used by Quigley et al., the Bethard et al. (1995) data set with weekly DMI was used. The results from two models, DMI = HEIFER + AGEW + BW and DMI = HEIFER + AGEW were evaluated. The root MSE and R-squared from these models for various age ranges is in Appendix Table H. The root MSE estimates from model A in Appendix Table H are lower for most age groups, thus they were used to regress MSE for each age period on age, using age in mo that were halfway between the age range values. Backward stepwise regression was performed on a model with linear, quadratic, cubic, and quartic terms for age. The selected model was:

(Equation 9)

$$\text{DMI MSE, 5 to 17 mo} = 4.555 - 1.24273652*AGEM + 0.12613215*AGEM^2 - 0.00398032*AGEM^3;$$

where AGEM = age in mo.

The R-squared (0.68) suggests this equation accounts for the majority of variation in MSE for DMI.

Equations for Heifers from 17 to 28 Months

The objective of equations for heifers in this age group were to predict BW and DMI for each week of life for use in the simulation. This group was considered separately because data sets were limited to heifers of this age range.

Data were obtained from a study conducted at the University of Minnesota evaluating ionophore and grain interactions (H. Chester-Jones and J. Linn, personal communication). The trial was designed as a 3 x 2 factorial, with three levels of corn supplementation (0, 1.4, and 2.7 kg/d) with or without ionophore. All diets contained alfalfa haylage as the forage source. Heifers were fed a TMR through Calan Door feeders where daily DMI were recorded. Diets were adjusted weekly based on DM of haylage to maintain an 88:12 and 78:22 ratio of haylage to corn for diets with 1.4 kg and 2.7 kg corn, respectively. Heifers represented in the data set were from a modern genetic herd or a control herd with 1964 genetics (Boettcher et al., 1993). Control herd heifers were eliminated because they did not represent current genetic growth potential of the Holstein breed. Rolling herd average was approximately 5902 and 9988 kg for control and modern genetic herds, respectively.

Heifers were fed treatment diets for 9 mo, and BW was recorded every 28 d. For the simulation, weekly observations were desired to enable weekly prediction of BW and DMI. Therefore, weekly BW were calculated from 28 d measurements, assuming linear growth between measurements. Daily DMI were averaged for each week, and ADG were calculated using weekly BW calculations. Statistics for the data set with weekly observations are in Table 20.

BW Equation

The equation developed to predict BW was for use in the simulation, therefore it must utilize variables predicted in the simulation that correspond to each week of a heifer's life. The DMI equation developed for heifers in this age group is similar to the Quigley et al. (1986b) DMI equation in that BW is a variable, indicating that BW must be predicted prior to DMI. Thus, the BW equation cannot use feed intakes from the current week. For this reason, previous week's feed intakes were used as variables.

Variables PBW (previous week BW, kg), PBW75 (previous week metabolic BW, or $BW^{.75}$, kg), PDMI (previous week daily DMI average, kg), AGEW (age in weeks), their squares and all one-way interactions were included in the initial model. This model was subject to backward, forward, and MAXR stepwise regression analysis. The best models chosen are in Table 21. The 6 variable model was chosen as the best MAXR selected model because it was the first model where C(p) approaches *p* (Figure 11). The three competing models all explain most of the variation in BW (R-squared >0.99), and all have a similar PRESS and MSE. The backward selected model, however, is the only model with C(p) < *p*. Considering the criterion mentioned and the C(p) plots, the 6 variable model was chosen because it was the simplest and because it meets Mallows (1964) suggestion that the best model is where C(p) first approaches *p*. The model chosen is:

(Equation 10)

$$\text{BW, kg} = -77.082427 + 5.479217*\text{PBW75} - 0.234414*\text{PDMI} - 0.611703*\text{AGEW} + 0.000143*\text{PBW}^2 + 0.002534*\text{AGEW}^2 + 0.005353*\text{PDMI}*\text{AGEW};$$

Where: PBW = previous week BW, kg; PBW75 = $PBW^{.75}$, kg; PDMI = previous week DMI, kg/d; AGEW = age in weeks.

Similar to previous equations, the desired variance component is within heifer variation for a given week. However, the data set contains only monthly measurements of BW, consequently weekly variation cannot be determined. Any estimate of variation using monthly measurements will likely discount the actual weekly variation. For this reason, weekly within heifer variation for 4 to 17 month old heifers, estimated by the equation 6.443 - 0.08535*age in mo (Equation 8), will also be applied to heifers of this age group. The equation has a small negative slope, indicating reduced variation as heifers age.

After the best model was chosen, variables were examined to determine their worth or impact on prediction of BW. The derivative equations and slopes are presented in Table 22. Using these criteria, it appears a unit change in any of the variables will reasonably impact BW prediction. The second criteria involved determining the effect of changing each main effect variable by one, two, or three SD units. Table 23 lists these calculations, and it appears that all variables have a reasonable impact on BW prediction, although PDMI and AGEW impacts were small.

A normal probability plot and a histogram provide evidence that BW are normally distributed (Figures 12 and 13). The histograms appear bell shaped similar to a normal curve. The normal probability plots are considered normal if the data points tend to be near the line connecting the "+"'s, which they do (SAS, 1990). Therefore, variation can be added to the prediction of BW by multiplying the SD estimate by a normal random deviate and adding to the prediction.

DMI Equation

In the simulation DMI is predicted after BW. Therefore, the variables BW (current week BW, kg), BW75 (current week metabolic BW, or $BW^{.75}$, kg), PDMI (previous week daily DMI average, kg), ADG (current week average daily gain, kg/d), AGEW (age in weeks), their squares and all one-way interactions were included in the initial model. This model was subject to backward, forward, and MAXR stepwise regression analysis. The best models chosen are in Table 24. There were minor differences in MSE, PRESS, R-squared, and Adjusted R-squared among the competing models. The 6 variable model selected by MAXR was chosen for two reasons. First, it was the first model where $C(p) < p$ (Figure 14) as suggested by Mallows (1964). Second, it was the simplest model with few model terms:

(Equation 11)

$$DMI = 3.795390 - 0.000006*BW^2 - 0.010968*PDMI^2 - 0.002321*BW*PDMI - 0.002461*PDMI*AGEW + 0.021244*BW75*PDMI + 0.043212*ADG*PDMI;$$

Where DMI = dry matter intake, kg/d; BW = body weight, kg; PDMI = previous week DMI, kg/d; AGEW = age in weeks; ADG = average daily gain, kg/d.

After the best model was chosen by regression analysis, class variables HEIFER and MONTH (month of year, 1..12) were added to the model and analyzed using the GLM procedure of SAS. The results, in Table 25, suggest class variables improved the model, as evidenced by lower MSE and higher adjusted R-squared in models with these terms. Model C in Table 25 was chosen as best by virtue of lowest MSE and highest adjusted R-squared:

(Equation 12)

$$DMI = 4.075177843 - 0.000002518*BW^2 - 0.013133393*PDMI^2 - 0.002918570*BW*PDMI - 0.004323657*PDMI*AGEW + 0.024831272*BW75*PDMI + 0.049499947*ADG*PDMI;$$

Where DMI = dry matter intake, kg/d; BW = body weight, kg; PDMI = previous week DMI, kg/d; AGEW = age in weeks; ADG = average daily gain, kg/d.

Parameter estimates for the class variables HEIFER (0.009249337) and MONTH (-0.018449729) were added to the intercept (4.084378235). The MONTH parameter estimates are -0.08762, 0.27065, 0.32470, -0.45453, -0.24914, 0.08491, 0.13711, -0.11075, -0.18033, -0.05138, 0.09198, and 0.0 for mo 1 to 12, respectively.

To estimate SD of DMI within a heifer for each week, the modeDMI = HEIFER + MONTH + AGEW (where MONTH = month 1..12, AGEW = age in weeks) was run for heifers of various age ranges. The results (Appendix Table I) demonstrate that MSE is not constant across age, therefore root MSE estimates were used to regressMSE for each age period on age, using age in mo that were halfway between the age range values. Backward stepwise regression was performed on a model with linear, quadratic, cubic, and quartic terms for age. The selected model was:

(Equation 13)

$$DMI\ MSE,\ 17\ to\ 24\ mo = -363.73267 + 70.84498*AGEM - 5.13005*AGEM^2 + 0.16410773*AGEM^3 - 0.00195622*AGEM^4,$$

where AGEM = age in mo.

The R-squared (0.82), suggest this equation accounted for most of the variation in MSE prediction for DMI. This model predicts accurately until 26 mo, at which time predicted MSE becomes negative. For this reason, MSE beyond 25 mo is fixed at 0.9667, the variation in Appendix Table I for heifers greater than 25 mo of age.

After the best model was chosen, variables were examined to determine their worth or impact on prediction of DMI. The derivative equations and slopes are presented in Table 26. The second criteria involved determining the effect of changing each main effect variable by one, two, or three SD units. Table 27 lists these calculations, and it appears that all variables have a reasonable impact on DMI prediction, although AGEW and ADG impacts were small in the model without HIEFER and MONTH.

A normal probability plot and a histogram provide evidence that BW are normally distributed (Figures 15 and 16). The histograms appear bell shaped similar to a normal curve. The normal probability plots are considered normal if the data points tend to be near the line connecting the “+”’s, which they do (SAS, 1990). Therefore, variation can be added to the prediction of DMI by multiplying the SD estimate by a normal random deviate and adding to the prediction.

First Lactation Milk Yield Equation

An equation was developed to predict 305 day first lactation milk yield of Holstein heifers. The objective was to develop an equation that would predict milk yield given the variables calculated for each heifer in the simulation. Previous research (Fisher et al., 1983; Keown and Everett, 1986) reported first lactation milk yield was influenced by age and BW at calving. One objective of the simulation is to evaluate profitability, so determining how various growth rates and ages at calving may influence first lactation milk yield is imperative to determine profitability of different rearing and management schemes for replacement heifers. Within the simulation, milk yield will be predicted after a heifer calves, given age and BW at calving.

The equation was developed from a master data set consisting of herds on DHIA test in Virginia from December, 1994 through November, 1995. The master data set contained records for all lactations for each cow in every herd. Two data sets were developed from the master data set, one that contained individual cow records and another that contained herd averages. For the first data set, first lactation Holstein records were selected, resulting in records from animals with birth dates ranging from Oct. 9, 1976 to May 8, 1993. Duplicate records were removed by selecting the last record for each cow. Criteria for elimination of individual records in the first data set included: age at first calving less than 547 or greater than 1216 days; first calving BW less than 400 or greater than 700 kg; days milked 3x greater than 0; and first lactation 305 milk yield less than 4000 kg. For the second data set, herd means for BW and 305 milk yield were calculated for first lactation animals and mature animals (those in third or later lactation). Duplicate records were removed by using only the last observation for each animal. For both data sets, criteria for elimination of herds (and therefore all animals within the herd) included: herd SD for first calving BW less than 10 kg; average mature BW less than 400 kg; average first lactation BW less than 400 kg or greater than 700 kg; average first lactation milk yield less than 4000 kg. All individual records from eliminated herds were also eliminated. The two data sets were merged by herd, resulting in a data set of first lactation records with accompanying herd averages (Table 28) representing 50,745 first lactation records from 664 herds.

Backward and forward stepwise regression procedures of SAS (1985) were initially used to fit an equation to the data. The variables BW (after calving BW, kg), AFC (Age at first calving, days), BW^2, AFC^2, BW*AFC, BWDEV (BW of mature cows in herd - BW), $BWDEV^2$, MATMILK (herd average 305 milk yield for mature cows, kg), BW*BWDEV, BW*MATMILK, AFC*MATMILK, and MATMILK*BWDEV were included in the full model. Producer estimates recorded through DHIA were used for BW. Previous researchers (Fisher et al., 1983; Keown and Everett, 1986) noted age and BW at calving significantly influenced first lactation milk yield. Squared terms for BW and AFC were added to provide a quadratic fit similar to Fisher et al. and Keown and Everett. To account for body size of animals in the herd, BWDEV was added, which is the difference of herd average mature BW and an individual first calving BW. Mature animals were those in third or later lactation. In other words, a 500 kg heifer in a herd with a 600 kg mean BW may not have the same level of production during first lactation as a 500 kg heifer in a 700 kg mean BW herd. Mature milk production (MATMILK, which is the herd average 305 milk yield of animals in third or later lactation) was included to account for differences in management quality or level of production of the herd. Mature milk production interactions with BW, AFC, and BWDEV were included to account for how these variables may influence 305 milk yield in different quality herds. For example, a light heifer at calving may have more difficulties in a poor herd, possibly due to inadequate nutrition.

The models selected by backward and forward Stepwise regression are in Table 29. Backward selection eliminated the variables BWDEV, BW^2, and BW*MATMILK, and forward selection eliminated the latter. The models were similar in terms of MSE, R-squared, and adjusted R-squared, however the PRESS statistic favored the backward selected model. Figure 17, a plot of C(p) against *p*, demonstrates that the forward selected model may be over-specified. The C(p) were generated by performing the MAXR Stepwise procedure to select the best one variable model, two variable model, etc. Using this plot as criteria, the 9 variable model ($p = 10$) is the first where C(p) is below *p*. This 9 variable MAXR selected model is identical to the backward selected model. The forward selected model (11 variables, $p = 12$) was beyond where C(p) is below *p*. Therefore, the backward selected model was chosen:

First Lactation 305 d milk yield: (Equation 14)

$$4250.23934054 - 2.55318777*BW - 2.30218181*AFC + 0.26728402*MATMILK - 0.00178746*AFC^2 - 0.01149011*BWDEV^2 + 0.00428820*BW*AFC + 0.02238066*BW*BWDEV + 0.00046924*AFC*MATMILK - 0.00098551*BWDEV*MATMILK$$

Where:

BW = post-calving BW (kg) for first lactation Holstein heifers;
AFC = age at first calving (days);
BWDEV = herd average BW for third and later lactation (mature) animals (kg) - BW (kg);
MATMILK = herd average 305 d milk yield for third and later lactation (mature) animals.

The General Linear Model (GLM) procedure of SAS (1985) was used to evaluate Equation 14 with the variable season added. SEASON, defined as the season when calving occurred [winter (Dec. 21-Mar. 20), spring (Mar. 21-Jun. 20), summer (Jun. 21-Sep. 20), and fall (Sep. 21- Dec. 20)], was added to account for seasonal differences in milk production. SEASON is a non-continuous variable, therefore regression analysis could not be used. For SEASON, four coefficients were calculated. These coefficients can be averaged and added to the intercept for a general model. However, for use in the simulation, a heifer calving in January would have the winter coefficient added to the intercept, a heifer calving in April would have the spring coefficient added, and so on. In this way, milk prediction will vary depending on when the heifer calves.

When SEASON was added to the model, the equation changed to:

First Lactation Milk Yield: (Equation 15)

$$4663.639328 - 2.743928*BW - 3.030839*AFC + 0.257743*MATMILK - 0.001483*AFC^2 - 0.011583*BWDEV^2 + 0.004452*BW*AFC + 0.022875*BW*BWDEV + 0.000484*AFC*MATMILK - 0.001013*BWDEV*MATMILK.$$

Season of calving estimates (-85.1617, -69.4104, -225.5667, and 0 for winter, spring, summer and fall, respectively) were averaged (-95.0097) and added to the intercept (4758.649).

Statistics for the model with season are in Table 29. The GLM procedure does not compute C(p) or Press statistics, therefore the only means of comparing all four models is R-squared, adjusted R-squared and root mean square error. Using these criteria, the models with SEASON are superior.

After the best models were chosen (with and without SEASON), main effect variables were examined to determine their worth or impact on prediction of 305 first lactation milk yield. The derivative equations and slopes are presented in Table 30. Using this criteria, it appears a unit change in BW results in the greatest change in predicted first lactation milk yield. However, all variables appear to influence milk yield prediction. The second criteria involves calculating the influence of changing each variable by one, two, or three SD units above or below it’s mean. The results in SD units and kg 305 day milk are in Table 31. Using this criteria, one SD unit change in MATMILK has the largest influence on milk yield prediction. However, within the range of +/- 3 SD, each variable can alter milk yield by at least 335 kg milk. Considering both criteria for evaluating the worth or impact of model terms, all variables have a reasonable impact on prediction of first lactation 305 milk yield for Holstein cows.

The reason for developing an equation to predict first lactation milk yield was to incorporate the equation into the simulation. For the equation to be meaningful and representative of a real situation, it must contain variation to account for differences between heifers within herds and between herds. To estimate variance of these components, the SAS (1990) procedure VARCOMP was used. This procedure estimates the variance of random variables within a model. For this application, the variation of MILK305 within and between herds was needed. Therefore, the model MILK305=HERD was used with HERD in the class statement. Using this model, VARCOMP estimated a herd variance component (388,955.89) and an error variance component (1,388,205.40), which correspond to between herd variation and between heifer variation within a herd, respectively. The SD or square root of the variances are:

SD of first lactation milk yield between herds: 623.7
SD of first lactation milk yield within herds: 1178.2

A normal probability plot and a histogram provide evidence that MILK305 and herd average MILK305 are normally distributed (Figures 18 - 21). The histograms appear bell shaped similar to a normal curve. The normal probability plots are considered normal if the data points tend to be near the line connecting the “+”’s, which they do (SAS, 1990). Therefore, variation can be added to the prediction of first lactation milk yield by multiplying the SD by a normal random deviate and adding to the prediction. Within herd variation is added for each individual heifer that is generated in the simulation. After a herd of individuals is generated, between herd variation is added.

Simulation

The simulation was developed using a spreadsheet (Microsoft Excel version 7.0, Microsoft Corp.) on a microcomputer. Spreadsheet format was chosen to enable future changes by any user familiar with spreadsheets. Although the spreadsheet is complex, a user equipped with basic spreadsheet skills should be capable of altering and running the simulation. In addition, Excel will run on most modern Apple or IBM compatible computers. The simulation contains several files (workbooks), each of which contains one or more sheets, all of which are linked. The simulation will generate one heifer every 20 to 60 seconds, depending on computer capabilities.

Variation

For the simulation to be representative of real life, variation must be included for each item predicted in a heifer’s life. For example, estrous cycle length may average 21 days, but every heifer will not have a 21 day estrous cycle. The variation can be best estimated by some estimate of SD. Assuming biological variables are Normally distributed, variation can be included by adding to the mean the SD multiplied by a Normal random deviate. Normal random deviates are generated in the simulation by the Excel function NORMINV(RAND(),0,1). This function randomly chooses Normally distributed deviates, which follow the Empirical Rule such that 99% of the values are between -3 and 3, 90% between -2 and 2, and 66% between -1 and 1 (Ott, 1993). This function is ideal because it can be included in prediction formulas. The function will generate a new Normal random deviate each time the spreadsheet is recalculated.

Probabilities

Probabilities are used to predict the occurrence of events such as death loss, heat observation, and conception. For these events, a percent occurrence can be estimated to determine if the event occurs. In Excel, random numbers uniformly distributed between 0 and 1 can be generated by the function RAND(). For example, if death loss is 10%, and the RAND function generates a number less than or equal to 0.10, then the heifer dies; if the number is greater than 0.10, the heifer lives. In this manner, probabilities associated with events can be included in the simulation. Excel generates a new random number each time the spreadsheet is recalculated.

Least Cost Ration Formulation and Feed Costs

Feed costs are estimated for each week of the simulation. Through a linear program, the user formulates least cost rations prior to running the simulation. For feeding purposes, heifers were grouped by age, with all heifers in a group receiving the same ration. Five groups were used: 1)baby calves (birth to 5 wk), 2)post-weaning calves (6 to 13 wk), 3)younger heifers (14 to 59 wk), 4)breeding age heifers (60 wk to 8 wk after conception) , and 5)bred heifers (8 wk after conception until calving). Heifers move from groups 1 to 2, 2 to 3, and 3 to 4 based on age.

For baby calves, starter is fed free choice, 0.46 kg milk fed daily until 28 d, and 0.23 kg milk fed daily from 28 to 35 d. Daily CP and TDN requirements for remaining groups were predicted using equations developed from NRC (1988) requirements for heifers with different growth rates:

$$TDN = (-3.12197 + 0.012251*BW + 2.995733*ADG)*0.454; \qquad \text{(Equation 16)}$$

Adjusted R-squared = 0.99.

$$CP = (-0.65757 + 0.002566*BW + 0.620722*ADG)*0.454; \qquad \text{(Equation 17)}$$

Adjusted R-squared = 0.96.

$$DMI = (-7.18725 + 0.023764*BW + 4.573441*ADG)*0.454; \qquad \text{(Equation 18)}$$

Adjusted R-squared = 0.99.

Where:

TDN = predicted daily TDN requirements, kilogram;
CP = predicted daily CP requirements, kilogram;
DMI = predicted daily DMI, kilogram;
BW = body weight, kilogram;
ADG = average daily gain, kilogram.

Minimum requirements for CP, TDN, and DMI were set at NRC requirements as predicted by the equations. Maximum requirements were five percent above minimums. For ADF, the user enters maximum and minimum values for each group.

The linear program predicts the proportion of each feed in the ration on a least cost basis. Excel has a linear program module, termed solver. By setting the solver on linear, a linear program is solved similar to the traditional simplex method for solving linear programs (Moore et al., 1993). The purpose of the linear program is to determine which feeds will be fed, and in what proportions they will be fed. The linear program will not predict actual quantities of feeds consumed. As an example, suppose available feed ingredients are corn silage, grass hay, and grain. The linear program would be set up as follows:

minimize z = cs*cs\$ + hay*hay\$ + grain*grain\$

subject to:

cs*csCP + hay*hayCP + grain*grainCP≤ CPmax
cs*csCP + hay*hayCP + grain*grainCP≥ CPmin
cs*csTDN + hay*hayTDN + grain*grainTDN ≤ TDNmax
cs*csTDN + hay*hayTDN + grain*grainTDN ≥ TDNmin

$\mathrm{cs} + \mathrm{hay} + \mathrm{grain} \leq \mathrm{DMImax}$
$\mathrm{cs} + \mathrm{hay} + \mathrm{grain} \geq \mathrm{DMImin}$
$\mathrm{cs}*\mathrm{csADF} + \mathrm{hay}*\mathrm{hayADF} + \mathrm{grain}*\mathrm{grainADF} \geq \mathrm{ADFmin}$
$\mathrm{cs}*\mathrm{csADF} + \mathrm{hay}*\mathrm{hayADF} + \mathrm{grain}*\mathrm{grainADF} \leq \mathrm{ADFmax}$
$\mathrm{cs} \leq \mathrm{csmax}$
$\mathrm{grain} \leq \mathrm{grainmax}$
$\mathrm{hay} \leq \mathrm{haymax}$

where:

cs= kg corn silage DM in ration
cs\$= corn silage cost/kg DM
hay= kg hay DM in ration
hay\$= hay cost/kg DM
grain= kg grain DM in ration
grain\$= grain cost/kg DM
csTDN= corn silage TDN content
csCP= corn silage CP content
csADF= corn silage ADF content
hayTDN= hay TDN content
hayCP = hay CP content
hayADF= hay ADF content
grainTDN= grain TDN content
grainCP= grain CP content
grainADF= grain ADF content
CPmin= minimum total kg CP in ration
CPmax= maximum total kg CP in ration
TDNmin= minimum total kg TDN in ration
TDNmax= maximum total kg TDN in ration
DMImin= minimum DMI
DMImax= maximum DMI
ADFmin= minimum total kg ADF in ration
csmin= minimum total kg of corn silage in ration
csmax= maximum total kg of corn silage in ration
grainmin= minimum total kg of grain in ration
grainmax= maximum total kg of grain in ration
haymin= minimum total kg of hay in ration
haymax= maximum total kg of hay in ration

This program solves for the variables cs, hay, and grain on a least cost basis. After quantity of each feed (kilograms) is determined, dividing that quantity by the total DM converts kilograms to percent of total ration DM. Therefore, the final ration as predicted by the linear program is expressed as % of total ration DM, which can be multiplied by predicted DMI to determine quantity of each feed consumed. The user enters feeds available and their corresponding price and nutritive values. The model is actually larger than the example presented, with seven variables (kilogram fed, cost/kilogram DM, minimum kilogram fed, maximum kilogram fed, TDN content, CP content, and ADF content) added to the model for each feed. If the model contains more feeds than are chosen by the user, the "extra" can have a high price assigned so they don't enter the solution. In addition, the minimum and maximum values for each feed allow a feed to be “forced” into or eliminated from the solution. For minerals, user specified quantity per day is “forced” into the solution. The resulting ration would meet or exceed protein and energy needs of the heifer at minimum total cost. The calculated cost per kilogram of DM for the ration is converted to kilograms, then multiplied by seven and DMI to determine weekly feed costs.

Rations are formulated once for each simulation run. Therefore, the user must run the LP ration programs before the simulation is run. The LP ration programs may not always find a solution that meets constraints. If this occurs, the program will formulate a ration to meet as many constraints as possible; the user must decide if the ration is acceptable. If it is not, then new feed inputs must be entered and the ration reformulated.

Breeding

Heifers are eligible to be bred when they exceed BW and age minimums specified by the user. Age at first estrus, estrous cycle length, gestation length and their accompanying SD are also specified by the user. By applying mean and SD values multiplied by a Normal random deviate, variation can be included. Gangwar et al. (1965) found that estrous cycles for 12-15 mo virgin Holstein heifers averaged 20 and 21 days under spring and summer conditions, respectively. Wishart (1972) reported the estrous cycle length of Fresian heifers averaged 22.02 days (SD = 3.5).

The simulation also allows for AI and natural service matings. For AI matings, percent possible heats observed, maximum number of services per heifer, and conception rates for first, second, and third and later services are entered by the user. If a heifer does not conceive by the specified maximum number of services, she is culled 8 wk later. Varied AI conception rates for different services were included to account for possible reduced conception rates for later services. Gwazdauskas et al. (1981) reported a 59.3% AI conception rate for virgin heifers at the Virginia Tech Dairy Center. In the same study, but including all cows and heifers, they reported AI conception rate was 51.8 and 47.9% for first and second services, respectively, but the difference was not significant. Slana et al. (1993) reported a 68% first service conception rate on 264 Holstein heifers, and a 64% overall conception rate on 374 Holstein heifers, but did not statistically analyze the data. Although these results show conception rates did not differ statistically by service number, the proportion of heifers incapable of breeding for physiological or other reasons may be higher for later services. For natural service, the user must input conception rate, percent possible heats observed, and maximum services for the bull. Natural service occurs after maximum number AI services are reached. For example, if three services are the maximum for AI, fourth and later services are natural, simulating a “clean up” bull. If a bull is not to be used for any services, the maximum number of services for the bull is set at zero. To use either a bull or AI for all services, the maximum number of services is set at zero for bull or AI, respectively.

The costs for natural service are applied only to the first natural service to conform with literature values. Johnston et al. (1987) reported the annual cost per cow and replacement for housing, feeding, and caring for a bull is $22.03, assuming the bull weighs 998 kg, is replaced every 2.5 years, and services 40 cows and 15 heifers. They included all fixed and variable costs of housing a bull in their calculations. The $22.03 calculated by Johnston et al. applies regardless of number of services per cow or heifer. Therefore, the simulation applies this figure only to the first natural service; second or later natural services are assigned a value of zero. The user can input a value other than $22.03.

Seasonal breeding is enabled by allowing the user to specify weeks of the year where breeding is allowed. For example, if a herd is breeding for fall calving (August, September), they may want to avoid calvings in May, June and July. In this situation, heifers eligible to breed in August, September, and October need to be held and bred in November, thus the user would specify no breedings in August - October. In this manner, seasonal breeding is possible in the simulation.

In the simulation, a heifer begins cycling at an age input by the user. The simulation assigns the first day of estrous as day one, the second day as day two, and continues to count days until the day of estrous equals the estrous cycle length added to SD multiplied by a normal random deviate. When this occurs, the heifer is labeled “in estrus.” If she meets minimum criteria for age and BW as specified by the user, she is eligible to be bred. A probability of observing the estrus is then applied. If the heifer’s estrus is observed, she is bred. Once bred, a probability of conception is applied. If she conceives, she is considered pregnant and remains so until calving, unless she aborts. Therefore, to become pregnant, a heifer must be of minimum age and BW, be in estrus, have estrus observed, and conceive. This is displayed schematically in Figure 22. If a heifer is in estrus and meets minimum age and BW requirements, the probability of conception is percent heats observed multiplied by conception rate. Once a heifer is pregnant and does not die or abort, she will calve based on user selected gestation length and SD.

Birth

If calves are born during all months of the year, birth distribution is determined randomly by Excel using the function RANDBETWEEN(1,365). This function randomly chooses a number between one and 365, corresponding to the day of year the calf is born. If calves are not born during certain months (seasonal calving), another method is used to determine birth date. Subtracting the total number of days in mo where calves are not born from 365 will give a new year length to use in the RANDBETWEEN function. If the random value generated by RANDBETWEEN is less than the day of year on the first day of the first month where no calves are born minus one, then the number is accepted as is. If the random number is greater than this number, then the number of days in all months where no calves are born is added to the random number. In this manner, days of year corresponding to months where no calves are born will not be chosen. For example, suppose calves are not born during June and July. In this scenario, the year length is no longer 365 days, but rather 365 - 30 - 31=304. A random number is selected using: RANDBETWEEN(1,304). If this number is less than 150 (June 1 is the 151st day of the year), then it is kept as the day of year for birth. If it is greater than 150, 61 is added to determine day of year for birth. Once day of year is determined, it is added to January 1 to get the date. The user is limited to choosing only consecutive months where calves are not born.

Growth and Dry Matter Intake

For all DMI predictions, minimums were set to avoid calculation of an unrealistically low or negative DMI. Minimums were set as follows for various ages: birth to 2 wk, 0 kg; 2 to 4 wk, 0.10 kg; 5 wk, 0.20 kg; wk 6 until calving, 1% of BW.

Birth to 42 days

Equations 1 - 6 are used to predict starter DMI and BW of heifers from birth to 42 d. Milk solids are fed at 0.46 kg/d to all heifers from birth to 28 d and 0.23 kg/d from 28 to 35 d, and all heifers are weaned at 35 d of age. Varied milk feeding rates and weaning dates are not appropriate because these parameters were constant in the data sets used to generate equations. Birth weight will be predicted from mean birth BW and SD as input by the user. Sieber et al. reported a mean birth weight of 39.5 kg (SD = 5.8 kg) from 1794 Holstein calves born between 1968 and 1986; mean birth weight from all female calves in data used to generate Equations 1 - 6 is 40.3 kg (SD = 5.8).

42 days to 17 months

For this age group, BW is predicted from Equation 7. The data used to generate this equation contained heifers that were at minimum 4 mo of age, although few observations were below 5 mo. Therefore, from approximately 42 d to 5 mo, there are no growth equations developed due to lack of data. Therefore, for this age period, 0.8 kg ADG is applied to predict BW. The Quigley et al. (1986) equation was used to predict DMI from 100 to 400 kg BW, and applies to heifers in this BW range. For heifers less than 100 kg BW, NRC predicted DMI as described by Toro (1987) will be used.

17 months to calving

Equations 10 and 12 will be used to predict BW and DMI, respectively. Heifers in the data set used to develop equations 10 and 12 were 16 to 28 mo of age. In the event of an age at first calving beyond 28 mo, equations will continue to apply, which assumes growth continues at a similar rate. No data were available beyond 28 mo to validate this assumption. To avoid excessive BW, a maximum BW (and SD) is input by the user.

Death Loss, Abortions, and Culling

The user must input death loss rates (percentage) for heifers at various stages of life: birth, birth to weaning, weaning to 14 mo, and 14 mo to 24 mo. These percentages apply to the entire period represented. For example, if the user specifies death loss from birth to weaning at 10%, then approximately 10% of the heifers will die sometime from birth to weaning. Using probabilities, heifers will “die” if a uniform deviate is less than the death loss probability. Abortions and postpartum culls are determined in a similar manner, based on user inputs.

Probability of death loss and abortion are determined on a weekly basis. If the death loss from birth to weaning is 10%, a weekly probability must be determined. The probability of death for each week is mutually exclusive, therefore it would seem logical that the sum of weekly probabilities should equal the overall probability. However, this is not exactly correct because a heifer can only die once. The probability of death in any given period is conditional on the fact that she has survived all prior periods. To account for this, weekly probability of death was determined from calculating the weekly probability of living. The probability of living is not mutually exclusive for each week. Therefore, the product of all weekly probabilities of living must equal (1 - death loss for the period). The formula to determine this is:

$1 - (1-x)^t = p$;

Where:

x = weekly probability of death or abortion;

t = period in weeks to which death loss rate applies;

p = probability of death for the period t.

By solving for x given t and p, the weekly probability of death or abortion can be calculated. The following example calculation demonstrates this, assuming 10% death loss from birth to weaning (5 wk):

$1 - (1-x)^5 = 0.10$

$(1-x)^5 = 0.90$

$5 * \ln(1-x) = \ln(0.90)$

$5 * \ln(1-x) = -0.105361$

$\ln(1-x) = -0.021072$

Applying the anti-natural log, or e^x, to each side of the equation yields:

$1-x = 0.979148$

$x = 0.020852$

Therefore, the weekly probability of death from birth to 5 wk is 2.0852%. This is close to (10%/5), which equals 2%. The difference is due to the previously mentioned fact that a heifer can only die once. A heifer cannot be subject repeatedly to the death probability.

The method used to determine weekly death loss probability is also applied to weekly probability of abortion. Animals that die, abort, or do not conceive are culled. Once culled, the animal is removed from the simulation, but her data are included in the summary sheet. If a heifer dies, her costs are accumulated up to the week of death, and include the initial value of the heifer at birth. If a heifer aborts, costs are accumulated for an additional 8 wk, assuming the abortion goes unnoticed for this time. Once a heifer aborts, she is culled rather than re-bred. When the maximum number of services is reached, the heifer is culled in a similar manner as heifers that abort (costs accumulated for additional 8 wk). Once a heifer is culled, a user specified cull price ($/kg) is applied to determine income generated from selling the heifer at a livestock auction.

Calving

A heifer calves when her age equals the age at conception plus gestation length added to a Normal random deviate x SD. After calving, Equation 15 predicts milk yield from post-calving BW, age at calving, mature BW of the herd, season of calving, deviation of post-calving BW from BW of mature animals in herd, and 305 d milk production of mature cows in the herd. Mature cows are those in third and later lactation. The user must input mature BW and milk yield. Post-calving BW (kg) is estimated by: BW at calving - 50 kg. Month of calving, determined from birth month, is used to adjust for season. Feed costs for the heifer during lactation are determined from user specified feed costs per cwt of milk. This approach is not precise, however, considering animals with higher milk yields within the same herd should have lower feed costs per cwt of milk. Other fixed and variable costs such as housing, labor, bedding, health, and milking are assumed to be constant for every heifer; the user specifies a total non-feed cost per day for a heifer in lactation. This assumption is invalid in real life, but data were not available to discern cost differences for heifers with varied age and BW at calving and milk yield during first lactation.

Varied Growth Rates

Growth rates are varied somewhat by feeding rations varying in energy content. As displayed in Figure 24, growth rates for 5 to 17 month old Holstein heifers as predicted by Equation 7 differ slightly depending on energy content of the diet. Average daily gain for heifers receiving high, medium, and low energy diets represented in Figure 24 are 0.83, 0.79, and 0.73 kg/d. The differences among these were considered too small to evaluate growth rate differences.

It was desired to alter growth rates significantly during three periods of life: 5 wk to 24 mo, 5 wk to 14 mo and 14 mo to 24 mo. The latter periods were chosen because they represent pre-breeding age and bred heifer groups on many farms. To accommodate widely divergent growth rates, an estimate of growth differences between slow and rapid versus average gaining heifers was needed for each week of life. This difference could simply be added or subtracted from predicted BW to obtain fast or slow rate of gain. The equations generated for the simulation represent average growth. The user inputs differences in BW at 14 mo or 24 mo, enabling all combinations of accelerated and reduced growth rates from 5 wk to 14 mo, 14 to 24 mo, and 5 wk to 24 mo. It was assumed that the differences in growth from the average increased linearly across all weeks, implying growth differences per week can be represented by (BW difference/ total weeks)*age in weeks. For example, if the BW difference at 24 mo (104 wk) was 80 kg, the difference at week 10 is (80/104)*10 = 7.69 kg; the linear equation 0.769*age in weeks represents this relationship. In this manner, BW can be added or subtracted from the predicted BW for each month to obtain varied growth rates.

Costs

Variable feed costs in the simulation are determined weekly from predicted DMI and the least cost ration formulated. The user has the option of using up to ten feeds. Nutritive values and cost per ton are also specified by the user.

Additional costs used in the simulation were obtained from a heifer enterprise budget developed by Willet et al. (1992) at Washington State University (Table 32). These costs are considered fixed in the simulation and will not vary from heifer to heifer. Willet et al. estimated breeding costs at $15 per service (not included in Table 32), and bedding costs at $40/ton. The estimated weekly costs in Table 32 will be used in the simulation. The initial value of a heifer is specified by the user.

Costs were accumulated throughout a heifer's life to determine feed, operating, and ownership costs at conception and calving. For heifers that die or are culled, costs are accumulated until the day they are sold or die. For lactation, feed costs are calculated based on user specified feed cost per cwt of milk. It is recognized, however, that animals with higher milk yields within the same herd should have lower feed costs per cwt of milk. Other daily costs such as housing, health, bedding, labor, and milking for lactating cows are entered by the user as one daily cost that is constant throughout lactation. Income is generated from selling a culled heifer, milk produced during first lactation, and value of a calf born to a heifer. For a calf born to a heifer, death loss probability used previously in the simulation is applied, as is a 50% chance of a heifer. The value of a heifer or bull calf is input by the user.

The value of a heifer at the end of first lactation ($1200) was also included as income. A 33% cull rate was applied, assuming a third of the animals would be culled and not continue to second lactation. First lactation cull rates reported in the literature include 6.0 to 12.6% (Asdell, 1951), 25.2% (Specht and McGilliard, 1960), 25.6% (1996 Virginia DHIA average), 27.4% (Rendel et al., 1951), 28.1 to 31.6% (Seath, 1940), and 29.6 to 29.8% (Miller et al., 1994). For culled animals, cull price x (post calving BW, kg + 70) was used to determine value. Post calving BW was increased by 70 kg to adjust for BW gain during first lactation (Lin et al., 1985). Culled animals were randomly chosen using the RAND() function in Excel.

The costs and income generated for a heifer occur at various points in time, depending on when a heifer calves. To enable comparison, all values must be moved to a common point in time. Three common points in time were evaluated: at birth, calving, and 24 mo. Dollars moved back in time were discounted to a present value, and dollars moved forward in time were compounded to a future value. A user defined discount rate or minimum attractive rate of return (MARR or *i*) was used in calculations. Dollars were moved through time using the following formulas:

$$PV = FV \times \left(\frac{1}{1+i} \right)^n$$

$$FV = PV \times (1+i)^n$$

Where PV = present value;
FV = future value;
i = interest rate; and
n = number of periods.

The interest rate is divided by n to get period interest rate. For example, if the discount rate is 8% and feed costs at 24 mo were $1000, the discounted cost at birth is $1000*[1/(1+0.08/52)]^{24*30.4/7}$ = $851.98. Note that annual discount rate is converted to a weekly discount rate (0.08/52), and n is in weeks. Feed, ownership, and operating costs for a heifer were compounded weekly using the FV formula. In this way, total accumulated costs at calving adjusted for user specified MARR or discount rate include interest or opportunity costs. Interest costs would be total costs adjusted for MARR minus total unadjusted costs. Other items such as income from a culled heifer and value of a heifer at birth occur only once, thus they are adjusted once using the appropriate formula.

Non-feed costs for lactating animals, entered on a cost per day basis by the user, were converted to time of calving using the Excel PV function. This function allows a present value calculation of a series of fixed payments. Non-feed costs per day during lactation were constant for every heifer within a simulation run. From this point, costs were converted to birth and 24 mo using the previously described present value and future value equations. Virginia Cooperative Extension Dairy Farm Budgets (1997) reported non-feed costs per day for lactating cows in Virginia are \$2.49, while Hoards Dairyman (1996) reported these costs for Southern California, Arizona, and Idaho dairies are \$2.30, \$2.73, and \$2.57 per day, respectively.

Milk income and feed costs during lactation were more difficult to move through time because weekly milk yield and feed costs during lactation were not simulated. Therefore, a lactation curve was plotted using the well know incomplete gamma function described by Wood (1967):

$$Y_t = at^b e^{-ct^n}$$

Where Y_t = daily milk yield in month t;
t = month in lactation;
e = base of natural logarithm;
t_m = month of maximum production;
t_f = final month of production;
$b = ct_m$;
$c = r/100*[(t_f + t_m)/ (t_f - t_m)]$;
r = monthly rate of decline;
$a = Y_m\ (ce/b)^b$; and
Y_m = maximum daily yield.

Using this formula, weekly milk yield was predicted. A 10% monthly rate of decline was used. Percentage of milk produced during each month (monthly milk yield/total 305 d milk yield) was identical using this equation regardless of 305 d milk yield. Each monthly percentage was discounted to time of calving using the user specified discount rate. The sum of monthly discounted percentages can be multiplied by the actual milk income (milk yield x milk price) to obtain a discounted milk income at calving. Although this factor (sum of monthly discounted percentages) is constant with varied 305 milk yield, it changes with different discount rates. Therefore, this factor is calculated in the simulation given the user specified discount rate. This same factor is multiplied by total feed costs during lactation (feed cost per cwt. x cwt. milk yield) to yield discounted feed costs at calving.

Net profit or loss was calculated for each heifer using dollar amounts converted to points in time representing birth, calving, and 24 mo of age. Net profit or loss for a heifer that calves in the simulation was calculated as: milk income - feed costs during lactation - other costs during lactation - rearing costs (feed, ownership, operating, breeding) - value of heifer at birth + value of calf born to heifer + value of heifer at end of first lactation - death and cull loss costs. Death and cull loss costs were determined by dividing the sum of costs for dead and culled heifers by the total number of live heifers. This number represents a per heifer cost of death and abortion and was determined once for each herd. For heifers that die, net loss is: -rearing costs (feed, ownership, operating. breeding) until the day of death - value of heifer at birth. For heifers that abort or are reproductive culls, net loss is: -rearing costs (feed, ownership, operating. breeding) until the day she is sold + value of heifer sold at auction - value of heifer at birth. All of the values used in net profit or loss equation were moved to the appropriate point in time before summing. Annual and monthly costs from birth to calving were determined using the following formula:

$$AV = PV \times \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right]$$

Where AV = annual or monthly value;
PV = present value rearing costs at birth, including value of heifer at birth;
n = number of periods (annual or monthly);
i = period interest rate (annual or monthly).

Running the Simulation

The simulation is run by a macro in Excel that generates *n* heifers in each run, with *n* specified by the user. With each calculation in each run, new random numbers are generated. The results, including BW gains, feed costs, first lactation milk yield, etc. are summarized on a worksheet in Excel. The following instructions, listed on a worksheet in the simulation, enable the user to run the simulation: (instructions must be followed in order):

A. Set recalculation to manual (Tools, options, calculation).
B. Open SIMMACRO.XLS.
C. From Simulation menu, run "Open Simulation Files" macro.
D. From Simulation menu, run "Open LP Ration Files" macro.
E. Complete input sheets in SIM.XLS file (inputs and feed inputs) and then recalulate (F9).
F. From Simulation menu, run "Close Simulation Files" macro.
G. Run LP rations for groups 2-5 using ration files listed below.
  1. Each LP ration is run by selecting Tools, Solver, Solve.
  2. The Solver module is not included in the typical Excel setup. To enable Solver, select Tools, Add-ins, Solver Add-ins (original floppies or CD required).
  3. If solver displays message that a feasible solution cannot be found, then re-key feed inputs or accept solution as is.
  4. When solver has found a solution, select OK to keep solution.
  5. Set a very high price or set maximum to zero for feeds not desired in the solution.
H. From Simulation menu, run "Open Simulation Files" macro.
I. Run the simulation from SIMMACRO.XLS file.
  1. Specify the number of heifers in a run.
  2. From the Simulation menu, select "Run Simulation".
  3. Results are summarized in the SIMMACRO.XLS file.

HINTS:
1. Recalculation may take a while (more than 30 seconds).
2. When new files are loaded, select "Yes" to re-establish links.
3. All macros are on Simulation menu.
4. Be sure to close all Excel files not involved in the simulation.
5. Close any other program that is open, such as a word processor.
6. The simulation will take 20 - 60 seconds/heifer, depending on computer capabilites.

Files in Simulation

1. SIM.XLS - weekly events for a heifers life plus inputs.
2. SIMBREEDING.XLS - accumulates breeding data.
3. SIMCALVING.XLS - accumulates calving data.
4. SIMBIRTH.XLS - predicts birth date.
5. SIMREPRO.XLS - simulates heats, breedings, etc..
6. SIMMACRO.XLS - contains macros to run simulation; summarizes data for each heifer from birth to calving.

Ration Files

1. 2RATION.XLS - rations for heifers from 6 to 13 wks.
2. 3RATION.XLS - rations for heifers from 14 to 60 wks.
3. 4RATION.XLS - rations for breeding age heifers.
4. 5RATION.XLS - rations for bred heifers.

Inputs are specified before the simulation is run. Therefore all heifers in a run will have the same inputs applied and consume the same rations formulated by the least cost rations.

Simulation Runs

The purpose of building the simulation was to evaluate management strategies for rearing dairy replacement heifers. Therefore, various simulation runs were performed to evaluate impacts of differing management strategies. For each simulation run, 10 herds of 100 heifers were run for each treatment. The impacts were measured financially by determining the cost of getting a heifer into the milking herd and the net profit/loss at calving milk yield, fixed costs, and feed costs during first lactation and value of animal at end of first lactation. All of these values were moved to time zero (birth) to get a present value cost, time of calving, or 24 mo of age by using a user defined discount rate. In this way, interest costs are considered.

A control situation was established with standard inputs for all parameters. Standard input values were used for all simulation runs, with specific inputs altered to achieve objectives for an individual run. For example, if two rates of heat detection were compared (40 and 45%), all inputs except percent heats observed remained as in the control situation. Standard inputs for running the simulation are listed in Table 33. Inputs noted in the table are from literature values. Remaining inputs were set to represent a herd with above average management.

Table 34 contains target ranges used by the least cost ration programs to formulate rations. Standard or control rations formulated by the least cost ration formulator are in Table 35. Baby calves (birth to weaning) were offered calf starter free choice and fed 0.46 kg/d milk solids ($0.80/lb) from birth to 28 d and 0.23 kg/d from 28 to 35 d. For Group 2 heifers (6 to 13 wk), all feeds except second-cut grass hay and calf grain were set a maximum of zero, thus eliminating them from the ration. For Groups 3 to 5, 0.45 kg/d soybean meal and 0.45 kg/d dry shelled corn were forced into the solution. In addition to the feeds in Table 35, whole cottonseed ($180/ton) was offered as a feed for Groups 3 to 5, but it was not selected. Groups 2 to 4 had 0.10 kg/d mineral force-fed and 0.20 kg/d was force fed for group 5.

Statistical Analysis of Results

Results were analyzed using the GLM procedure of SAS (1985). Dependent variables were analyzed using the following model:

$Y_{ijk} = \mu + T_i + H_{(i)j} + E_{(ij)k}$, where:

Y_{ij} = dependent variable of heifer k in herd j and treatment i;

μ = population mean;

T_i = fixed effect of treatment, i = 1 to i where i is number of treatments;

$H_{(i)j}$ = random effect of herd, j = 1 to 10;

$E_{(ij)}$ = random residual; effect of k^{th} heifer in j^{th} herd, k = 1 to 1000.

Treatment effects were tested using the nested herd term as error. Contrasts were used to detect linear and quadratic trends and Tukey's mean separation procedure was used to teste differences with respect to treatment. The nested term was used as the error term for testing contrasts, calculating Tukey's critical values, and calculating standard errors. Tukey's procedure and contrasts were only applied for variables where treatment was significant ($P < 0.05$) in the model. The SAS (1985) procedure PROC NESTED was also run on all data sets to determine the percent variation attributed to treatment, herd, and error terms.

Growth Rates

Growth rates were studied by adjusting growth rates during three periods, 5 wk of age to calving (period I), 5 wk to 14 mo (period II), or 14 mo to calving as previously described. Six scenarios were evaluated: normal in both periods (Control:Control), accelerated in both periods (ACC:ACC), slow in both periods (Slow:Slow), normal growth for period I and accelerated growth for period II (Control:ACC), accelerated growth for period I and normal growth for period II (ACC:Control), or slow growth for period I and accelerated growth for period II (Slow:ACC). All simulation inputs were control (Table 33) except for those described in Table 36. Dry matter intake as a percent of BW was calculated as average DMI from birth to calving divided by average BW from birth to calving. Average BW from birth to calving was determined as 40 kg + ADG overall x (age at calving/2). The 40 kg is an estimate of BW at birth.

Treatment differences or pairwise comparisons were determined using Tukey's studentized range test (SAS Institute, 1985). The SAS statistical package computes Tukey's critical values using raw means. This data was unbalanced due to varying death loss rates between herds, therefore least squares means must be used. Tukey's critical values were computed manually as follows:

Critical Value = $(q_{\alpha,\,t,\,d.f.})$ x $\sqrt{MS / r}$; where

$q_{\alpha,\,t,\,d.f.}$ = Studentized range table value for α significance, t treatments, and d.f. degrees of freedom for the error term;

MS = mean square for treatment error term;

r = number of observations in a treatment mean.

For variable number of observations per treatment, $r = t/(1/r_1 + 1/r_2 + \ldots + 1/r_t)$ (harmonic mean).

Varied Feed Costs

Feed costs per unit would likely change for heifers receiving a diet formulated to achieve accelerated growth rates. This scenario was not considered in the previously described analysis of growth rates; it was assumed that herds with accelerated growth had similar feed costs per unit as herds with slow growth rates. In reality, the accelerated diet would likely have higher concentrations of energy and protein, thus having a higher cost per unit of DM.

The previously described accelerated group (5 wk of age until calving) from the growth rate analysis was used to evaluate the impact of varying feed costs on heifer rearing costs. Feed costs were increased 5, 10, and 15% from controls, resulting in a control and three treatments. The simulation generated data only for treatment one (normal feed costs, control); for increased feed costs where feed costs were increased by the desired percentage, and all other variables that were calculated from feed costs were also recalculated. Linear, quadratic, and cubic contrasts were used to evaluate trends related to changing feed costs. Coefficients for linear, quadratic, and cubic contrasts were [-3, -1, 1, 3]; [1, -1, -1, 1]; and [-1, 3, -3, 1]; respectively (Lentner, 1993).

Heat Detection Efficiency

Three heat detection efficiencies (40, 50, and 60%) were evaluated at three sets of conception rates. The three sets of conception rates were 40, 65, and 80%. These conception rates were for first service; for second and third services, rates decreased two percentage points from first service rate. All other inputs were at control (Table 33). Heat detection efficiencies were evaluated independently for each level of conception rate using linear and quadratic contrasts. Coefficients for contrasts were -1, 0, 1 (linear); and 1, -2, 1 (quadratic).

Death Loss

Two death loss scenarios were evaluated, either at birth (5, 10, and 15%) or from birth to weaning (1, 10, and 15%). All other inputs were at control (Table 33). Linear and quadratic trends were evaluated independently for each age period using linear and quadratic contrasts. Coefficients for linear and quadratic contrasts were -1, 0, 1; and 1, -2, 1; respectively for death loss at birth and -2.3, 0.4, 1.9; and 0.1043046, -0.2920530, 0.1877484; respectively for death loss from birth to weaning. The non-integer coefficients were due to unequal spacing between losses of 1, 10, and 15%.

Abortions

Three different abortion rates (1, 5 and 10%) were evaluated with all other inputs at control (Table 33). Linear and quadratic trends were evaluated independently for each age period using linear and quadratic contrasts. Coefficients for contrasts were -2.6, -0.2, 2.8 (linear) and 0.295082, -0.5311476, 0.2360656 (quadratic). The non-integer coefficients were due to unequal spacing between abortion rates of 1, 5, and 10%.

Results and Discussion

Equations

The calf BW model (Equation 1) explained 93% of the variation associated with calf BW from birth to 42 d of age. The positive coefficient for age demonstrates that BW increased with age, as displayed graphically in Figure 23. The equation predicted 38.9 kg BW at birth; however, birth BW in Figure 23 is mean birth BW (40.3 kg) for the data set, implying that heifers lose BW during the first week, then gain slowly during the second week of life. From week 2 until 6, BW gain appears to be fairly constant.

The equations to predict starter DMI (Equations 2 to 4, 6) explained from 45 to 99% of the variation in starter DMI. All variables in all equations had positive slopes from derivative equations (Tables 10 and 14), suggesting heifers that were born larger and gained BW faster consumed more starter DM. However, from Tables 11, 12, and 15, it is evident that increasing GAIN014 in the 14 to 28 d and 28 to 35 d models depressed starter DMI. The negative coefficients for the quadratic GAIN014 term for these models is evidenced by lower starter DMI when gain was increased or decreased from the mean (Table 12).

The BW equation for 5 to 17 mo old heifers (Equation 7) explained 91% of the variation in BW. As expected, previous BW, metabolic BW, and DMI all had positive slopes for the derivative equations, suggesting heifers that were heavier and consumed more feed the previous week were heavier for the predicted week. Age also had a positive slope, again demonstrating that heifers were gaining BW with time, or growing. Previous ADF intake appropriately had a negative slope, likely due to the negative relationship between ADF and energy content of feeds (Waldo and Jorgenson, 1981).

Figure 24 graphically displays Equation 7 for diets varying in energy content. As energy content increased and ADF decreased, growth rates increased. For this graph, DMI was predicted using the equation of Quigley et al. (1986), and assumed BW at 22 wk was 147 kg. Average daily gain for heifers receiving high, medium, and low energy diets represented in Figure 24 are 0.83, 0.79, and 0.73 kg.

Equation predicting BW (Equation 10) for 17 to 28 month old Holstein heifers explained 99% of the variation in BW. The variables PBW, PBW75, and PDMI had positive slopes as expected for their respective derivative equations (Table 22), suggesting BW was higher for heifers that were heavier and consumed more DM the week before. The negative slope for AGEW was unexpected, suggesting BW decreased as age increased. However, another interpretation is that a younger heifer at a given BW gained more than an older heifer at the same BW, reflective of the higher growth rate of the younger animal. Also, AGEW*DMI was in the model, suggesting that a young heifer with the same BW and DMI of an older heifer will gain more. From Figure 25, it appears growth predicted by Equation 10 is approximately linear.

Average daily gain from 17 to 24 mo for this graph was 0.85 kg/d. The equation should be interpreted with caution below 18 or above 28 mo, as few observations were available.

Equation predicting DMI (Equation 12) for 17 to 28 month old Holstein heifers explained 61% of the variation in DMI. Slopes from derivative equations for PDMI, ADG, and BW75 were positive (Table 26), suggesting DMI was higher for heifers that were heavier, consumed more DM, and gained more BW the previous week. The negative slope for BW is misleading, as it suggests DMI was higher for smaller heifers. However, BW is also accounted for with the variable BW75, so their net effect is positive. The slope for AGEW was also negative, similar to the BW equation. In this equation AGEW is not a main effect; it only occurs in the model interacted with PDMI. An interpretation for the negative slope may be that young heifers with high previous DMI had reduced DMI predicted for the current week, or older heifers with low previous DMI had higher DMI predicted for the current week. From the graph of this equation (Figure 25), it appears maximum DMI from 17 to 32 mo of age occurs between about 19 and 23 mo. After 23 mo of age, DMI declined until calving. However, this situation is magnified in the graph by the small scale for DMI. The equation should be interpreted with caution below 18 or above 28 mo, as few observations were available. In addition, adaptation to Calan door feeders may have resulted in lower than expected DMI for heifers below 18 mo of age.

The equation to predict first lactation milk yield (Equation 15) explained 17% of the variation in milk yield. Although the R-squared (0.17) indicates considerable variation was not explained by the equation, C(p) statistic being less than *p* suggests the model predicts accurately. All slopes from derivative equations were positive for BW, AFC, BWDEV, and MATMILK (Table 30). The positive AFC and BW slopes support previous conclusions (Fisher et al., 1983; Keown and Everett, 1986) that older, heavier calving heifers have greater first lactation milk yields. The positive slope for BWDEV was surprising, suggesting that smaller heifers with comparably more growth yet to occur have higher milk yields. However, changing this difference one, two, or three SD units below or above the mean resulted in lower milk yields (Table 31), reflective of the quadratic term for this variable in the model. For AFC, BW, and MATMILK, changing the variable one, two, or three SD units above and below their mean increased and decreased milk yield, respectively, again suggesting these variables positively impact milk yield (Table 31). The season coefficients suggest that milk yield is highest for heifers calving in the fall, and lowest for heifers calving in the summer. This may be due to seasonal variations in temperature, or management changes at different times of the year. For example, herds in this data set were from Virginia, most of which were likely concerned with making base in the fall. These herds may have received a ration higher in energy and protein to promote production during the fall base period.

Figure 26 graphically displays milk yield prediction for Holstein heifers at various calving ages and BW. For a given post-calving BW, younger heifers produced less milk, similar to other reports (Fisher et al., 1983; Keown and Everett, 1986). In addition, highest milk yields at each age at first calving occurred when post-calving BW was approximately 545 to 590 kg. Maximum milk yield for heifers calving at 20, 22, 24, 26, 28, and 30 mo occurred when post-calving BW was 550, 554, 558, 561, 565, and 569 kg, respectively. This agrees closely with the findings of Keown and Everett (1986), who reported that 544 to 567 kg post-calving BW was associated with highest first lactation milk yield. Unlike Keown and Everett, however, this equation predicts decreased milk yield as post-calving BW exceeds 590 kg, with a sharp decrease when post-calving BW exceeded 636 kg. Hoffman et al. (1997) supports this conclusion in a review, proposing that post-calving BW in excess of 635 kg is detrimental to first lactation milk yield of Holstein heifers. Grummer et al. (1995) reported pre-calving BW or body condition score in excess of 660 kg or 3.5, respectively, are unwarranted and result in elevated NEFA, 👓-hydroxybutyrate, and liver triglycerides, thus predisposing the animal to metabolic disorders.

Growth Rates

Least squares means from growth rate analysis representing six growth rate scenerios are in Table 37, and standard errors of least squares means are in Appendix Table J. Each treatment represented 10 herds of 100 heifers, or 1000 heifers per treatment. Death loss and abortions did not differ by treatment, and averaged 8.4% and 1.7%, respectively, for all treatments. Thus, the average number of heifers that calved across treatments was 899, or 89.9%. The desired growth rate differences were achieved ($P < 0.05$), with Control:Control, ACC:ACC, and Slow:Slow heifers averaging 0.78, 0.90, and 0.62 kg ADG from birth to calving. These differences are considered to be representative of real life differences in management among replacement enterprises. Average daily gains from birth to conception (ADG I), conception to calving (ADG II), and birth to calving (ADG overall) differed ($P < 0.05$) by treatment for all pairwise comparisons except ACC:ACC and Slow:ACC for ADG II and Control:Control and Control:ACC for ADG overall. The latter differed due to varied age at conception or length of period I. Accordingly, post-calving BW and BW at conception differed by treatment in a similar manner. Post-calving BW were within recommended ranges for all treatments except Slow:Slow and ACC:Control (Keown and Everett, 1986), and similar to field observations from farms representing above average management (Karszes, 1994). However, post-calving BW of ACC:ACC heifers approached the point of diminishing returns (Grummer et al., 1995; Hoffman, 1997).

Dry matter intakes from birth to calving differed ($P < 0.05$) by treatment except for Control:ACC and ACC:Control, with Slow:Slow heifers consuming the least DM per day and ACC:ACC the most. Daily DMI as a percent of BW was similar among treatments: 2.2, 2.2, 2.2, 2.3, 2.3, and 2.2% for Control:Control, ACC:ACC, Slow:Slow, Control:ACC, ACC:Control, and Slow:ACC heifers. Thus, differences in daily DMI appeared to be related primarily to BW. Total DMI from birth to calving was 5624, 5527, 5448, 4986, 4929, and 4909 kg, respectively. Total DMI from birth to calving was 8.9, 8.2, 9.9, 8.4, 8.7, and 8.1 times BW at calving (post-calving BW + 50), respectively. Total DMI calculations reflect the additional feed required for delayed calving of Control:Control and Slow:Slow heifers. Although total DMI was relatively high for ACC:ACC heifers, total DMI was a comparatively lower multiple of BW, reflecting higher growth rates.

Age at conception and calving for Control:Control and Slow:Slow differed from other treatments, primarily due to a higher minimum breeding age (Table 36). With the exception of Slow:Slow and Control:Control heifers, average age at first calving for each treatment was within the recommended 22 to 24 month range (Cady and Smith, 1996; Heinrichs, 1993; Keown and Everett, 1986; Gill and Allaire, 1976). Age at first calving field observations of above average western New York dairy farms (23.3 mo) were similar (Karszes, 1994). First lactation milk yields differed as expected considering the varied calving age and post-calving BW. Highest milk yields were for Control:Control, Slow:Slow, and Slow:ACC treatments. The treatments with accelerated growth before breeding had slightly lower milk yields, although equation to predict first lactation milk yield did not account for the reported milk yield reduction from accelerated pre-pubertal growth (Foldager and Sejrsen, 1982; Sejrsen et al, 1982; Sejrsen and Purup, 1997; Swanson, 1960). In addition, equations to predict milk yield did not consider the reported metabolic disorders related to over-conditioned heifers at calving (Grummer et al., 1995).

Total cash rearing costs from birth to calving were highest for Control:Control and Slow:Slow treatments, and lowest for ACC:Control and Slow:ACC treatments. Cash rearing costs per day (total cash rearing costs/calving age in days) for Control:Control, ACC:ACC, Slow:Slow, Control:ACC, ACC:Control, and Slow:ACC were 1.33, 1.41, 1.21, 1.32, 1.32, and 1.30 $/d. The Slow:Slow heifers had high total cash rearing costs but low costs per day due to delayed age at first calving (27.4 mo). Similarly, Miller and Amos (1986) proposed a low cost pasture system for rearing dairy replacements where average age at first calving was 31 mo. The virtue of such a system was reduced feed, labor, and housing costs. Their estimated total rearing costs from birth to calving ($700) included value of calf at birth ($150), feed costs ($270), health costs ($45), labor ($90), interest ($105), and building and equipment fixed costs ($40) as a part of total rearing expenses. Unlike heifers in the Miller and Amos study, slow growing heifers in this study (Slow:Slow) had higher total costs than rapid growing heifers due to delayed calving. Feed costs were the major cost difference between Miller and Amos heifers and the Slow:Slow heifers in this study ($401 difference). If this study had assumed minimal feed expenses, as did Miller and Amos, the conclusion would change. On a cash basis only, it appears Control:ACC, ACC:Control, and Slow:ACC treatments were the least costly. The Control:Control and Slow:Slow treatments were more costly due to delayed age at first calving, resulting in higher total feed costs from birth to calving. The ACC:ACC group was costly due to high growth rates that resulted in high daily DMI and feed costs. Feed costs, which differed by treatment in a similar manner as cash rearing costs, accounted for the majority of differences in cash rearing cost. It is important to note, however, that this analysis assumed feed costs per kilogram of feed were similar regardless of growth rate, i.e. faster growing heifers had higher feed costs solely because they consumed more DM per day. This approach may be accurate in situations where dairy producers do not feed heifers to appetite. Greater BW gains may be achieved in such situations simply by offering more feed, thus increasing DM and nutrient intake.

Interest costs were higher as expected for Control:Control and Slow:Slow treatments, due to older age at first calving (25.1 and 27.4 mo, respectively). In addition, interest costs were high for ACC:ACC heifers due to high feed costs. Interest costs determined in this study were higher (Basset, 1992; Karszes, 1994), similar (Willet, 1992), and lower (Willet et al., 1984) than other estimates. Higher estimates may have been due to higher interest (13%) rates (Willet et al., 1984), and lower estimates may have been a result of not including interest costs for all expenses.

Total rearing costs, a more accurate measure of heifer rearing costs than total cash costs, differed by treatment ($P < 0.05$). Total rearing costs included non-cash costs such as interest and death and abortion costs. Differences with respect to treatments were similar to total cash rearing cost differences. The Slow:Slow and Control:Control heifers were most costly to rear, reflective of their delayed age at first calving. The ACC:ACC heifers were costly due to higher DMI and feed costs resulting from higher growth rates. The Slow:ACC heifers were least costly, in part due to reduced age at first calving and feed costs. Although all treatments differed, as a group the last three treatments appeared to be least costly. Considering the risks of accelerated pre-pubertal growth (Foldager and Sejrsen, 1982; Sejrsen et al, 1982; Sejrsen and Purup, 1997; Swanson, 1960), the Slow:ACC and Control:ACC treatments were optimal in terms of least cost to calving at minimal risk. The most important aspect related to lowest rearing costs appeared to be reduced age at first calving, with the exception of ACC:ACC treatment. This treatment was not desirable for two reasons. First, rearing costs were high as previously mentioned. Second, there are considerable risks associated with excessive calving BW and pre-partum ADG, particularly reduced post-partum milk yield and higher incidence of metabolic disorders (Grummer, 1995).

Average total rearing costs across all six treatments were $1196.49, slightly higher than field observations ($1150, Karszes, 1994). The difference may be attributed to differences in interest costs, because feed and operating costs were similar. The present study considered all interest costs, including those for feed, ownership and operating expenses, and initial value of the heifer at birth. Willet et al. (1984, 1992) estimated rearing costs similar to treatments 1 to 3 in this study. Basset (1992) estimated it costs $836.19 to rear dairy replacements in north Florida, although feed costs were estimated at $460, significantly less than estimates in this study and others (Karczes, 1994; Willet et al., 1984, 1992).

Table 38 contains total rearing costs for the six treatments on a percentage basis. Feed costs from birth to calving accounted for the largest portion, representing 52.6 to 56.3% of total rearing expenses. Feed costs from conception to calving were slightly less than those from birth to conception, although the time period for each was different. When considering this time period difference, it is evident that feed costs per day are higher for bred heifers, reflecting higher DMI. This emphasizes the importance of properly balancing diets for bred heifers to avoid overfeeding or underfeeding. Operating costs were the next largest item, accounting for 19.7 to 21.1% of total rearing costs. Interest costs were also a substantial portion of total rearing costs (7.6 to 9.0%). The Slow:Slow heifers had comparatively higher interest costs due to delayed calving. For this analysis, 8% interest rate was assumed. During periods of higher interest, interest rates become critical in determining total rearing costs of a replacement enterprise.

Possibly the most desirable measure of the true cost of heifer rearing is net profit or loss at calving, primarily because it accounts for reported differences in milk yield for heifers with varying BW and age at calving (Keown and Everett, 1986). However, the first lactation milk yield equations predicted only small differences in milk yield between treatments, resulting in similar rankings for net profit/loss at calving and total rearing costs. The results suggest that accelerated growth schemes to achieve larger heifers at calving (>600 kg) are costly and not necessary, even though equations do not consider the reported post-partum difficulties of over-conditioned heifers at calving (Grummer et al., 1995). Modest growth rates from birth to calving (0.75 to 0.80 kg/d), accompanied by reduced first calving age (<24 mo), is most desirable. However, Sejrsen and Purup (1997) caution that mammary development and future lactation potential may be impaired when Holstein heifers gain more than 0.70 kg/d during the pre-pubertal period. Conversely, delayed calving (>24 mo) is costly and merits faster growth rates with earlier breeding.

Table 39 contains correlations ($P < 0.05$) for individual heifers for selected variables measured in growth rate analysis. Average daily gains were not highly correlated with total rearing costs or total cash rearing costs. However, there were high correlations between cash and total rearing costs and post-calving BW and BW at conception, age at conception, and age at calving. Thus, these correlations reflect the high costs of delayed calving and/or slow growth rates that result in low post-calving BW. The variables most highly related to total rearing costs ($r > 0.86$) were DMI I, age at calving, feed costs I and overall, operating costs I and overall, ownership costs I and overall, total cash rearing costs, and interest costs. Feed, operating, and ownership costs from birth to conception were related more to total costs than those from conception to calving. Considering that feed, operating, and ownership costs are highly correlated with age at first calving ($-1.0 > r > -0.79$), it is apparent that age at first calving has a crucial impact on total rearing costs. Net profit/loss at calving was correlated the highest with first lactation milk yield, emphasizing the importance of first lactation milk yield to the profitability of a heifer replacement enterprise.

Appendix Table K contains MSE, Tukeys Critical Values, and Proc Nested results for all variables. For most variables, treatment and error accounted for the majority of total variance in the model. Herd variance was the major component for death and abortion costs, reflective of identical death and abortion costs within a herd.

Feed Costs

Least squares means and standard errors from analysis of varied feed costs for accelerated growth heifers are in Table 40. Feed costs were the only item adjusted, therefore feed costs, interest costs, total cash rearing costs, total rearing costs, monthly and annual costs, and net profit/loss at calving were the only items that differed. Remaining variables were constant across treatments. As expected, variables that were altered by linearly increasing feed costs (0, 5, 10, or 15%) were also linearly altered ($P < 0.05$). Feed costs from birth to conception, birth to calving, and conception to calving, total cash rearing costs, and total rearing costs were increased 3.31, 6.87, 3.56, 6.88, and 7.33 $/heifer, respectively, for each percentage point increase in feed costs. Net profit loss at calving was reduced $7.33 for each percentage point increase in feed costs.

For the previous growth rate analysis, it was assumed feed costs per unit did not change with growth rate. If feed costs increased and decreased 10% for ACC:ACC and Slow:Slow, total rearing costs would increase or decrease $73.27. The $73.27 was the difference in total rearing costs between 0% and 10% increase in feed costs (Table 40). With this assumption, total rearing costs ($/heifer) changed from 1220.91 to 1294.18 for ACC:ACC heifers and from 1275.76 to 1202.49 for Slow:Slow heifers. This would accordingly change net profit/loss at calving ($/heifer) from 407.15 to 333.88 for ACC:ACC heifers and from 319.84 to 393.11 for Slow:Slow heifers. For Control:Control heifers, total rearing costs and net profit/loss at calving were 1246.93 and 399.78, respectively. Under this scenario of varied feed costs, ACC:ACC heifers were least profitable. This illustrates the importance of considering feed cost changes per unit of DM that may be needed to achieve high growth rates.

Heat Detection Efficiency

Heat detection efficiencies (40, 50, and 60%) were analyzed at three different conception rates (40, 65, and 80%). For each conception rate scenario, second and third services were two percentage points lower than for first service.

Forty Percent Conception

Least squares means from heat detection analysis at 40% conception are in Table 41, and standard errors of least squares means are in Appendix Table L. As expected, age at conception and calving and BW at conception and post-calving BW decreased linearly ($P < 0.05$) with improved heat detection efficiency. In addition, all costs measured except monthly and annual costs, feed costs from birth to calving, breeding costs, and death and abortion costs decreased linearly ($P < 0.05$) with improved heat detection; monthly and annual costs tended ($P < 0.06$) to decrease. Quadratic trends were also significant for most of these variables, reflective of the comparatively smaller change from 50 to 60% heat detection. Net profit/loss at calving and total rearing costs improved linearly but not quadratically with increased heat detection efficiency, although the change was numerically largest when heat detection efficiency changed from 40 to 50%. Marginal cost savings of improving heat detection efficiency from 40 to 50% for feed costs from birth to conception and birth to calving, total cash rearing costs, and total rearing costs were 30.25, 31.09, 37.40, and 48.59 $/heifer; marginal cost savings for improving heat detection efficiency from 50 to 60% were 14.22, 15.42, 19.91, and 36.54 $/heifer, respectively. Marginal net/profit loss at calving reductions from improving heat detection efficiency from 40 to 50% and 50 to 60% were 65.88 and 29.79 $/heifer, respectively.

Sixty-Five Percent Conception

Least squares means for the 65% conception scenario are in Table 42, and standard errors of least squares means are in Appendix Table M. Similar to the 40% conception rate scenario, improving heat detection linearly decreased age at conception and calving and post calving BW and BW at conception and increased profit/loss at calving ($P < 0.05$). Costs were altered similarly as the 40% conception rate scenario. Net profit/loss at calving was similar for 50 and 60% heat detection, due to the lower predicted milk yields for the 60% heat detection group. Differences in milk yield were due to lower post-calving BW and age at first calving. Marginal cost savings for improving heat detection efficiency from 40 to 50% for feed costs from birth to conception and birth to calving, total cash rearing costs, and total rearing costs were 19.11, 20.44, 25.21, and 41.09 $/heifer; marginal cost savings for improving heat detection efficiency from 50 to 60% were 13.05, 14.42, 17.36, and 7.66 $/heifer, respectively. Marginal net/profit loss at calving costs of improving heat detection efficiency from 40 to 50% and 50 to 60% were 43.91 and 0.75 $/heifer, respectively.

Eighty Percent Conception

Least squares means from the 80% conception scenario are in Table 43, and standard errors of least squares means are in Appendix Table N. Similar to the other conception rate scenarios, improving heat detection linearly decreased age at conception and calving and post calving BW and BW at conception ($P < 0.05$). Costs were also altered similarly as the other conception rate scenarios. Linear or quadratic trends were not significant for net profit/loss at calving, although there were numerical increases with improved heat detection. Marginal cost savings for improving heat detection efficiency from 40 to 50% for feed costs from birth to conception and birth to calving, total cash rearing costs, and total rearing costs were 12.84, 15.02, 18.02, and 29.47 $/heifer; marginal cost savings for improving heat detection efficiency from 50 to 60% were 9.59, 12.03, 14.29, and 4.46 $/heifer, respectively. Marginal net/profit loss at calving costs of improving heat detection efficiency from 40 to 50% and 50 to 60% were 6.12 and 9.33 $/heifer, respectively.

Across all conception rate scenarios, improving heat detection efficiency from 40 to 50% reduced total rearing costs by $39.72; the reduction was $16.22 when improving heat detection efficiency from 50 to 60%. These results demonstrate that heat detection efficiency is proportionately more costly at lower heat detection rates, emphasizing the costs of poor heat detection. The sum of these figures ($55.94), or the reduction in rearing costs from improving heat detection from 40 to 60%, also displays the significance of heat detection to the cost of heifer rearing. Results also suggest that poor heat detection is more costly at low conception rates, which logically corresponds to higher costs of poor heat detection at low heat detection rates, since pregnancy rate is the product of heat detection efficiency and conception rate. Across all heat detection and conception rate scenarios evaluated in the heat detection analysis, total rearing costs for each heifer entering the milking herd decreased $2.80 for each percent increase in heat detection efficiency. Economics of heat detection aids that improve heat detection can be evaluated using this figure.

The heat detection analysis performed for this study could also be interpreted as an age at first calving analysis. In reality, lowering heat detection efficiency without changing other variables delays breeding, thereby proportionally increasing age at first calving. Therefore, total rearing cost reductions in this study attributed to heat detection improvements can similarly be attributed to reduced age at first calving. With this in mind, simple regressions were used to determine relationships between age at first calving and total rearing costs and net profit/loss at calving (Figure 27). Data from the three heat detection scenarios were used to determine relationships, with two scenarios averaged (50% heat detection at 80% conception and 60% heat detection at 65% conception) due to similar age at first calving (24.7 mo). Therefore, total degrees of freedom for each regression were 7, with age at first calving range of 24.4 to 26.6 mo. The relationship between age at first calving and total rearing costs was -584.38 + 73.49 x calving age in mo (R-squared = 0.97); the relationship with net profit/loss at calving was 2225.01 - 73.29 x calving age in mo (R-squared = 0.95). Thus, rearing costs were increased $73.49 and net/profit loss reduced $73.29 for each additional month of age at first calving. These equations display the significant impact age at first calving has on costs of heifer rearing. However, extreme caution should be used when applying these equations outside the range of the data, specifically for age at first calving less than 24 mo or greater than 27 mo. These differences can also be interpreted as due to lower BW at calving, as post-calving BW declined with age at first calving (Table 44). This supports earlier conclusions from growth rate analysis that excessive BW at calving is not necessary. The impacts of reduced BW on total rearing costs would be from reduced feed and interest costs, while the impacts of reduced age at first calving on total rearing costs would be from reduced feed costs, interest costs, operating costs, and ownership costs. Although it is not possible to clearly separate BW or age at first calving impacts on total rearing costs, it appears age at first calving differences accounted for the majority of change in total rearing costs.

Death Loss

Birth

Least squares means for death loss at birth analysis are in Table 45, and standard errors of least squares means are in Appendix Table O. Total death loss from birth to calving was higher (8.6, 12.7, and 19.2% for 5, 10, and 15% death loss at birth treatments) than death loss at birth due to additional death loss throughout the life of a heifer (Table 33). Death and abortion costs, total rearing costs, monthly costs, annual costs, and net profit/loss at calving increased linearly ($P < 0.05$) with higher death loss rates at birth. Total cash operating costs were not different, as death loss does not impact cash expenditures per heifer. Marginal costs for each percentage point of increased death loss between 5 and 10% were $4.31/heifer for death and abortion costs and $5.17/heifer for total rearing costs. For each percentage point increase in death loss between 10 and 15%, death and abortion costs increased $1.73/heifer and total rearing costs increased $0.61/heifer. Marginal net/profit loss at calving reductions for increasing death loss at birth from 5 to 10% and 10 to 15% were 4.25 and 6.34 $/heifer, respectively.

Birth to Weaning

Least squares means for death loss from birth to weaning analysis are in Table 46, and standard errors of least squares means are in Appendix Table P. Total death loss from birth to calving was higher than death loss rates from birth to weaning due to death loss occurring at birth and later in life (Table 33). Total death loss rates from birth to calving were similar to death loss at birth analysis. Similar to death loss at birth analysis, death and abortion costs, total rearing costs, and monthly and annual costs linearly increased ($P < 0.05$) with increased death loss from birth to weaning. Net profit/loss at calving tended ($P < 0.10$) to decline as death loss from birth to weaning increased. Total cash operating costs were not different, as death loss does not impact cash expenditures per heifer. Likewise, interest costs did not differ. Marginal costs for each percent increase in death loss for increasing death loss from birth to weaning from 1 to 10% for death and abortion costs and total rearing costs were 2.65 and 1.86 $/heifer; marginal total rearing costs for each percent increased death loss from 10 to 15% were 2.19 and 2.98 $/heifer, respectively. Marginal net/profit loss at calving reductions for increasing death loss at birth from 1 to 10% and 10 to 15% were 1.86 and 3.61 $/heifer, respectively.

It is apparent that death loss has a comparatively small but meaningful impact on total rearing costs of the replacement enterprise. Costs are not excessive for death loss prior to weaning, primarily because little has been invested in a heifer at such a young age. Death loss costs would presumably be higher for older or more valuable heifers. Across all treatments for both death loss scenarios, marginal total rearing costs for each percent increase in death loss was $2.40. Therefore, high death loss rates (>20%) for young heifers can add approximately $48 to total rearing costs for each live heifer entering the milking herd. Investments such as housing, labor, or medications to reduce death loss at birth and from birth to weaning can be considered economical if they are less costly than death loss costs.

Abortions

Least squares means from abortion rate analysis are in Table 47, and standard errors of least squares means are in Appendix Table Q. Total abortion rate for all treatments was near desired levels (1.3, 4.5, and 9.7% for 1, 5, and 10% abortion rate). As abortion rate heightened, death and abortion costs, total rearing costs, and monthly and annual costs increased and net profit/loss at calving declined. Total cash and interest costs were not influenced by abortion rate. Marginal costs for each percent increase in abortion rate from 1 to 5% for death and abortion costs and total rearing costs were 7.38 and 8.84 $/heifer; the marginal costs for each percent increase in abortion rate from 5 to 10% were 11.41 and 9.35 $/heifer, respectively. Marginal net/profit loss at calving reductions for increasing abortion rate from 1 to 5% and 5 to 10% were 5.94 and 8.78 $/heifer, respectively.

Abortion costs are comparatively higher than death loss costs for young heifers because more has been invested in feed, labor, etc. for older heifers. Heifers that abort are sold, so abortion costs would be less than death loss rates for equivalent age heifers. However, cull price ($0.84 per kg in this study) is significantly less than rearing costs, thus abortion is costly. Across all abortion rates evaluated in this study, each percent increase in abortion adds $9.10 to the cost of getting a live heifer into the herd.

Table 1. Nonlinear growth curves[1] as described by Perotto et al. (1992) and Richards (1959).

Function	Equation	Defining Relation	Weight at inflection	Absolute growth rate
Monomolecular	$W=A(1-be^{-kt})$	$k(A-W)$	0	$Akbe^{-kt}$
Logistic	$W=A/(1+ be^{-kt})$	$kW(A-W)/W$	0.5A	$(Akbe^{-kt})(1+be^{-kt})^{-2}$
Richards	$W=A(1- be^{-kt})^{M}$	$kW[A/W)^{1-m}-1]/(1-m)$	$A[(M-1)/M]^{M}$	$Makbe\text{-}^{kt}(1-be^{-kt})^{M}(1-be^{-kt})^{-1}$
Gompertz	$W=Ae^{-x}$	$kW(\ln(A/W)$	Ae^{-1}	$(Akbe^{-kt})e^{x}$

[1] $x = -be^{-kt}$; W = size at time t; A = maximal W or asymptotic weight; e = 2.7183, the base of the natural logarithm; k = rate parameter or maturing index; M = inflection paramater; m = (M-1)/M; b is constant of integration, determined by solving for b when W is initial weight.

Table 2. Regression parameter estimates for weight (kg) and height (cm) of Holstein heifers (Heinrichs and Hargrove, 1987).

	Regression Coefficients				
Dependent Variable	Intercept	Linear (month)	Quadratic (month^2)	Cubic (month^3)	R^2
Weight					
Mean	40.274 [b]	19.870 [b]	0.285 [a]	-0.0119 [b]	>0.99
Mean +1 SD	46.461 [b]	23.779 [b]	0.237 [c]	-0.0120 [a]	>0.99
Mean -1 SD	34.088 [b]	15.962 [b]	0.333 [a]	-0.0119 [a]	>0.99
Height					
Mean	75.413 [b]	5.153 [b]	-0.158 [b]	0.00177 [b]	>0.99
Mean +1 SD	78.767 [b]	5.733 [b]	-0.203 [b]	0.00279 [b]	>0.99
Mean -1 SD	72.060 [b]	4.573 [b]	-0.112 [b]	0.00074	>0.99

[a] $P < 0.05$
[b] $P < 0.01$
[c] $P < 0.10$

Table 3. Statistics from data set used to develop BW equation for pre-weaned Holstein calves.

Variable	n	Mean	SD	Minimum	Maximum
Calf	97				
Birth BW, kg	59	40.3	5.8	24.1	49.5
3 d BW, kg	38	39.7	4.1	33.6	50.8
14 d BW, kg	24	41.3	5.8	28.6	52.2
28 d BW, kg	38	47.1	6.1	35.4	62.2
35 d BW, kg	61	49.8	6.3	36.8	68.1
42 d BW, kg	61	54.6	7.2	38.6	71.7
49 d BW, kg	35	58.7	7.2	44.9	73.1
Age, days		24.4	17.7	0	49

Table 4. General Linear Model (SAS, 1985) analysis of models to predict BW of pre-weaned Holstein heifers.

	Model	
	CALF + AGE^2	DATASET + AGE^2
	-------------- Parameter Estimates --------------	
Intercept	53.86553	39.69627
AGE^2	0.00808071	0.00810330
CALF	-13.983309	
DATASET		0.0907848
	----------------- Model Criteria -----------------	
R-squared	0.932	0.545
Adjusted R-squared	0.901	0.540
Mean Square Error	8.22	38.31

Table 5. Statistics from data set used to develop DMI equations for pre-weaned Holstein calves.

Variable	n	Mean	SD	Minimum	Maximum
Calf	24				
DMI[1], 3-14 d, kg/d	24	0.084	0.087	0	0.356
DMI, 14-28 d, kg/d	24	0.402	0.248	0.006	1.054
DMI, 28-35 d, kg/d	24	1.038	0.473	0.104	2.056
DMI, 35-42 d, kg/d	24	1.529	0.414	0.259	2.108
Birth BW, kg	24	40.5	5.4	30	49
14 d BW, kg	24	41.3	5.8	29	52
28 d BW, kg	24	47.7	6.7	35	62
35 d BW, kg	24	51.7	7.8	37	68
42 d BW, kg	24	56.5	8.2	41	72
BW gain, 0-14 d, kg	24	0.71	2.88	-7.00	5.00
BW gain, 14-28 d, kg	24	6.43	2.64	1.00	11.00
BW gain, 28-35 d, kg	24	4.00	2.00	0	9.00
BW gain, 35-42 d, kg	24	4.79	1.84	1.00	8.00

[1] DMI are average daily DMI during that age period

Table 6. Models[1] to predict daily starter DMI for pre-weaned calves from 3 to 14 days of age selected using the backward and forward Stepwise regression procedures of SAS (1996).

	Backward		Forward	
Variable[2]	parameter estimate	*P*	parameter estimate	*P*
Intercept	0.05494947	0.0160	-0.01842361	0.770
BWBIRTH				
GAIN014	-0.15107596	0.0209	-0.12531031	0.061
BWBIRTH^2			0.00004734	0.227
GAIN014^2	0.00392042	0.0653	0.00294086	0.184
BWBIRTH*GAIN014	0.00383509	0.0137	0.00324912	0.040
MSE	0.00551936		0.00536856	
PRESS[3]	0.2249		0.1992	
p	4		5	
C(p)	3.58		4.10	
R-squared	0.365		0.413	
Adjusted R-squared	0.269		0.289	

[1] Full model contains all variables in table.
[2] BWBIRTH = birth BW, kg; GAIN014 = BW gain 0 to 14 days, kg.
[3] Prediction Residual Sum of Squares.

Table 7. Models[1] to predict daily starter DMI for pre-weaned Holstein heifers from 14 to 28 days of age selected using the backward and forward Stepwise regression procedures of SAS (1996).

	Backward		Forward	
Variable[2]	parameter estimate	*P*	parameter estimate	*P*
Intercept	2.09668455	0.1099	2.07052033	0.1253
BWBIRTH	-0.11280908	0.0892	-0.11072214	0.1061
GAIN014	-0.04967251	0.0491	-0.05047972	0.0537
GAIN1428				
BWBIRTH^2	0.00163432	0.0521	0.00157723	0.0741
GAIN014^2	-0.00633109	0.0048	-0.00639544	0.0059
GAIN1428^2	0.00408185	0.0001	0.00313176	0.3365
BWBIRTH*GAIN014				
BWBIRTH*GAIN1428			0.00031756	0.7619
GAIN014*GAIN1428	0.00991946	0.0085	0.00997457	0.0103
MSE	0.01061111		0.01120774	
PRESS[3]	0.4084		0.4294	
p	7		8	
C(p)	4.54		6.45	
Adjusted R-squared	0.828		0.818	
R-squared	0.873		0.873	

[1] Full model contains all variables in table.

[2] BWBIRTH = birth BW, kg; GAIN014 = BW gain 0 to 14 days, kg; GAIN1428 = BW gain 14 to 28 days, kg.

[3] Prediction Residual Sum of Squares.

Table 8. Models[1] to predict daily starter DMI for pre-weaned Holstein heifers from 28 to 35 days of age selected by the backward and forward Stepwise regression procedures and the best 6 variable model selected by the MAXR Stepwise regression procedure of SAS (1996).

	Backward		Forward		Best 6 Variable Model	
Variable[2]	parameter estimate	*P*	parameter estimate	*P*	parameter estimate	*P*
Intercept	4.06321059	0.1169	5.01847657	0.0604	4.51268265	0.0909
BWBIRTH	-0.29783910	0.0256	-0.25672673	0.0530	-0.22759548	0.0882
GAIN014						
GAIN1428			0.09571919	0.2962	0.08892551	0.0001
GAIN2835	0.79303530	0.0206				
BWBIRTH^2	0.00558919	0.0045	0.00353098	0.0358	0.00317912	0.0593
GAIN014^2	-0.01194778	0.0949	-0.01564420	0.0076	-0.01853156	0.0001
GAIN1428^2	0.02189361	0.0247	0.00670142	0.3013		
GAIN2835^2	0.02093624	0.0878	0.02594486	0.1352		
BWBIRTH* GAIN014			-0.00378790	0.0225	-0.00319008	0.0145
BWBIRTH* GAIN1428	-0.00530104	0.0969				
BWBIRTH* GAIN2835	-0.02079936	0.0304				
GAIN014* GAIN1428	0.02237707	0.0056	0.03972080	0.0082	0.02717998	0.0014
GAIN014* GAIN2835	-0.02683902	0.0525	-0.01669506	0.1562		
GAIN1428* GAIN2835			-0.02781209	0.2491		
MSE	0.03798628		0.03839865		0.04290581	
PRESS[3]	3.0542		2.1714		1.1528	
p	11		11		7	
C(p)	8.70		8.82		5.81	
R-squared	0.904		0.902		0.858	
Adjusted R-squared	0.830		0.828		0.808	

[1] Full model contains all variables in table.

[2] BWBIRTH = birth BW, kg; GAIN014 = BW gain 0 to 14 days, kg; GAIN1428 = BW gain 14 to 28 days, kg; GAIN2835 = BW gain 28 to 35 days, kg.

[3] Prediction Residual Sum of Squares.

Table 9. Models[1] to predict daily starter DMI for weaned Holstein heifers from 35 to 42 days of age using the backward and forward Stepwise regression procedures of SAS (1985).

Variable[2]	Backward parameter estimate	Backward *P*	Forward parameter estimate	Forward *P*
Intercept	0.27193912	0.0843	0.00046953	0.9978
BWBIRTH				
GAIN014	-0.11365592	0.0875		
GAIN1428	-1.06693112	0.0001		
GAIN2835	1.99842947	0.0001	0.41355239	0.0001
GAIN3542				
BWBIRTH^2				
GAIN014^2	-0.01073528	0.0021	-0.00687203	0.0495
GAIN1428^2	0.00827101	0.0530		
GAIN2835^2	0.02519841	0.0060		
GAIN3542^2	-0.02686572	0.0012		
BWBIRTH*GAIN014	0.00940889	0.0004		
BWBIRTH*GAIN1428	0.01272710	0.0001	-0.00183420	0.0892
BWBIRTH*GAIN2835	-0.03143912	0.0001		
BWBIRTH*GAIN3542	0.00738574	0.0004	0.00448572	0.0006
GAIN014*GAIN1428	0.01265885	0.0121	0.02397963	0.0042
GAIN014*GAIN2835				
GAIN014*GAIN3542	-0.04418419	0.0003	-0.02120947	0.0193
GAIN1428*GAIN2835	-0.02460145	0.0224	0.01222773	0.1706
GAIN1428*GAIN3542	0.11857928	0.0001	0.03290926	0.0003
GAIN2835*GAIN3542	-0.14991667	0.0001	-0.06420630	0.0006
MSE	0.00250858		0.02466560	
PRESS[3]	0.6133		1.6836	
p	17		10	
C(p)	15.20		98.32	
R-squared	0.996		0.912	
Adjusted R-squared	0.985		0.856	

[1] Full model contains all variables in table.

[2] BWBIRTH = birth BW, kg; GAIN014 = BW gain 0 to 14 days, kg; GAIN1428 = BW gain 14 to 28 days, kg; GAIN2835 = BW gain 28 to 35 days, kg; GAIN3542 = BW gain 35 to 42 days, kg.

[3] Prediction Residual Sum of Squares.

Table 10. Derivatives of equations[1] to predict daily starter DMI for Holstein pre-weaned and weaned heifers. age.

Derivative	Derivative Equation	Slope[2]
3 to 14 d Model		
BWBIRTH	0.0038*BWBIRTH + 0.0023*GAIN014	0.00614
GAIN014	-0.1253 + 0.0042*GAIN014 + 0.1316*BWBIRTH	0.01046
14 to 28 d Model		
BWBIRTH	-0.1128 + 0.1324*BWBIRTH	0.01957
GAIN014	-0.0497 - 0.0090*GAIN014 + 0.0638*GAIN1428	0.00512
GAIN1428	0.0525*GAIN1428 + 0.0070*GAIN014	0.05954
28 to 35 d Model		
BWBIRTH	-0.2276 + 0.2575*BWBIRTH - .0023**GAIN014	0.027648
GAIN014	-0.0263*GAIN014 - 0.1292*BWBIRTH + 0.1748*GAIN1428	0.019254
GAIN1428	0.0889 + 0.0192*GAIN014	0.108223
35 to 42 d Model		
BWBIRTH	0.0067*GAIN014 + 0.0818*GAIN1428 - 0.1258*GAIN2835 + 0.0353*GAIN3542	-0.001863
GAIN014	-0.1137 - 0.0152*GAIN014 + 0.3811*BWBIRTH + 0.0814*GAIN1428 - 0.2116*GAIN3542	0.121914
GAIN1428	-1.0669 + 0.1064*GAIN1428 + 0.5154*BWBIRTH + 0.0090*GAIN014 - 0.0984*GAIN2835 + 0.5680*GAIN3542	0.033458
GAIN2835	1.9984 + 0.2016*GAIN2835 - 1.2733*BWBIRTH - 0.1582*GAIN1428 - 0.7181*GAIN3542	0.050444
GAIN3542	-0.2574*GAIN3542 + .2991*BWBIRTH - 0.0314*GAIN014 + 0.7625*GAIN1428 - 0.5997*GAIN2835	0.173176

[1] 3 to 14 d Model: BWBIRTH + GAIN014 + BWBIRTH^2 + GAIN014^2 + BWBIRTH*GAIN014; 14 to 28 d model: BWBIRTH + GAIN014 + GAIN1428 + BWBIRTH^2 + GAIN014^2 + GAIN1428^2 + BWBIRTH*GAIN014 + BWBIRTH*GAIN1428 + GAIN014*GAIN1428; 28 to 35 d Model: BWBIRTH + GAIN014 + GAIN1428 + GAIN2835 + BWBIRTH^2 + GAIN014^2 + GAIN1428^2 + GAIN2835^2 + BWBIRTH*GAIN014 + BWBIRTH*GAIN1428 + BWBIRTH*GAIN2835 + GAIN014*GAIN1428 + GAIN014*GAIN2835 + GAIN1428*GAIN2835; 35 to 42 d Model: BWBIRTH + GAIN014 + GAIN1428 + GAIN2835 + GAIN3542 + BWBIRTH^2 + GAIN014^2 + GAIN1428^2 + GAIN2835^2 + GAIN3542^2 + BWBIRTH*GAIN014 + BWBIRTH*GAIN1428 + BWBIRTH*GAIN2835 + BWBIRTH*GAIN3542 + GAIN014*GAIN1428 + GAIN014*GAIN2835 + GAIN014*GAIN3542 + GAIN1428*GAIN2835 + GAIN1428*GAIN3542 + GAIN2835*GAIN3542; where BWBIRTH = birth BW, kg; GAIN014 = BW gain 0 to 14 days, kg; GAIN1428 = BW gain 14 to 28 days, kg; GAIN2835 = BW gain 28 to 35 days, kg; GAIN3542 = BW gain 35 to 42 days, kg.

[2] Determined by solving equations with variables at their mean.

Table 11. Influence of varying BWBIRTH, GAIN014, GAIN1428, GAIN2835, and GAIN3542 one, two, or three SD units from their mean on prediction of daily starter DMI for 3 to 14 d and 14 to 28 d old pre-weaned Holstein heifers[1].

	BWBIRTH	GAIN014	GAIN1428
Mean	40.5	0.71	6.43
SD	5.4	2.88	2.64
3 to 14 d Model			
Prediction at mean[2]	0.065	0.065	
	difference from prediction at mean in SD units		
mean - 3 SD	1.00	1.49	
mean - 2 SD	0.70	0.43	
mean - 1 SD	0.37	0.07	
mean	0	0	
mean + 1 SD	0.40	0.63	
mean + 2 SD	0.83	1.82	
mean + 3 SD	1.29	3.57	
	difference from prediction at mean in kg DMI		
mean - 3 SD	-0.09	0.13	
mean - 2 SD	-0.06	0.04	
mean - 1 SD	-0.03	-0.01	
mean	0	0	
mean + 1 SD	0.03	0.05	
mean + 2 SD	0.07	0.16	
mean + 3 SD	0.11	0.31	
14 to 28 d Model			
Prediction at mean[3]	0.384	0.384	0.384
	difference from prediction at mean in SD units		
mean - 3 SD	0.45	2.08	0.87
mean - 2 SD	0.08	0.96	0.81
mean - 1 SD	0.23	0.27	0.52
mean	0	0	0
mean + 1 SD	0.62	0.15	0.75
mean + 2 SD	1.62	0.73	1.72
mean + 3 SD	3.01	1.73	2.93
	difference from prediction at mean in kg DMI		
mean - 3 SD	0.11	-0.52	-0.22
mean - 2 SD	-0.02	-0.24	-0.20
mean - 1 SD	-0.06	-0.07	-0.13
mean	0	0	0
mean + 1 SD	0.15	-0.04	0.19
mean + 2 SD	0.40	-0.18	0.43
mean + 3 SD	0.75	-0.43	0.73

[1] 3 to 14 d model: BWBIRTH + GAIN014 + BWBIRTH^2 + GAIN014^2 + BWBIRTH*GAIN014; 14 to 28 d model: BWBIRTH + GAIN014 + GAIN1428 + BWBIRTH^2 + GAIN014^2 + GAIN1428^2 + BWBIRTH*GAIN014 + BWBIRTH*GAIN1428 + GAIN014*GAIN1428; where BWBIRTH = birth BW, kg; GAIN014 = BW gain 0 to 14 days, kg; GAIN1428 = BW gain 14 to 28 days, kg; GAIN2835 = BW gain 28 to 35 days, kg; GAIN3542 = BW gain 35 to 42 days, kg.

[2] Daily starter DMI for 3 to 14 d old heifers, kg. (SD = 0.087).

[3] Daily starter DMI for 14 to 28 d old heifers, kg. (SD = 0.248).

Table 12. Influence of varying BWBIRTH, GAIN014, GAIN1428, GAIN2835, and GAIN3542 one, two, or three SD units from their mean on prediction of daily starter DMI for 28 to 35 d old pre-weaned and 35 to 42 d old weaned Holstein heifers[1].

	BWBIRTH	GAIN014	GAIN1428	GAIN2835	GAIN3542
Mean	40.5	0.71	6.43	4.0	4.79
SD	5.4	2.88	2.64	2.0	1.84
35 to 42 d Model					
Prediction at mean[2]	1.43	1.43	1.43	1.43	1.43
	difference from prediction at mean in SD units				
mean - 3 SD	0.07	4.48	0.61	1.46	4.28
mean - 2 SD	0.05	2.56	0.13	0.49	2.42
mean - 1 SD	0.02	1.06	0.07	0	0.99
mean	0	0	0	0	0
mean + 1 SD	0.02	0.63	0.35	0.49	0.55
mean + 2 SD	0.05	0.84	0.98	1.46	0.66
mean + 3 SD	0.07	0.61	1.89	2.92	0.33
	difference from prediction at mean in kg DMI				
mean - 3 SD	0.03	-1.85	0.25	0.60	-1.77
mean - 2 SD	0.02	-1.06	0.05	0.20	-1.00
mean - 1 SD	0.01	-0.44	-0.03	0	-0.41
mean	0	0	0	0	0
mean + 1 SD	-0.01	0.26	0.15	0.20	0.23
mean + 2 SD	-0.02	0.35	0.41	0.60	0.27
mean + 3 SD	-0.03	0.25	0.78	1.21	0.14
28 to 35 d Model					
Prediction at mean[3]	1.104	1.104	1.104	1.104	1.104
	difference from prediction at mean in SD units				
mean - 3 SD	0.82	3.28	1.81		
mean - 2 SD	0.15	1.53	1.21		
mean - 1 SD	0.12	0.44	0.60		
mean	0	0			
mean + 1 SD	0.51	0.21	0.60		
mean + 2 SD	1.42	1.07	1.21		
mean + 3 SD	2.71	2.57	1.81		
	difference from prediction at mean in kg DMI				
mean - 3 SD	0.39	-1.55	-0.86		
mean - 2 SD	0.07	-0.73	-0.57		
mean - 1 SD	-0.06	-0.21	-0.29		
mean	0	0	0		
mean + 1 SD	0.24	-0.10	0.29		
mean + 2 SD	0.67	-0.50	0.57		
mean + 3 SD	1.28	-1.22	0.86		

[1] 35 to 42 d model: BWBIRTH + GAIN014 + GAIN1428 + GAIN2835 + GAIN3542 + BWBIRTH^2 + GAIN014^2 + GAIN1428^2 + GAIN2835^2 + GAIN3542^2 + BWBIRTH*GAIN014 + BWBIRTH*GAIN1428 + BWBIRTH*GAIN2835 + BWBIRTH*GAIN3542 + GAIN014*GAIN1428 + GAIN014*GAIN2835 + GAIN014*GAIN3542 + GAIN1428*GAIN2835 + GAIN1428*GAIN3542 + GAIN2835*GAIN3542; 28 to 35 d model: BWBIRTH + GAIN014 + GAIN1428 + GAIN2835 + BWBIRTH^2 + GAIN014^2 + GAIN1428^2 + GAIN2835^2 + BWBIRTH*GAIN014 + BWBIRTH*GAIN1428 + BWBIRTH*GAIN2835 + GAIN014*GAIN1428 + GAIN014*GAIN2835 + GAIN1428*GAIN2835;where BWBIRTH = birth BW, kg; GAIN014 = BW gain 0 to 14 days, kg; GAIN1428 = BW gain 14 to 28 days, kg; GAIN2835 = BW gain 28 to 35 days, kg; GAIN3542 = BW gain 35 to 42 days, kg.

[2] Daily starter DMI for 35 to 42 d old heifers, kg. (SD = 0.414).
[3] Daily starter DMI for 28 to 42 d old heifers, kg. (SD = 0.473).

Table 13. Holstein heifer daily starter DMI models for 35 to 42 d with BW removed (Model A), Model A subject to backward stepwise regression (Model B), and model with BW and GAIN014 removed (Model C).

	Model A		Model B		Model C	
Variable[2]	parameter estimate	*P*	parameter estimate	*P*	parameter estimate	*P*
Intercept	0.38510852	0.2307	0.44492331	0.015	0.32920826	0.074
GAIN014	-0.10128599	0.3524	-0.10130838	0.033		
GAIN1428	-0.00490182	0.9808				
GAIN2835	0.33192893	0.1012	0.25386737	0.0003	0.27863287	0.0002
GAIN014^2	-0.00677993	0.2324				
GAIN1428^2	0.00186484	0.8874				
GAIN2835^2	0.01959047	0.3875				
GAIN3542^2	0.01539805	0.2356	0.02107852	0.004	0.02061021	0.009
GAIN014* GAIN1428	0.03094293	0.0331	0.01738231	0.018		
GAIN014* GAIN3542	-0.01051268	0.6101				
GAIN1428* GAIN2835	-0.03421967	0.2913				
GAIN1428* GAIN3542	0.03087725	0.2654	0.01100621	0.011	0.01048293	0.021
GAIN2835* GAIN3542	-0.05441203	0.0778	-0.04383520	0.003	-0.04158731	0.007
MSE	0.03880		0.03707		0.04677	
PRESS[2]	6.32		1.4978		1.6611	
R-squared	0.892		0.840		0.775	
Adjusted R-squared	0.774		0.784		0.727	

[1] GAIN014 = BW gain 0 to 14 days, kg; GAIN1428 = BW gain 14 to 28 days, kg; GAIN2835 = BW gain 28 to 35 days, kg; GAIN3542 = BW gain 35 to 42 days, kg.

[2] Prediction Residual Sum of Squares.

Table 14. Derivatives of equations[1] to predict daily starter DMI for Holstein pre-weaned and weaned heifers.

Derivative	Derivative Equation	Slope[2]
35 to 42 d Model A		
GAIN014	-0.1013 + 0.1118*GAIN1428	0.014598
GAIN1428	0.0123*GAIN014 + 0.0527*GAIN3542	0.065061
GAIN2835	0.2539 - 0.2100*GAIN3542	0.043897
GAIN3542	0.2019*GAIN3542 + 0.0708*GAIN1428 - 0.1753*GAIN2835	0.097361
35 to 42 d Model B		
GAIN1428	0.0502*GAIN3542	0.050213
GAIN2835	0.2786 - 0.1999*GAIN3542	0.079430
GAIN3542	0.1974*GAIN3542 + 0.0674*GAIN1428 - 0.1663*GAIN2835	0.098502

[1] 35 to 42 d Model A: BWBIRTH + GAIN014 + GAIN1428 + GAIN2835 + GAIN3542 + BWBIRTH^2 + GAIN014^2 + GAIN1428^2 + GAIN2835^2 + GAIN3542^2 + BWBIRTH*GAIN014 + BWBIRTH*GAIN1428 + BWBIRTH*GAIN2835 + BWBIRTH*GAIN3542 + GAIN014*GAIN1428 + GAIN014*GAIN2835 + GAIN014*GAIN3542 + GAIN1428*GAIN2835 + GAIN1428*GAIN3542 + GAIN2835*GAIN3542; 35 to 42 d Model B: GAIN014 + GAIN2835 + GAIN3542^2 + GAIN014*GAIN1428 + GAIN1428*GAIN3542 + GAIN2835*GAIN3542; where GAIN014 = BW gain 0 to 14 days, kg; GAIN1428 = BW gain 14 to 28 days, kg; GAIN2835 = BW gain 28 to 35 days, kg; GAIN3542 = BW gain 35 to 42 days, kg.

[2] Determined by solving equations with variables at their mean.

Table 15. Influence of varying GAIN014, GAIN1428, GAIN2835, and GAIN3542 one, two, or three SD units from their mean on prediction of daily starter DMI for 35 to 42 d old weaned Holstein heifers[1].

	GAIN014[1]	GAIN1428	GAIN2835	GAIN3542
Mean	0.71	6.43	4.00	4.79
SD	2.88	2.64	2.00	1.84
Model A				
prediction at mean[2]	1.451	1.451	1.451	1.451
	difference from prediction at mean in SD units			
mean - 3 SD	0.22	1.24	0.64	0.25
mean - 2 SD	0.15	0.83	0.42	0.18
mean - 1 SD	0.07	0.41	0.21	0.26
mean	0	0	0	0
mean + 1 SD	0.07	0.41	0.21	0.60
mean + 2 SD	0.15	0.83	0.42	1.55
mean + 3 SD	0.22	1.24	0.64	2.85
	difference from prediction at mean in kg DMI			
mean - 3 SD	-0.09	-0.52	-0.26	0.10
mean - 2 SD	-0.06	-0.34	-0.18	-0.07
mean - 1 SD	-0.03	-0.17	-0.09	-0.11
mean	0	0	0	0
mean + 1 SD	0.03	0.17	0.09	0.25
mean + 2 SD	0.06	0.34	0.18	0.64
mean + 3 SD	0.09	0.52	0.26	1.18
Model B				
prediction at mean[2]		1.443	1.443	1.443
	difference from prediction at mean in SD units			
mean - 3 SD		0.96	1.15	0.20
mean - 2 SD		0.64	0.77	0.20
mean - 1 SD		0.32	0.38	0.27
mean		0	0	0
mean + 1 SD		0.32	0.38	0.61
mean + 2 SD		0.64	0.77	1.55
mean + 3 SD		0.96	1.15	2.83
	difference from prediction at mean in kg DMI			
mean - 3 SD		-0.40	-0.48	0.08
mean - 2 SD		-0.27	-0.32	-0.08
mean - 1 SD		-0.13	-0.16	-0.11
mean			0	0
mean + 1 SD		0.13	0.16	0.25
mean + 2 SD		0.27	0.32	0.64
mean + 3 SD		0.40	0.48	1.17

[1] Model A: GAIN014 + GAIN2835 + $GAIN3542^2$ + GAIN014*GAIN1428 + GAIN1428*GAIN3542 + GAIN2835*GAIN3542; where GAIN014 = BW gain 0 to 14 days, kg; GAIN1428 = BW gain 14 to 28 days, kg; GAIN2835 = BW gain 28 to 35 days, kg; GAIN3542 = BW gain 35 to 42 days, kg.

[2] Starter DMI, 35-42 d, kg. (SD = 0.4141)

Table 16. Statistics from data set used to develop BW equation for Holstein heifers from 5 to 17 mo of age.

Variable	n	Mean	SD	Minimum	Maximum
HEIFER	120				
AGE, weeks	1906	45.8	11.59	18.0	75.0
BW, kg	1906	259.3	73.9	90.0	493.0
ADG[1], kg/d	1906	0.85	0.86	-0.519	7.13
DMI, kg/d	1906	6.56	1.86	1.4	14.4
CPI[2], kg/d	1906	0.92	0.26	0.20	1.96
ADFI[3], kg/d	1906	2.05	0.64	0.51	5.13
TDNI[4], kg/d	1906	4.12	1.27	0.84	8.61
WH[5], cm	1906	113.8	9.18	87.9	138.4
WHI[6], kg/cm	1906	2.24	0.48	1.00	3.57
Birth Month[7]	1906	5.97	3.83	1.0	12.0

[1] Average daily gain.

[2] Crude protein intake.

[3] ADF intake.

[4] TDN intake.

[5] Wither height.

[6] Wither height index.

[7] Months numbered 1-12 for January-December.

Table 17. Models[1] to predict BW for Holstein heifers from 5 to 17 mo of age using the backward and forward Stepwise regression and General Linear Model (GLM) procedures of SAS (1985).

	Backward		Forward		GLM	
Variable[2]	parameter estimate	*P*	parameter estimate	*P*	parameter estimate	*P*[3]
Intercept	-89.577381	0.0001	-87.775367	0.0756	-78.874896	0.0001
HEIFER					6.063426	0.0001
PBW	-1.265556	0.0014	-1.250476	0.0771	-1.753142	0.0001
PBW75			-0.365198	0.9181		
PDMI	36.233789	0.0005	40.418624	0.0004	48.916044	0.0001
AGEW	11.391521	0.0001	11.651259	0.0001	11.939864	0.0001
PADFI			-11.906502	0.2694		
PBW^2	-0.015509	0.0001	-0.015733	0.0001	-0.017584	0.0001
PBW75^2	0.388606	0.0001	0.394866	0.0001	0.448677	0.0001
PDMI^2	-1.267786	0.0001	-1.362297	0.0826	-0.577510	0.0541
AGEW^2	-0.033456	0.0004	-0.037437	0.0002	-0.055314	0.0001
PADFI^2	9.382541	0.0001	11.138492	0.0987	5.502365	0.0340
PBW*PDMI	0.476714	0.0002	0.502271	0.0001	0.692272	0.0001
PBW*AGEW	0.145433	0.0001	0.145970	0.0001	0.143837	0.0001
PBW*PADFI			0.043054	0.4808		
PDMI*AGEW	0.378948	0.0001	0.274472	0.0382	0.404681	0.0001
PDMI*PADFI			-0.245219	0.9554		
AGEW*PADFI	-1.067062	0.0001	-0.714318	0.0802	-0.654430	0.0083
PBW75*PDMI	-2.419201	0.0003	-2.481930	0.0003	-3.700355	0.0001
PBW75*AGEW	-0.706797	0.0001	-0.707489	0.0001	-0.678824	0.0001
PBW75*PADFI						
MSE	483.63		484.30		458.18	
PRESS[4]	914114		924719			
p	15		19			
C(p)	12.52		19.00			
R-squared	0.909		0.909		0.920	
Adjusted R-squared	0.909		0.908		0.913	

[1] Full model contains all variables in table except HEIFER. The GLM model only contains HEIFER and variables selected by backward Stepwise regression.

[2] PBW = previous BW, kg; PBW75 = PBW$^{.75}$, kg; PDMI = previous DMI, kg/d; PADFI = previous ADF intake, kg/d; AGEW = age in weeks.

[3] Determined from Type III Sum of Squares.

[4] Prediction Residual Sum of Squares.

Table 18. Derivatives of equation[1] to predict BW for Holstein heifers from 5 to 17 mo of age.

Derivative	Derivative Equation	Slope[2]
PBW	-1.27 - 7.89PBW + 3.07*PDMI + 6.66*AGEW	0.57
PBW75	49.13*PBW75 - 15.58*PDMI - 32.37*AGEW	1.18
PDMI	39.23 - 16.33*PDMI + 121.33*PBW + 17.36*AGEW - 152.94*PBW75	5.65
AGEW	11.39 - 3.06*AGEW + 37.02*PBW + 2.44*PDMI - 2.13*PADFI - 44.68*PBW75	0.97
PADFI	37.51*PADFI - 48.87*AGEW	-11.36

[1] BW = PBW + PDMI + AGEW + PBW^2 + $PBW75^2$ + $PDMI^2$ + $AGEW^2$ + $PADFI^2$ + PBW*PDMI + PBW*AGEW + PDMI*AGEW + AGEW*PADFI + PBW75*PDMI + PBW75*AGEW; where PBW = previous BW, kg; PBW75 = $PBW^{.75}$, kg; PDMI = previous DMI, kg/d; PADFI = previous ADF intake, kg/d; AGEW = age in weeks.

[2] Determined by solving equation with variables at their mean.

Table 19. Influence of varying PBW, PBW75, PDMI, AGEW, and PADFI one, two, or three SD units from their mean on prediction of BW for Holstein heifers from 5 to 17 mo of age[1].

	PBW	PBW75	PDMI	AGEW	PADFI
Mean	254.5	83.2	6.4	45.8	2.0
SD	72.9	13.7	1.9	11.6	0.6
Prediction at mean[2]	265.9	265.9	265.9	265.9	265.9
	difference from prediction at mean in SD units				
mean - 3 SD	11.7	8.2	0.9	1.0	0.7
mean - 2 SD	5.6	3.5	0.5	0.6	0.4
mean - 1 SD	1.7	0.8	0.2	0.2	0.1
mean	0	0	0	0	0
mean + 1 SD	0.6	1.2	0.1	0.1	0.1
mean + 2 SD	3.3	4.4	0.1	0.1	0
mean + 3 SD	8.3	9.5	0.1	0.1	0.2
	difference from prediction at mean in kg BW				
mean - 3 SD	-865.8	607.0	-69.1	-74.1	52.6
mean - 2 SD	-412.6	259.0	-37.6	-40.4	28.0
mean - 1 SD	-123.9	56.7	-14.6	-15.7	10.5
mean	0	0	0	0	0
mean + 1 SD	-40.9	89.0	6.1	6.7	-3.4
mean + 2 SD	-246.0	323.6	3.7	4.5	0.2
mean + 3 SD	-616.0	703.8	7.2	6.8	10.8

[1] BW = PBW + PDMI + AGEW + PBW^2 + $PBW75^2$ + $PDMI^2$ + $AGEW^2$ + $PADFI^2$ + PBW*PDMI + PBW*AGEW + PDMI*AGEW + AGEW*PADFI + PBW75*PDMI + PBW75*AGEW; where PBW = previous BW, kg; PBW75 = $PBW^{.75}$, kg; PDMI = previous DMI, kg/d; PADFI = previous ADF intake, kg/d; AGEW = age in weeks.

[2] BW, kg. (SD = 73.9).

Table 20. Statistics from data set[1] used to develop weekly BW and DMI equations for 16 to 28 month old Holstein heifers.

Variable	n	Mean	SD	Minimum	Maximum
Heifer	54				
Age, months	1695	20.60	2.50	15.20	28.00
BW, kg	1695	545.15	73.46	359.00	766.00
ADG[1], kg/d	1641	0.975	0.351	-1.49	1.94
DMI, kg/d	1695	11.49	1.99	3.85	21.03

[1] DMI and BW measured every 7 and 28 d, respectively. Weekly BW calculated from monthly measurements using monthly ADG. Control herd with 1964 genetics (Boettcher et al, 1994) not included.
[2] Average daily gain.

Table 21. Competing models[1] to predict BW of 16 to 28 mo old Holstein heifers using the backward, forward, and MAXR Stepwise regression procedures of SAS (1985).

	Backward		Forward		Best 6 variable Model	
Variable[2]	parameter estimate	*P*	parameter estimate	*P*	parameter estimate	*P*
INTERCEPT	-80.991966	0.0001	-140.18564	0.0109	-77.082427	0.0001
PBW			-0.310536	0.3019		
PBW75	5.251117	0.0001	8.110965	0.0005	5.479217	0.0001
PDMI	-10.174675	0.0064	-0.293851	0.3601	-0.234414	0.4591
AGEW	1.136351	0.0385	-0.625357	0.0001	-0.611703	0.0001
PBW^2			0.000420	0.0834	0.000143	0.0001
PBW75^2	0.004992	0.0106	-0.011460	0.2696		
PDMI^2						
AGEW^2	0.002164	0.0927	0.002572	0.0001	0.002534	0.0001
PBW*PDMI	-0.054659	0.0070				
PBW*AGEW	0.009286	0.0013				
PDMI*AGEW			0.005986	0.0840	0.005353	0.1172
PBW75*PDMI	0.357029	0.0065				
PBW75*AGEW	-0.059277	0.0018				
MSE	5.501		5.517		5.515	
PRESS[3]	8797.34		8823.97		8801.86	
p	10		9		7	
C(p)	8.47		12.22		9.55	
R-squared	0.999		0.999		0.999	
Adjusted R-squared	0.999		0.999		0.999	

[1] Full model contains all variables in table.

[2] PBW = previous BW, kg; PBW75 = PBW$^{.75}$, kg; PDMI = previous DMI, kg/d; AGEW = age in weeks.

[3] Prediction Residual Sum of Squares.

Table 22. Derivatives of equation[1] to predict BW for Holstein heifers from 17 to 28 mo of age.

Derivative	Derivative Equation	Slope[2]
PBW	2*0.1549*PBW	0.155
PBW75	5.4792	5.479
PDMI	-0.23441 + 0.4789*AGEW	0.245
AGEW	-0.6117 + 0.4534*2*AGEW + 0.0616*PDMI	-0.097

[1] $BW = PBW75 + PDMI + AGEW + PBW^2 + AGEW^2 + PDMI*AGEW$; where PBW = previous BW, kg; $PBW75 = PBW^{.75}$, kg; PDMI = previous DMI, kg/d; AGEW = age in weeks.

[2] Determined by solving with variables at their mean.

Table 23. Influence of varying PBW, PBW75, PDMI, and AGEW one, two, or three SD units from their mean on prediction of BW for Holstein heifers from 17 to 28 mo of age[1].

	PBW	PBW75	PDMI	AGEW
Mean	541.77	112.11	11.5	89.47
SD	71.81	11.18	1.99	10.87
Prediction at mean[2]	547.53	547.53	547.53	547.53
	difference from prediction at mean in SD units			
mean - 3 SD	0.36	2.50	0.02	0.08
mean - 2 SD	0.26	1.67	0.01	0.04
mean - 1 SD	0.14	0.83	0.01	0.02
mean	0	0	0	0
mean + 1 SD	0.16	0.83	0.01	0.01
mean + 2 SD	0.34	1.67	0.01	0.01
mean + 3 SD	0.54	2.50	0.02	0.01
	difference from prediction at mean in kg BW			
mean - 3 SD	-26.74	-183.77	-1.46	-5.84
mean - 2 SD	-19.30	-122.52	-0.97	-3.30
mean - 1 SD	-10.39	-61.26	0.49	-1.35
mean	0	0	0	0
mean + 1 SD	11.86	61.26	0.49	-0.75
mean + 2 SD	25.20	122.52	0.97	-0.90
mean + 3 SD	40.02	183.77	1.46	-0.46

[1] BW = PBW75 + PDMI + AGEW + PBW^2 + AGEW^2 + PDMI*AGEW; where PBW = previous BW, kg; PBW75 = PBW$^{.75}$, kg; PDMI = previous DMI, kg/d; AGEW = age in weeks.

[2] BW, kg. (SD = 73.5).

Table 24. Competing models[1] to predict DMI of 16 to 28 mo old Holstein heifers using the backward, forward, and MAXR Stepwise regression procedures of SAS (1985).

	Backward		Forward		Best 6 variable Model	
Variable[2]	parameter estimate	*P*	parameter estimate	*P*	parameter estimate	*P*
INTERCEPT	3.074424	0.0003	6.704102	0.0026	3.795390	0.0001
BW						
BW75						
PDMI			-1.357541	0.0974		
AGEW						
ADG						
BW^2			0.000020	0.2921	-0.000006	0.0263
BW75^2						
PDMI^2	-0.013812	0.0030	-0.012566	0.0154	-0.010968	0.0141
AGEW^2	0.000644	0.0086	0.001343	0.0582		
ADG^2			-0.098905	0.5003		
BW*PDMI	-0.002527	0.0046	-0.009513	0.0262	-0.002321	0.0122
BW*AGEW	-0.000134	0.0024				
PDMI*AGEW	-0.006203	0.0032	-0.004182	0.1786	-0.002461	0.0001
BW75*PDMI	0.025791	0.0001	0.069535	0.0085	0.021244	0.0001
BW75*AGEW			-0.002129	0.1002		
ADG*BW						
ADG*BW75			-0.013496	0.4114		
ADG*PDMI	0.043166	0.0001	0.065720	0.1617	0.043212	0.0001
ADG*AGEW			0.015919	0.3780		
MSE	1.5342		1.5360		1.5377	
PRESS[3]	2473.3		2494.1		2476.0	
p	8		13		7	
C(p)	1.60		8.45		4.17	
R-squared	0.612		0.613		0.611	
Adjusted R-squared	0.611		0.610		0.610	

[1] Full model contains all variables in table.

[2] BW75 = BW$^{.75}$, kg; PDMI = previous DMI, kg/d; AGEW = age in weeks; ADG = average daily gain, kg.

[3] Prediction Residual Sum of Squares.

Table 25. Competing models to predict DMI of 16 to 28 mo old Holstein heifers using the General Linear Model of SAS (1985).

Variable[2]	Model A	Model B	Model C
	--	parameter estimate	--
INTERCEPT	4.375114592	3.835704689	4.084378235
HEIFER	-0.040918827		0.009249337
MONTH		0.053956195	-0.018449729
BW^2	-0.000003418	-0.000005924	-0.000002518
$PDMI^2$	-0.011599434	-0.011680863	-0.013133393
BW*PDMI	-0.002706307	-0.002237770	-0.002918570
PDMI*AGEW	-0.002721239	-0.002614388	-0.004323657
BW75*PDMI	0.022387457	0.020999260	0.024831272
ADG*PDMI	0.048354900	0.044809339	0.049499947
MSE	1.45999	1.51071	1.42208
R-squared	0.643	0.621	0.655
Adjusted R-squared	0.629	0.617	0.639

[1] MONTH = month of year, 1..12; BW75 = $BW^{.75}$, kg; PDMI = previous DMI, kg/d; AGEW = age in weeks; ADG = average daily gain, kg.

Table 26. Derivatives of equations[1] to predict DMI for Holstein heifers from 17 to 28 mo of age.

Derivative	Derivative Equation	Slope[2]
Model A		
BW	-0.0065*2*BW - 0.0267*PDMI	-0.033
BW75	0.2443-PDMI	0.244
PDMI	-0.2523**PDMI - 1.2575*BW - 0.2202*AGEW + 2.3817*BW75 + 0.4966*ADG	1.148
AGEW	-0.0283*PDMI	-0.028
ADG	0.4969*PDMI	0.497
Model B		
BW	-0.0027*2*BW - 0.0336*PDMI	-0.036
BW75	0.2856*PDMI	0.286
PDMI	-0.3021*2*PDMI - 1.5812*BW - 0.3868*AGEW + 2.7838*BW75 + 0.5688*ADG	1.083
AGEW	-0.0497*DMI	-0.050
ADG	0.5692*DMI	0.569

[1] Model A: DMI = BW^{2} + PDMI^{2} + BW*PDMI + PDMI*AGEW + BW75*PDMI + ADG*PDMI; Model B: DMI = HEIFER + MONTH + BW^{2} + PDMI^{2} + BW*PDMI + PDMI*AGEW + BW75*PDMI + ADG*PDMI; where BW = body weight, kg; BW75 = BW$^{.75}$, kg; PDMI = previous DMI, kg/d; ADG = average daily gain, kg/d; AGEW = age in weeks; MONTH = month of year (1..12).

[2] Determined by solving with variables at their mean.

Table 27. Influence of varying BW, BW75, DMI, AGEW, and ADG one, two, or three SD units from their mean on prediction of DMI for Holstein heifers from 17 to 28 mo of age[1].

	BW	BW75	PDMI	AGEW	ADG
Mean	541.77	112.11	11.50	89.47	11.49
SD	71.81	11.18	1.99	10.87	0.613
Prediction at mean[2]	16.69	16.69	16.69	16.69	16.69
Model A	difference from prediction at mean in SD units				
mean - 3 SD	3.45	4.12	3.64	0.46	0.46
mean - 2 SD	2.33	2.75	2.38	0.31	0.31
mean - 1 SD	1.18	1.37	1.17	0.15	0.15
mean	0	0	0	0	0
mean + 1 SD	1.21	1.37	1.13	0.15	0.15
mean + 2 SD	2.46	2.75	2.21	0.31	0.31
mean + 3 SD	3.73	4.12	3.25	0.46	0.46
	difference from prediction at mean in kg DMI				
mean - 3 SD	6.87	-8.19	-7.25	0.92	-0.91
mean - 2 SD	4.64	-5.46	-4.74	0.62	-0.61
mean - 1 SD	2.35	-2.73	-2.33	0.31	-0.30
mean	0	0	0	0	0
mean + 1 SD	-2.41	2.73	2.24	-0.31	0.30
mean + 2 SD	-4.89	5.46	4.40	-0.62	0.61
mean + 3 SD	-7.43	8.19	6.46	-0.92	0.91
Model B	difference from prediction at mean in SD units				
mean - 3 SD	3.87	4.81	3.48	0.81	0.53
mean - 2 SD	2.59	3.21	2.27	0.54	0.35
mean - 1 SD	1.30	1.60	1.11	0.27	0.18
mean	0	0	0	0	0
mean + 1 SD	1.32	1.6	1.06	0.27	0.18
mean + 2 SD	2.65	3.21	2.06	0.54	0.35
mean + 3 SD	3.99	4.81	3.01	0.81	0.53
	difference from prediction at mean in kg DMI				
mean - 3 SD	7.70	-9.58	-6.93	1.62	-0.53
mean - 2 SD	5.16	-6.39	-4.52	1.08	-0.35
mean - 1 SD	2.59	-3.19	-2.21	0.54	-0.18
mean	0	0	0	0	0
mean + 1 SD	-2.62	3.19	2.10	-0.54	0.18
mean + 2 SD	-5.26	6.39	4.10	-1.08	0.35
mean + 3 SD	-7.94	9.58	5.99	-1.62	0.53

[1] Model A: DMI = BW^2 + $PDMI^2$ + BW*PDMI + PDMI*AGEW + BW75*PDMI + ADG*PDMI; Model B: DMI = HEIFER + MONTH + BW^2 + $PDMI^2$ + BW*PDMI + PDMI*AGEW + BW75*PDMI + ADG*PDMI; where BW = body weight, kg; BW75 = $BW^{.75}$, kg; PDMI = previous DMI, kg/d; ADG = average daily gain, kg/d; AGEW = age in weeks; MONTH = month of year (1..12).

[2] DMI, kg. (SD = 1.99).

Table 28. Statistics from data set used to develop 305 d milk yield equation for first lactation Holstein cows.

Variable	Mean	n	Min.	Max.	SD
Herd		664			
Cow		50,745			
Herd mean for 1st lactation BW, kg	529.4	50,745	460	673	26.4
Herd mean for 1st t lactation 305 day milk yield, kg	7,326.6	50,745	4805	9,536	709.6
Herd mean for 3rd and later lactation 305 day milk yield, kg	8,329.0	50,745	4,407	12,133	865.8
Herd mean for 3rd and later lactation BW	642.9	50,745	549	770	27.9
Birth date (SD in days)	11-4-89	50,745	10-9-76	5-8-93	801.9
Calving date (SD in days)	4-7-92	50,745	8-8-79	3-7-95	785.9
Individual heifer 1st lactation milk yield, kg	7,321.7	50,745	4,002.1	13,748.2	1332.7
Individual heifer after calving BW, kg	528	50,745	408.2	698.5	46.0
Age at first calving, days	884.7	50,745	550	1215	122.3

Table 29. Statistics for models[1] selected by backward and forward Stepwise regression to predict 305 d milk yield for first lactation Holstein cows.

	Backward		Forward		GLM
Variable[2]	parameter estimate	*P*	parameter estimate	*P*	parameter estimate
INTERCEPT	4250.23934054	0.0001	5217.43658918	0.0028	4758.649046
SEASON					-95.0097183
BW	-2.55318777	0.0055	-5.18923803	0.3013	-2.743928
AFC	-2.30218181	0.0072	-2.35424950	0.0062	-3.030839
BWDEV			-4.17797152	0.4352	
MATMILK	0.26728402	0.0001	0.26650570	0.0001	0.257743
BW^2			0.00175342	0.6443	
AFC^2	-0.00178746	0.0001	-0.00177921	0.0001	-0.001483
$BWDEV^2$	-0.01149011	0.0001	-0.00762359	0.1374	-0.011583
BW*AFC	0.00428820	0.0001	0.00434985	0.0001	0.004452
BW*BWDEV	0.02238066	0.0001	0.02855796	0.0006	0.022875
BW*MATMILK					
AFC*MATMILK	0.00046924	0.0001	0.00046983	0.0001	0.000484
BWTDEV* MATMILK	-0.00098551		-0.00098368	0.0001	-0.001013
Root MSE	1216.07		1216.09		1211.98
PRESS[3]	74725572455		74730988472		
p	10		12		
C(p)	7.81		11.14		
R-squared	0.167		0.167		0.173
Adjusted R-squared	0.167		0.167		0.173

[1] Full model contains all variables in table.

[2] BW = after calving BW (kg) for first lactation animals; AFC = age at first calving (days); MATMILK = herd average 305 milk yield for third and later lactation (mature) animals (kg); BWDEV = herd average BW for third and later lactation (mature) animals (kg) - BW (kg)

[3] Prediction Residual Sum of Squares

Table 30. Derivatives of equation to predict 305 d milk yield for first lactation Holstein cows.

Derivative[1]	Derivative Equation	Slope[2]
Equation without season [3]		
BW	-2.553 + 3.794*AFC + 2.573*BWDEV	3.813
AFC	-2.302 - 3.163*2*AFC + 2.264*BW + 3.908*MATMILK	0.707
BWDEV	-2.642*2*BWDEV - 11.816*BW - 8.208*MATMILK	0.966
MATMILK	0.267 + 0.415*AFC - 0.113*BWDEV	0.569
Equation with season [4]		
BW	-2.744 + 3.939*AFC + 2.629*BWDEV	3.824
AFC	-3.031 - 2.624*2*AFC + 2.350*BW + 4.031*MATMILK	0.727
BWDEV	-2.666*2*BWDEV - 12.077*BW - 8.437*MATMILK	0.977
MATMILK	0.258 + 0.428*AFC - 0.116*BWDEV	0.570

[1] BW = after calving BW (kg) for first lactation animals; AFC = age at first calving (days); MATMILK = herd average 305 milk yield for third and later lactation (mature) animals (kg); BWDEV = herd average BW for third and later lactation (mature) animals (kg) - BW (kg)

[2] Determined by solving equation with variables at their mean.

[3] First lactation milk yield = BW + AFC + MATMILK + AFC^2 + $BWWDEV^2$ + BW*AFC + BW*BWDEV + AFC*MATMILK + BWDEV*MATMILK.

[4] First lactation milk yield = SEASON + BW + AFC + MATMILK + AFC^2 + $BWWDEV^2$ + BW*AFC + BW*BWDEV + AFC*MATMILK + BWDEV*MATMILK.

Table 31. Influence of varying BW, BWDEV, AFC, or MATMILK one, two, or three SD units from their mean on prediction of 305 d milk yield for first lactation Holstein cows.

	BW[1]	AFC	BWDEV	MATMILK
Mean	528.0	884.8	115.0	8329.0
SD	46.0	122.4	44.6	865.8
Equation without season[2]				
prediction at mean[3]	7416	7416	7416	7416
	difference from prediction at mean in SD units			
mean - 3 SD	0.39	0.38	0.25	1.11
mean - 2 SD	0.26	0.21	0.13	0.74
mean - 1 SD	0.13	0.09	0.05	0.37
mean	0	0	0	0
mean + 1 SD	0.13	0.04	0.02	0.37
mean + 2 SD	0.26	0.05	0.00	0.74
mean + 3 SD	0.39	0.01	0.06	1.11
	difference from prediction at mean in kg milk			
mean - 3 SD	-526	-500	-335	-1478
mean - 2 SD	-351	-280	-177	-986
mean - 1 SD	-175	-113	-66	-493
mean	0	0	0	0
mean + 1 SD	175	60	20	493
mean + 2 SD	351	66	-5	986
mean + 3 SD	526	19	-76	1478
Equation with season[4]				
prediction at mean[3]	7431	7431	7431	7431
	difference from prediction at mean in SD units			
mean - 3 SD	0.40	0.35	0.25	1.11
mean - 2 SD	0.26	0.20	0.13	0.74
mean - 1 SD	0.13	0.08	0.05	0.37
mean	0	0	0	0
mean + 1 SD	0.13	0.05	0.02	0.37
mean + 2 SD	0.26	0.07	0	0.74
mean + 3 SD	0.40	0.05	0.06	1.11
	difference from prediction at mean in kg milk			
mean - 3 SD	-528	-467	-338	-1479
mean - 2 SD	-352	-267	-179	-986
mean - 1 SD	-176	-111	-67	-493
mean	0	0	0	0
mean + 1 SD	176	67	21	493
mean + 2 SD	352	69	-6	986
mean + 3 SD	528	67	-76	1479

[1] BW = after calving BW (kg) for first lactation animals; AFC = age at first calving (days); MATMILK = herd average 305 milk yield for third and later lactation (mature) animals (kg); BWDEV = herd average BW for third and later lactation (mature) animals (kg) - BW (kg)

[2] First lactation milk yield = BW + AFC + MATMILK + AFC^2 + BWWDEV^2 + BW*AFC + BW*BWDEV + AFC*MATMILK + BWDEV*MATMILK.

[3] First lactation 305 day milk yield, kg. (SD = 1332.74)

[4] First lactation milk yield = SEASON + BW + AFC + MATMILK + AFC^2 + BWWDEV^2 + BW*AFC + BW*BWDEV + AFC*MATMILK + BWDEV*MATMILK.

Table 32. Selected inputs and costs for raising a Holstein heifer estimated by Willett et al, 1992.

Expense	0-2 Months	3-12 Months	13 - 24 Months	Each Month over 24 Months
Operating Expenses				
Labor, hr	8	6	5.5	0.8
Veterinary and medicine, $	11.00	25.00	10.00	
Bedding, lb	250	900	250	
Supplies, power, etc., $	4.00	5.50	11.00	1.00
Ownership Expenses, $				
Building Depreciation	1.14	5.71	6.85	0.57
Building Interest	1.20	5.99	7.19	0.60
Building Taxes	0.21	1.02	1.23	0.10
Building Insurance	0.06	0.28	0.34	0.03
Building Repairs	0.11	0.57	0.68	0.06
Equipment Depreciation	0.40	2.00	2.40	0.20
Equipment Interest	0.11	0.53	0.63	0.05
Equipment Insurance	0.01	0.02	0.03	
Equipment Repairs	0.04	0.20	0.24	0.02
Weekly prorated costs[1]				
Operating Expenses				
Labor, hr	0.921	0.138	0.106	0.184
Veterinary and medicine, $	1.266	0.576	0.192	
Bedding, lb	28.783	20.724	4.797	
Supplies, power, etc., $	0.461	0.127	0.211	0.230
Total weekly operating costs[2], $	9.67	2.22	1.35	1.70
Ownership Expenses, $				
Building Depreciation	0.131	0.131	0.131	0.131
Building Interest	0.138	0.138	0.138	0.138
Building Taxes	0.024	0.023	0.024	0.023
Building Insurance	0.007	0.006	0.007	0.007
Building Repairs	0.013	0.013	0.013	0.014
Equipment Depreciation	0.046	0.046	0.046	0.046
Equipment Interest	0.013	0.012	0.012	0.012
Equipment Insurance	0.001	0.000	0.001	0.000
Equipment Repairs	0.005	0.005	0.005	0.005
Total weekly ownership costs	0.378	0.376	0.376	0.375

[1] Estimated by dividing totals by (number of months in period x 30.4/7).

[2] Assuming labor costs of $8/h and bedding costs of $40/ton.

Table 33. Standard inputs entered by user to run simulation.

Input	units	mean	SD
Value of bull calf at birth	$	50.00	
Value of heifer calf at birth	$	100.00	
Milk Price (mailbox)	$/cwt	13.00	
Feed cost/cwt milk for milking cows	$	5.00	
Milking cow daily non-feed cost[1]	$/day	2.49	
Cull price	$/lb	0.38	
Discount rate (MARR)	%	8	
Death loss			
birth	%	5	
birth to weaning	%	2	
weaning to 14 mo	%	1	
14 mo to calving	%	1	
Abortion rate	%	2	
Birth weight[2]	kg	40.5	5.4
Maximum pre-calving BW	kg	800	
Age at puberty[3]	months	382.2	5.0
Minimum first breeding age	months	14	
Minimum first breeding BW	kg	340	
Artificial Insemination			
percent heats observed	%	50	
maximum services per heifer	services	3	
conception rates			
first breeding	%	65	
second breeding	%	62	
third and later breedings	%	62	
cost	$/service	15	
Bull (non-AI breeding)			
percent heats observed	%	85	
maximum heats serviced	services	3	
conception rate	%	85	
cost[4]	$/heifer	22.03	
Estrous Cycle Length[5]	days	22.02	3.5
Gestation Length[6]	months	9.2	0.2
Third and later lactation cows			
BW	kg	635	
305 d milk yield	kg	10000	

[1] Virginia Cooperative Extension, 1997.

[2] Chester-Jones et al., 1994, personal communication; Ziegler et al., 1995, 1996.

[3] Lin et al., 1986.

[4] Johnston et al., 1987.

[5] Wishart, 1972.

[6] Slana et al., 1993.

Table 34. Standard inputs for heifer groups in simulation used to formulate least cost rations.

Target ranges for heifer groups	Average daily gain kg	ADF minimum % DM	ADF maximum, % DM
6 to 13 wk old heifers	0.8	20	35
14 to 59 wk old heifers	0.8	20	35
60 wk to 8 wk post conception	1.0	25	40
8 wk post conception to calving	1.0	25	40

Table 35. Standard rations and feed costs used in simulation for heifer groups[1].

Feed	Cost	Group 2	Group 3	Group 4	Group 5
	$ per ton		% DM		
Corn silage	30		51.35	29.60	21.64
Alfalfa Silage	50		18.13	21.80	21.15
First cutting grass hay	80		14.91	39.90	49.67
Second cutting grass hay	120	32.03			
Soybean meal	300		7.36	4.10	3.36
Shelled corn	160		7.36	4.10	3.36
Calf starter	240	67.97			
Mineral	340		0.90	0.50	0.82
Ration content					
TDN, % DM		76.3	68.9	63.7	62.0
CP, % DM		17.2	13.6	12.6	12.3
ADF, % DM		23.0	24.3	31.5	34.0
Cost per kg DM		0.2468	0.1203	0.1135	0.1135

[1] Group 2 = 6 to 13 wk, Group 3 = 14 to 59 wk, Group 4 = 60 wk to 8 wk post-conception, Group 5 = 8 wk post-conception until calving.

Table 36. Selected simulation inputs for growth rate evaluation.

Growth Rate[1]	BW difference[2] from normal growth, kg calving	Period I	Period II	Minimum Breeding BW, kg	Minimum Breeding Age, mo
Control:Control				340	14
Accelerated:Accelerated	80			340	12
Slow:Slow	-80			340	14
Control:Accelerated			25	320	12
Accelerated:Control		25		340	12
Slow:Accelerated		-25	25	300	12

[1] Growth rates for period I (5wk to 14 mo) and period II (14 mo to calving).
[2] BW difference from control growth at the end of each period

Table 37. Least squares means[1] from simulation results evaluating various growth rates[2] of Holstein heifers.

Item[3]	Control: Control	ACC:ACC	Slow:Slow	Control:ACC	ACC:Control	Slow:ACC
Herds, n	10	10	10	10	10	10
Heifers, n	1000	1000	1000	1000	1000	1000
Death loss, %	8.6	7.9	8.7	6.9	8.5	10.0
Abortion, %	1.3	2.3	1.7	2.0	1.9	1.2
ADG I, kg/d	0.74 ^{a}	0.91 ^{b}	0.61 ^{c}	0.80 ^{d}	0.84 ^{e}	0.76 ^{f}
ADG II, kg/d	0.84 ^{a}	0.89 $^{b, f}$	0.63 ^{c}	0.77 ^{d}	0.62 ^{e}	0.87 ^{f}
ADG overall, kg/d	0.78 $^{a, d}$	0.90 ^{b}	0.62 ^{c}	0.78 ^{d}	0.75 ^{e}	0.80 ^{f}
DMI I, kg/d	5.55 $^{a, b}$	5.57 ^{b}	5.33 $^{c, e}$	5.12 ^{d}	5.31 ^{e}	4.84 ^{f}
DMI II, kg/d	10.60 ^{a}	11.45 ^{b}	8.97 ^{c}	10.20 ^{d}	9.77 ^{e}	10.36 ^{f}
DMI overall, kg/d	7.37 ^{a}	7.87 ^{b}	6.54 ^{c}	7.10 $^{d, e}$	7.05 ^{e}	6.99 ^{f}
Services	1.55	1.54	1.54	1.52	1.51	1.58
Age at conception, mo	16.1 ^{a}	14.1 $^{b, d, e, f}$	18.4 ^{c}	14.1 $^{d, e, f}$	14.1 $^{e, f}$	14.1 ^{f}
Age at calving, mo	25.1 ^{a}	23.1 $^{b, d, e, f}$	27.4 ^{c}	23.1 $^{d, e, f}$	23.0 $^{e, f}$	23.1 ^{f}
BW at conception, kg	404 ^{a}	431 ^{b}	380 $^{c, d}$	383 ^{d}	396 ^{e}	367 ^{f}
Post calving BW, kg	583 ^{a}	625 ^{b}	503 ^{c}	543 ^{d}	514 ^{e}	555 ^{f}
First lactation milk yield, kg	8077 $^{a, b, e}$	7950	8028 $^{b, d}$	7863 ^{c}	7873 ^{d}	7972 ^{e}
Feed costs I, $	366.04 ^{a}	331.70 ^{b}	393.46 ^{c}	306.90 ^{d}	316.02 ^{e}	291.96 ^{f}
Feed costs II, $	328.61 ^{a}	355.87 ^{b}	278.11 ^{c}	317.01 ^{d}	303.88 ^{e}	321.91 ^{f}
Feed costs overall, $	694.64 $^{a, b}$	687.58 ^{b}	671.57 ^{c}	623.91 $^{d, e}$	619.91 $^{e, f}$	613.87 ^{f}
Operating costs I, $	198.23 ^{a}	186.82 $^{b, d, e, f}$	211.72 ^{c}	186.80 $^{d, e, f}$	186.35 $^{e, f}$	186.74 ^{f}
Operating costs II, $	54.53 ^{a}	53.27 $^{b, d, e, f}$	57.85 ^{c}	53.27 $^{d, e, f}$	53.27 $^{e, f}$	53.25 ^{f}
Operating costs overall, $	252.76 ^{a}	240.08 $^{b, d, e, f}$	269.57 ^{c}	240.07 $^{d, e, f}$	239.62 $^{e, f}$	240.00 ^{f}
Ownership costs I, $	26.27 ^{a}	23.09 $^{b, d, e, f}$	30.01 ^{c}	23.09 $^{d, e, f}$	22.96 $^{e, f}$	23.07 ^{f}
Ownership costs II, $	14.66 ^{a}	14.66 $^{b, d, e, f}$	14.65 ^{c}	14.66 $^{d, e, f}$	14.66 $^{e, f}$	14.66 ^{f}
Ownership costs overall, $	40.93 ^{a}	37.75 $^{b, d, e, f}$	44.66 ^{c}	37.75 $^{d, e, f}$	37.62 $^{e, f}$	37.73 ^{f}
Breeding Costs, $	23.54	23.49	23.37	22.85	22.80	23.99
Total cash rearing costs[4], $	1011.88 $^{a, c}$	988.90 ^{b}	1009.17 ^{c}	924.58 ^{d}	919.95 $^{e, f}$	915.59 ^{f}
Interest costs, $	103.31 ^{a}	92.25 ^{b}	115.38 ^{c}	88.57 $^{d, e, f}$	88.95 $^{e, f}$	87.09 ^{f}
Death and abortion costs[5], $	31.75	39.76	51.20	35.75	39.14	35.75
Total rearing costs[6], $	1246.93 ^{a}	1220.91 ^{b}	1275.76 ^{c}	1148.89 ^{d}	1148.03 ^{e}	1138.43 ^{f}
Monthly costs[7], $	45.80 $^{a, d, e, f}$	48.93 ^{b}	42.61 ^{c}	46.05 $^{d, e, f}$	46.18 $^{e, f}$	45.65 ^{f}
Annual costs[8], $	567.77 $^{a, d, e, f}$	606.68 ^{b}	528.09 ^{c}	570.97 ^{d}	572.67 ^{e}	566.01 ^{f}
Net Profit/Loss[9], $	399.78 $^{a, b, d, e}$	407.15 $^{b, d, e}$	319.84 ^{c}	441.55 $^{d, e, f}$	432.62 $^{e, f}$	463.24 ^{f}

[a, b, c, d, e, f] Means within a row with unlike superscripts differ ($P < 0.05$); death loss, abortions, and death and abortion costs not tested; services and breed costs not tested due to treatment $P > 0.05$.

[1] Raw treatment means (n=6) for death loss and abortions.

[2] Control:Control = normal growth, birth to calving; ACC:ACC = accelerated growth, birth to calving; Slow:Slow = slow growth, birth to calving; Control:ACC = normal growth 5 wk to 14 mo, accelerated growth 14 mo to calving; ACC:Control = accelerated growth 5 wk to 14 mo, normal growth 14 mo to calving; Slow:ACC = slow growth 5 wk to 14 mo, accelerated growth 14 mo to calving.

[3] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[4] Includes feed, ownership, operating, and breeding costs.

[5] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[6] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[7] Total rearing costs adjusted to a monthly basis using 8% interest.

[8] Total rearing costs adjusted to an annual basis using 8% interest.

[9] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Table 38. Rearing costs as a percentage of total rearing expenses from growth rate analysis[1].

Item[2]	Control: Control	ACC: ACC	Slow: Slow	Control: ACC	ACC: Control	Slow: ACC
Feed costs I	29.4	27.2	30.8	26.7	27.5	25.7
Feed costs II	26.4	29.2	21.8	27.6	26.5	28.3
Feed costs overall	55.7	56.3	52.6	54.3	54.0	53.9
Operating costs I	15.9	15.3	16.6	16.3	16.2	16.4
Operating costs II	4.4	4.4	4.5	4.6	4.6	4.7
Operating costs overall	20.3	19.7	21.1	20.9	20.9	21.1
Ownership costs I	2.1	1.9	2.4	2.0	2.0	2.0
Ownership costs II	1.2	1.2	1.2	1.3	1.38	1.3
Ownership costs overall	3.3	3.1	3.5	3.3	3.3	3.3
Breeding Costs	1.9	1.9	1.8	2.00	2.0	2.1
Interest costs	8.3	7.6	9.0	7.7	7.8	7.7
Death and abortion costs[3]	2.6	3.3	4.0	3.1	3.4	3.1
Value of heifer at birth ($100)	8.0	8.2	7.9	8.7	8.7	8.8

[1] Control:Control = normal growth, birth to calving; ACC:ACC = accelerated growth, birth to calving; Slow:Slow = slow growth, birth to calving; Control:ACC = normal growth 5 wk to 14 mo, accelerated growth 14 mo to calving; ACC:Control = accelerated growth 5 wk to 14 mo, normal growth 14 mo to calving; Slow:ACC = normal growth 5 wk to 14 mo, slow growth 14 mo to calving.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

Table 39. Selected correlations[1] ($P < 0.05$) from simulation results evaluating various growth rates of Holstein heifers.

Item[2]	Total Rearing Costs	Total Cash Rearing Costs	Net Profit/Loss at Calving	Age at Calving	Post Calving BW	First Lactation Milk Yield
ADG I, kg/d	-0.32	-0.27	0.08	-0.63	0.17	-0.08
ADG II, kg/d	0.37	0.42		0.10	0.83	0.14
ADG overall, kg/d	0.08	0.15	0.06	-0.31	0.76	0.07
DMI I, kg/d	0.87	0.89	-0.22	0.69	0.66	0.09
DMI II, kg/d	0.39	0.46	-0.04		0.86	0.07
DMI overall, kg/d	0.54	0.60	-0.09	-0.13	0.88	0.08
Services	0.66	0.68	-0.16	0.51	0.49	0.08
Age at conception, mo	0.89	0.86	-0.23	1.0	0.37	0.12
Age at calving, mo	0.89	0.86	-0.23		0.37	0.12
BW at conception, kg	0.76	0.79	-0.20	0.53	0.71	0.05
Post calving BW, kg	0.69	0.75	-0.11	0.37		0.13
First lactation milk yield, kg	0.13	0.13	0.54	0.12	0.13	
Feed costs I	0.96	0.95	-0.25	0.95	0.53	0.11
Feed costs II	0.38	0.45	-0.03		0.85	0.08
Feed costs overall	0.97	0.99	-0.22	0.79	0.81	0.13
Operating costs I	0.89	0.86	-0.23	0.99	0.37	0.12
Operating costs II	0.82	0.78	-0.22	0.95	0.30	0.10
Operating costs overall	0.89	0.85	-0.23	0.99	0.37	0.12
Ownership costs I	0.89	0.86	-0.23	1.0	0.37	0.12
Ownership costs II	-0.73	-0.69	0.21	1.0	-0.24	-0.08
Ownership costs overall	0.89	0.86	-0.23	-0.86	0.37	0.12
Breeding Costs	0.65	0.68	-0.16	0.50	0.48	0.08
Total cash rearing costs[3]	0.99		-0.23	0.86	0.75	0.13
Interest costs	0.95	0.93	-0.24	0.98	0.49	0.11
Death and abortion costs[4]	0.21	0.07	-0.08	0.18	-0.08	0.02
Total rearing costs[5]		0.99	-0.24	0.89	0.69	0.13
Monthly costs[6]	0.20	0.24		-0.27	0.66	0.03
Annual costs[7]	0.19	0.24		-0.27	0.65	0.02
Net Profit/Loss[8]	0.24	0.23		0.23	0.11	0.54

[1] All costs entered as positive values.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Includes feed, ownership, operating, and breeding costs.

[4] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[5] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[6] Total rearing costs adjusted to a monthly basis using 8% interest.

[7] Total rearing costs adjusted to an annual basis using 8% interest.

[8] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Table 40. Least squares means[1] from simulation results evaluating varying feed costs for accelerated growth Holstein heifers.

Item[2]	Increase in Feed Costs, %				
	0	5	10	15	SE
Herds, n	10	10	10	10	
Heifers, n	1000	1000	1000	1000	
Death loss, %	7.9	7.9	7.9	7.9	
Abortions, %	2.3	2.3	2.3	2.3	
ADG I, kg/d	0.91	0.91	0.91	0.91	0.002
ADG II, kg/d	0.89	0.89	0.89	0.89	0.005
ADG overall, kg/d	0.90	0.90	0.90	0.90	0.002
DMI I, kg/d	5.57	5.57	5.57	5.57	0.015
DMI II, kg/d	11.45	11.45	11.45	11.45	0.036
DMI overall, kg/d	7.87	7.87	7.87	7.87	0.017
Services	1.54	1.54	1.54	1.54	0.026
Age at conception, mo	14.1	14.1	14.1	14.1	0.073
Age at calving, mo	23.1	23.1	23.1	23.1	0.073
BW at conception, kg	431	431	431	431	1.59
Post calving BW, kg	625	625	625	625	2.64
First lactation milk yield, kg	7950	7950	7950	7950	41.83
Feed costs I	331.70	348.29	364.87	381.46	2.50*
Feed costs II	355.87	373.67	391.46	409.25	1.18*
Feed costs overall	687.58	721.95	756.33	790.71	3.56*
Operating costs I	186.82	186.82	186.82	186.82	0.43
Operating costs II	53.27	53.27	53.27	53.27	0.072
Operating costs overall	240.08	240.08	240.08	240.08	0.49
Ownership costs I	23.09	23.09	23.09	23.09	0.119
Ownership costs II	14.66	14.66	14.66	14.66	0.0001
Ownership costs overall	37.75	37.75	37.75	37.75	0.119
Breeding Costs	23.49	23.49	23.49	23.49	0.43
Total cash rearing costs[3]	988.90	1023.28	1057.66	1092.04	4.45*
Interest costs	92.25	94.50	96.76	99.01	0.65*
Death and abortion costs[4]	39.76	39.76	39.76	39.76	5.57
Total rearing costs[5]	1220.91	1257.55	1294.18	1330.81	7.49*
Monthly costs[6]	48.93	-50.39	51.86	53.32	0.232*
Annual costs[7]	606.68	624.85	643.02	661.20	2.88*
Net Profit/Loss[8]	407.15	370.52	333.89	297.25	14.56*

[*] Significant linear contrast (*P* < 0.01).

[1] Accelerated growth, 5 wk to to calving.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Includes feed, ownership, operating, and breeding costs.

[4] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[5] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[6] Total rearing costs adjusted to a monthly basis using 8% interest.

[7] Total rearing costs adjusted to an annual basis using 8% interest.

[8] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Table 41. Least squares means[1] from simulation results evaluating various heat detection rates[2] at 40, 38, and 38% conception for first, second, and third services for Holstein heifers.

	Heat Detection Efficiency, %			Contrasts *P* <	
Item[3]	40	50	60	Linear	Quadratic
Herds, n	10	10	10		
Heifers, n	1000	1000	1000		
Death loss, %	9.2	9.5	9.6		
Abortion, %	2.5	2.3	2.0		
ADG I, kg/d	0.75	0.75	0.75	0.01	NS[10]
ADG II, kg/d	0.85	0.85	0.84	NS	NS
ADG overall, kg/d	0.78	0.78	0.78	0.01	NS
DMI I, kg/d	5.91	5.72	5.63	0.01	0.01
DMI II, kg/d	10.73	10.71	10.67	NS	NS
DMI overall, kg/d	7.57	7.47	7.42	0.01	0.02
Services	2.19	2.34	2.21	NS	NS
Age at conception, mo	17.7	16.8	16.4	0.01	0.03
Age at calving, mo	26.6	25.8	25.4	0.01	0.03
BW at conception, kg	445	423	412	0.01	0.02
Post calving BW, kg	626	604	591	0.01	0.04
First lactation milk yield, kg	8083	8176	8168	NS	NS
Feed costs I	421.22	390.97	376.75	0.01	0.01
Feed costs II	332.71	331.87	330.67	NS	NS
Feed costs overall	753.93	722.84	707.42	0.01	0.02
Operating costs I	207.49	202.69	200.09	0.01	0.02
Operating costs II	56.76	55.61	54.98	0.01	0.03
Operating costs overall	264.25	258.30	255.08	0.01	0.03
Ownership costs I	28.83	27.51	26.79	0.01	0.03
Ownership costs II	14.65	14.66	14.66	0.01	0.01
Ownership costs overall	43.48	42.17	41.45	0.01	0.03
Breeding Costs	33.87	34.82	34.27	NS	NS
Total cash rearing costs[4]	1095.52	1058.12	1038.21	0.01	0.04
Interest costs	117.92	110.44	106.72	0.01	0.02
Death and abortion costs[5]	57.76	54.05	41.14	NS	NS
Total rearing costs[6]	1371.20	1322.61	1286.07	0.01	NS
Monthly costs[7]	47.12	47.01	46.57	0.06	NS
Annual costs[8]	584.01	582.75	577.38	0.06	NS
Net Profit/Loss[9]	265.64	331.52	361.31	0.01	NS

[1] Raw treatment means (n=3) for death loss and abortions.

[2] Fourth and later services were natural with 85% heat detection efficiency and conception.

[3] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[4] Includes feed, ownership, operating, and breeding costs.

[5] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[6] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[7] Total rearing costs adjusted to a monthly basis using 8% interest.

[8] Total rearing costs adjusted to an annual basis using 8% interest.

[9] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

[10] $P > 0.05$.

Table 42. Least squares means[1] from simulation results evaluating various heat detection rates[2] at 65, 62, and 62% conception for first, second, and third services for Holstein heifers.

	Heat Detection Efficiency, %			Contrasts *P* <	
Item[3]	40	50	60	Linear	Quadratic
Herds, n	10	10	10		
Heifers, n	1000	1000	1000		
Death loss, %	9.6	8.6	10.0		
Abortion, %	1.7	1.3	1.9		
ADG I, kg/d	0.75	0.74	0.74	0.02	0.02
ADG II, kg/d	0.83	0.84	0.83	NS	NS
ADG overall, kg/d	0.78	0.78	0.77	NS[10]	NS
DMI I, kg/d	5.67	5.55	5.46	0.01	NS
DMI II, kg/d	10.64	10.60	10.56	0.03	NS
DMI overall, kg/d	7.44	7.37	7.32	0.01	NS
Services	1.55	1.55	1.59	NS	NS
Age at conception, mo	16.6	16.1	15.7	0.01	NS
Age at calving, mo	25.6	25.1	24.7	0.01	NS
BW at conception, kg	420	404	396	0.01	0.09
Post calving BW, kg	597	583	572	0.01	NS
First lactation milk yield, kg	8065	8078	8052	NS	NS
Feed costs I	385.15	366.04	352.99	0.01	NS
Feed costs II	329.92	328.61	327.23	0.03	NS
Feed costs overall	715.08	694.64	680.22	0.01	NS
Operating costs I	201.49	198.23	196.02	0.01	NS
Operating costs II	55.30	54.53	53.99	0.01	NS
Operating costs overall	256.79	252.76	250.01	0.01	NS
Ownership costs I	27.17	26.27	25.65	0.01	NS
Ownership costs II	14.66	14.66	14.66	0.01	NS
Ownership costs overall	41.83	40.93	40.32	0.01	NS
Breeding Costs	23.40	23.54	23.98	NS	NS
Total cash rearing costs[4]	1037.09	1011.88	994.52	0.01	NS
Interest costs	108.13	103.31	100.11	0.01	NS
Death and abortion costs[5]	42.79	31.75	44.63	NS	0.02
Total rearing costs[6]	1288.02	1246.93	1239.27	0.01	0.02
Monthly costs[7]	46.19	45.80	46.28	NS	0.02
Annual costs[8]	572.62	567.77	573.80	NS	0.02
Net Profit/Loss[9]	358.17	402.08	402.83	0.02	NS

[1] Raw treatment means (n=3) for death loss and abortions.

[2] Fourth and later services were natural with 85% heat detection efficiency and conception.

[3] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[4] Includes feed, ownership, operating, and breeding costs.

[5] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[6] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[7] Total rearing costs adjusted to a monthly basis using 8% interest.

[8] Total rearing costs adjusted to an annual basis using 8% interest.

[9] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

[10] $P > 0.05$.

Table 43. Least squares means[1] from simulation results evaluating various heat detection rates[2] at 80, 78, and 78% conception for first, second, and third services for Holstein heifers.

	Heat Detection Efficiency, %			Contrasts $P <$	
Item[3]	40	50	60	Linear	Quadratic
Herds, n	10	10	10		
Heifers, n	1000	1000	1000		
Death loss, %	8.3	8.8	10.2		
Abortion, %	1.9	1.5	1.4		
ADG I, kg/d	0.75	0.75	0.75	NS[10]	NS
ADG II, kg/d	0.83	0.82	0.81	NS	NS
ADG overall, kg/d	0.77	0.77	0.77	0.01	NS
DMI I, kg/d	5.55	5.46	5.39	0.01	NS
DMI II, kg/d	10.60	10.53	10.45	0.01	NS
DMI overall, kg/d	7.37	7.31	7.26	0.01	NS
Services	1.24	1.26	1.28	NS	NS
Age at conception, mo	16.0	15.7	15.4	0.01	NS
Age at calving, mo	25.0	24.7	24.4	0.01	NS
BW at conception, kg	406	395	390	0.01	NS
Post calving BW, kg	581	570	560	0.01	NS
First lactation milk yield, kg	8159	8113	8135	NS	NS
Feed costs I	365.20	352.36	342.77	0.01	NS
Feed costs II	328.54	326.36	323.93	0.01	NS
Feed costs overall	693.75	678.73	666.70	0.01	NS
Operating costs I	198.00	195.85	194.12	0.01	NS
Operating costs II	54.48	53.97	53.58	0.01	NS
Operating costs overall	252.48	249.81	247.70	0.01	NS
Ownership costs I	26.20	25.60	25.12	0.01	NS
Ownership costs II	14.66	14.66	14.66	0.01	NS
Ownership costs overall	40.86	40.26	39.79	0.01	NS
Breeding Costs	18.65	18.92	19.24	NS	NS
Total cash rearing costs[4]	1005.74	987.72	973.43	0.01	NS
Interest costs	102.72	99.57	97.12	0.01	NS
Death and abortion costs[5]	42.65	34.34	46.64	NS	NS
Total rearing costs[6]	1251.11	1221.64	1217.18	0.01	NS
Monthly costs[7]	46.04	45.69	46.13	NS	NS
Annual costs[8]	570.84	566.49	571.93	NS	NS
Net Profit/Loss[9]	405.51	411.63	420.96	NS	NS

[1] Raw treatment means (n=3) for death loss and abortions.

[2] Fourth and later services were natural with 85% heat detection efficiency and conception.

[3] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[4] Includes feed, ownership, operating, and breeding costs.

[5] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[6] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[7] Total rearing costs adjusted to a monthly basis using 8% interest.

[8] Total rearing costs adjusted to an annual basis using 8% interest.

[9] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

[10] $P > 0.05$.

Table 44. Heat detection rate data[1] sorted by age at first calving.

	--------------------------- Age at First Calving, mo ---------------------------							
Item[2]	26.6	25.8	25.6	25.4	25.1	25	24.7	24.4
Herds, n	10	10	10	10	10	10	10	10
Heifers, n	1000	1000	1000	1000	1000	1000	1000	1000
Death loss, %	9.2	9.5	9.6	9.6	8.6	8.3	9.4	10.2
Abortion, %	2.5	2.3	1.7	2	1.3	1.9	1.7	1.4
ADG I, kg/d	0.75	0.75	0.75	0.75	0.74	0.75	0.745	0.75
ADG II, kg/d	0.85	0.85	0.83	0.84	0.84	0.83	0.825	0.81
ADG overall, kg/d	0.78	0.78	0.78	0.78	0.78	0.77	0.77	0.77
DMI I, kg/d	5.91	5.72	5.67	5.63	5.55	5.55	5.46	5.39
DMI II, kg/d	10.73	10.71	10.64	10.67	10.6	10.6	10.5	10.45
DMI overall, kg/d	7.57	7.47	7.44	7.42	7.37	7.37	7.315	7.26
Services	2.19	2.34	1.55	2.21	1.55	1.24	1.43	1.28
Age at conception, mo	17.7	16.8	16.6	16.4	16.1	16	15.7	15.4
BW at conception, kg	445	423	420	412	404	406	395.5	390
Post calving BW, kg	626	604	597	591	583	581	571	560
First lactation milk yield, kg	8083	8176	8065	8168	8078	8159	8082.5	8135
Feed costs I	421.22	390.97	385.15	376.75	366.04	365.2	352.68	342.77
Feed costs II	332.71	331.87	329.92	330.67	328.61	328.54	326.80	323.93
Feed costs overall	753.93	722.84	715.08	707.42	694.64	693.75	679.48	666.7
Operating costs I	207.49	202.69	201.49	200.09	198.23	198	195.94	194.12
Operating costs II	56.76	55.61	55.3	54.98	54.53	54.48	53.98	53.58
Operating costs overall	264.25	258.3	256.79	255.08	252.76	252.48	249.91	247.7
Ownership costs I	28.83	27.51	27.17	26.79	26.27	26.2	25.63	25.12
Ownership costs II	14.65	14.66	14.66	14.66	14.66	14.66	14.66	14.66
Ownership costs overall	43.48	42.17	41.83	41.45	40.93	40.86	40.29	39.79
Breeding Costs	33.87	34.82	23.4	34.27	23.54	18.65	21.45	19.24
Total cash rearing costs[3]	1095.52	1058.12	1037.09	1038.21	1011.88	1005.74	991.12	973.43
Interest costs	117.92	110.44	108.13	106.72	103.31	102.72	99.84	97.12
Death and abortion costs[4]	57.76	54.05	42.79	41.14	31.75	42.65	39.49	46.64
Total rearing costs[5]	1371.2	1322.61	1288.02	1286.07	1246.93	1251.11	-1230.46	1217.18
Monthly costs[6]	47.12	47.01	46.19	46.57	45.8	46.04	45.99	46.13
Annual costs[7]	584.01	582.75	572.62	577.38	567.77	570.84	570.15	571.93
Net Profit/Loss[8]	265.64	331.52	358.17	361.31	402.08	405.51	407.23	420.96

[1] Raw treatment means (n=3) for death loss and abortions; data includes all data from 9 combinations of heat detection and conception rate; two combinations yielded 24.7 mo age at first calving, therefore their data were averaged.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Includes feed, ownership, operating, and breeding costs.

[4] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[5] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[6] Total rearing costs adjusted to a monthly basis using 8% interest.

[7] Total rearing costs adjusted to an annual basis using 8% interest.

[8] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Table 45. Least squares means[1] from simulation results evaluating various death loss rates at birth for Holstein heifers.

	Death Loss at Birth, %			Contrasts $P <$	
Item[2]	5	10	15	Linear	Quadratic
Herds, n	10	10	10		
Heifers, n	1000	1000	1000		
Death loss, %	8.6	12.7	19.2		
Abortion, %	1.3	2.7	1.5		
ADG I, kg/d	0.74	0.75	0.75	NS[9]	NS
ADG II, kg/d	0.84	0.84	0.83	NS	NS
ADG overall, kg/d	0.78	0.78	0.77	NS	NS
DMI I, kg/d	5.55	5.55	5.54	NS	NS
DMI II, kg/d	10.60	10.62	10.59	NS	NS
DMI overall, kg/d	7.37	7.37	7.36	NS	NS
Services	1.55	1.54	1.51	NS	NS
Age at conception, mo	16.1	16.0	16.0	NS	NS
Age at calving, mo	25.1	25.0	25.0	NS	NS
BW at conception, kg	404	405	403	NS	NS
Post calving BW, kg	583	583	580	NS	NS
First lactation milk yield, kg	8078	8099	8097	NS	NS
Feed costs I	366.04	365.23	363.72	NS	NS
Feed costs II	328.61	329.27	328.12	NS	NS
Feed costs overall	694.64	694.50	691.84	NS	NS
Operating costs I	198.23	198.01	197.79	NS	NS
Operating costs II	54.53	54.50	54.45	NS	NS
Operating costs overall	252.76	252.51	252.23	NS	NS
Ownership costs I	26.27	26.21	26.15	NS	NS
Ownership costs II	14.66	14.66	14.66	NS	NS
Ownership costs overall	40.93	40.87	40.81	NS	NS
Breeding Costs	23.54	23.31	22.85	NS	NS
Total cash rearing costs[3]	1011.88	1011.19	1007.73	NS	NS
Interest costs	103.31	103.08	102.68	NS	NS
Death and abortion costs[4]	31.75	53.33	60.26	0.01	NS
Total rearing costs[5]	1246.93	1267.60	1270.67	0.02	NS
Monthly costs[6]	45.80	46.63	46.82	0.01	NS
Annual costs[7]	567.77	578.10	580.49	0.01	NS
Net Profit/Loss[8]	392.28	371.01	345.62	0.01	NS

[1] Raw treatment means (n=3) for death loss and abortions.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Includes feed, ownership, operating, and breeding costs.

[4] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[5] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[6] Total rearing costs adjusted to a monthly basis using 8% interest.

[7] Total rearing costs adjusted to an annual basis using 8% interest.

[8] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

[9] $P > 0.05$.

Table 46. Least squares means[1] from simulation results evaluating various death loss rates from birth to weaning for Holstein heifers.

	Death Loss From Birth to Weaning, %			Contrasts $P <$	
Item[2]	1	10	15	Linear	Quadratic
Herds, n	10	10	10		
Heifers, n	1000	1000	1000		
Death loss, %	8.6	16.1	18.5		
Abortion, %	1.3	1.7	2.1		
ADG I, kg/d	0.74	0.74	0.75	NS[9]	NS
ADG II, kg/d	0.84	0.82	0.83	NS	NS
ADG overall, kg/d	0.78	0.77	0.78	NS	NS
DMI I, kg/d	5.55	5.53	5.54	NS	NS
DMI II, kg/d	10.60	10.52	10.59	NS	NS
DMI overall, kg/d	7.37	7.34	7.36	NS	NS
Services	1.55	1.52	1.56	NS	NS
Age at conception, mo	16.1	16.0	16.0	NS	NS
Age at calving, mo	25.1	25.0	25.0	NS	NS
BW at conception, kg	404	403	404	NS	NS
Post calving BW, kg	583	577	581	NS	NS
First lactation milk yield, kg	8078	8121	8124	NS	NS
Feed costs I	366.04	363.54	364.11	NS	NS
Feed costs II	328.61	326.00	328.25	NS	NS
Feed costs overall	694.64	689.54	692.36	NS	NS
Operating costs I	198.23	197.77	197.86	NS	NS
Operating costs II	54.53	54.43	54.46	NS	NS
Operating costs overall	252.76	252.20	252.32	NS	NS
Ownership costs I	26.27	26.14	26.17	NS	NS
Ownership costs II	14.66	14.66	14.66	NS	NS
Ownership costs overall	40.93	40.80	40.83	NS	NS
Breeding Costs	23.54	22.91	22.69	NS	NS
Total cash rearing costs[3]	1011.88	1005.45	1009.20	NS	NS
Interest costs	103.31	102.60	102.83	NS	NS
Death and abortion costs[4]	31.75	55.61	66.54	0.01	NS
Total rearing costs[5]	1246.93	1263.66	1278.57	0.01	NS
Monthly costs[6]	45.80	46.57	47.09	0.01	NS
Annual costs[7]	567.77	577.41	583.81	0.01	NS
Net Profit/Loss[8]	389.10	372.40	354.35	0.08	NS

[1] Raw treatment means (n=3) for death loss and abortions.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Includes feed, ownership, operating, and breeding costs.

[4] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[5] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[6] Total rearing costs adjusted to a monthly basis using 8% interest.

[7] Total rearing costs adjusted to an annual basis using 8% interest.

[8] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

[9] $P > 0.05$.

Table 47. Least squares means[1] from simulation results evaluating various abortion rates for Holstein heifers.

	Abortions, %			Contrasts $P <$	
Item[2]	1	5	10	Linear	Quadratic
Herds, n	10	10	10		
Heifers, n	1000	1000	1000		
Death loss, %	8.6	7.7	9.4		
Abortion, %	1.3	4.5	9.7		
ADG I, kg/d	0.74	0.75	0.75	NS[9]	NS
ADG II, kg/d	0.84	0.84	0.83	NS	NS
ADG overall, kg/d	0.78	0.78	0.78	NS	NS
DMI I, kg/d	5.55	5.57	5.54	NS	NS
DMI II, kg/d	10.60	10.63	10.57	NS	NS
DMI overall, kg/d	7.37	7.39	7.35	NS	NS
Services	1.55	1.59	1.51	NS	NS
Age at conception, mo	16.1	16.2	16.0	NS	NS
Age at calving, mo	25.1	25.1	25.0	NS	NS
BW at conception, kg	404	407	404	NS	NS
Post calving BW, kg	583	586	581	NS	NS
First lactation milk yield, kg	8078	8140	8078	NS	NS
Feed costs I	366.04	369.10	364.37	NS	NS
Feed costs II	328.61	329.44	327.47	NS	NS
Feed costs overall	694.64	698.54	691.84	NS	NS
Operating costs I	198.23	198.67	197.99	NS	NS
Operating costs II	54.53	54.65	54.48	NS	NS
Operating costs overall	252.76	253.32	252.47	NS	NS
Ownership costs I	26.27	26.39	26.20	NS	NS
Ownership costs II	14.66	14.66	14.66	NS	NS
Ownership costs overall	40.93	40.05	40.86	NS	NS
Breeding Costs	23.54	24.04	-22.78	NS	NS
Total cash rearing costs[3]	1011.88	1016.96	1007.95	NS	NS
Interest costs	103.31	104.09	102.83	NS	NS
Death and abortion costs[4]	31.75	61.27	118.30	0.01	NS
Total rearing costs[5]	1246.93	1282.31	1329.08	0.01	NS
Monthly costs[6]	45.80	46.94	48.92	0.01	NS
Annual costs[7]	567.77	581.94	606.48	0.01	NS
Net Profit/Loss[8]	385.64	361.89	317.98	0.01	NS

[1] Raw treatment means (n=3) for death loss and abortions.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Includes feed, ownership, operating, and breeding costs.

[4] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[5] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[6] Total rearing costs adjusted to a monthly basis using 8% interest.

[7] Total rearing costs adjusted to an annual basis using 8% interest.

[8] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

[9] $P > 0.05$.

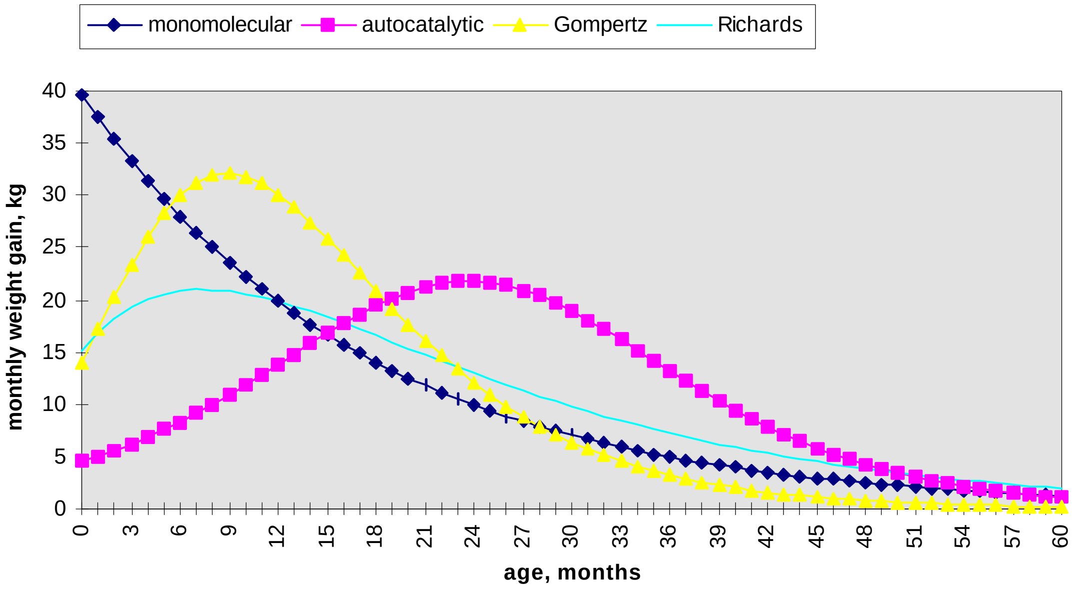
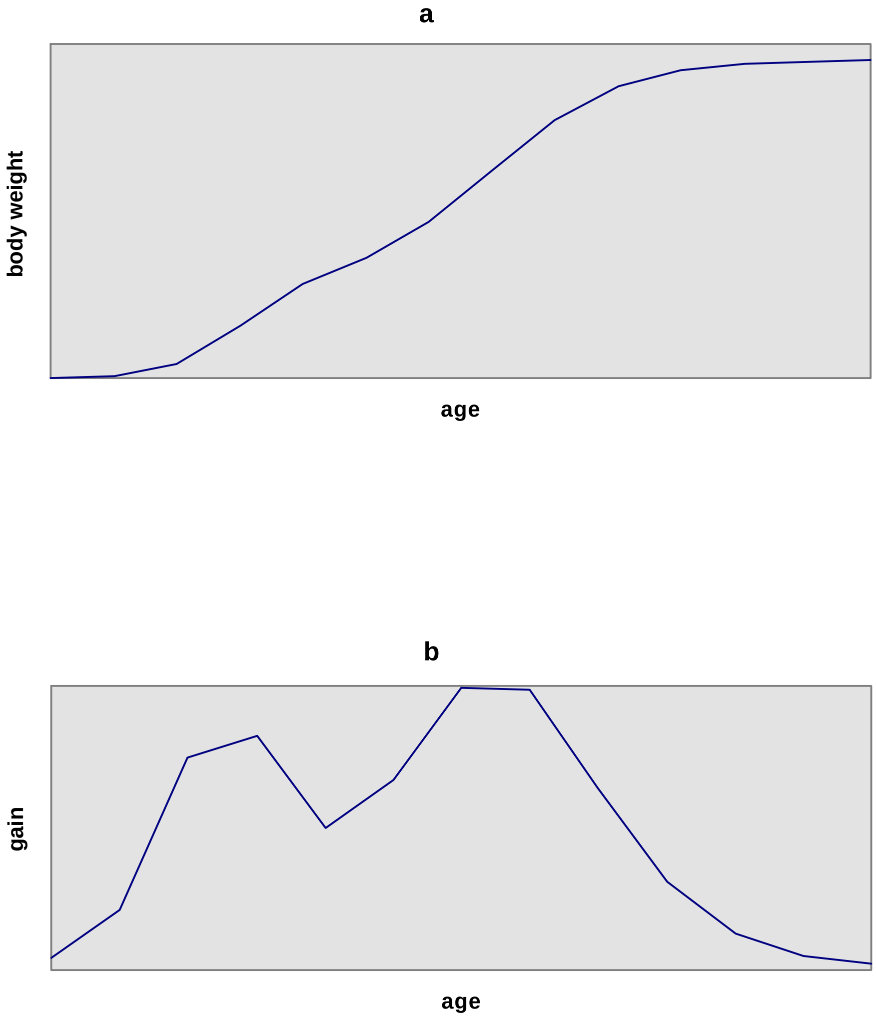


Figure 1. Growth Rates corresponding to the monomolecular, autocatalytic (logistic), Richards, and Gompertz functions.



Figures 2a, 2b. Multiphasic growth (a) and gain (b) curve.

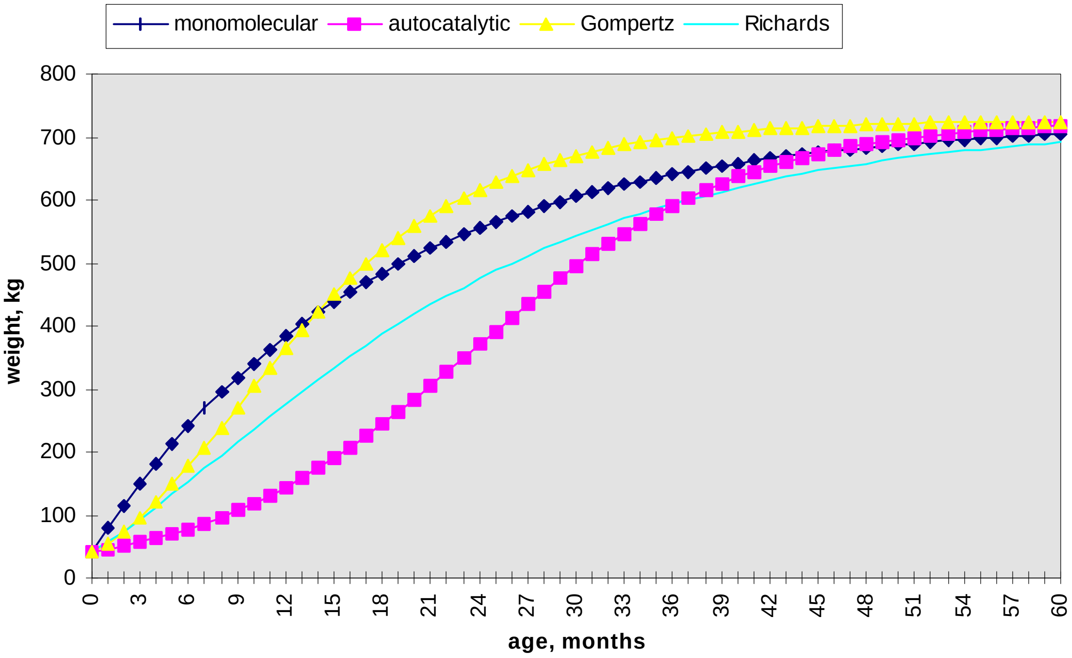


Figure 3. The monomolecular, autocatalytic (logistic), Gompertz, and Richards functions.

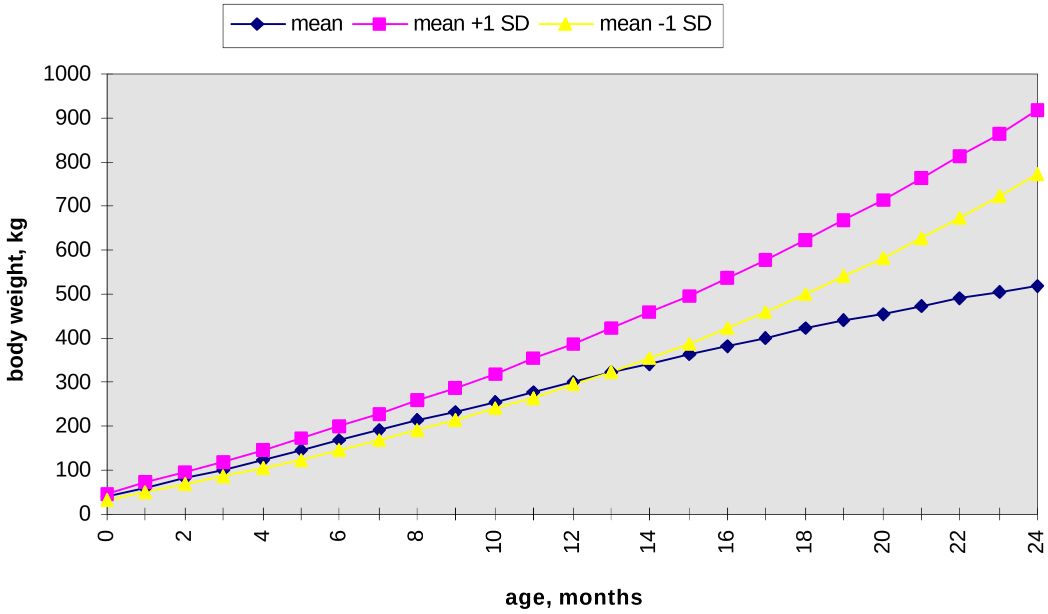
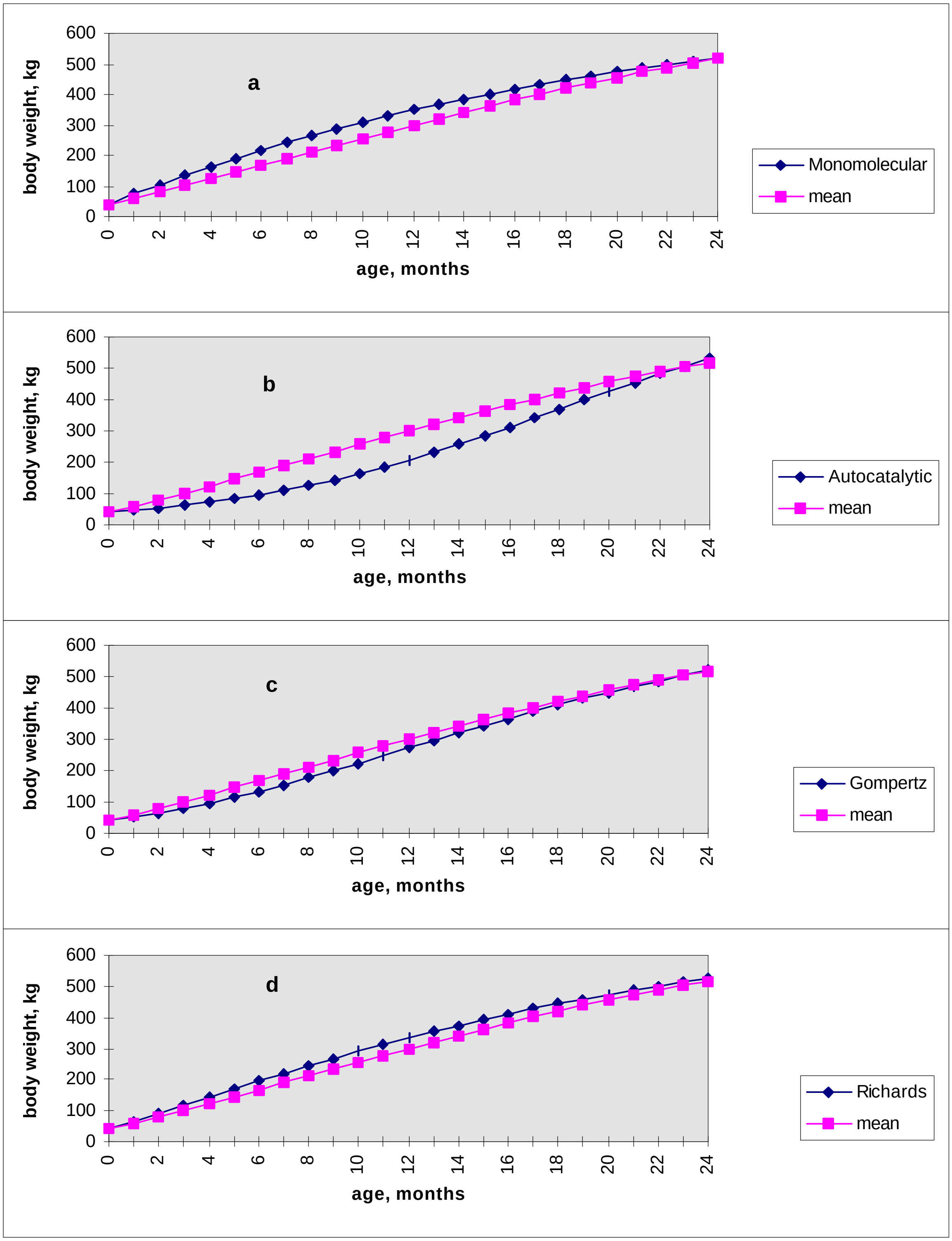


Figure 4. Growth curves described by Heinrichs and Hargrove (1987) from 163 commercial Holstein herds in Pennsylvania.



Figures 5a, 5b, 5c, and 5d. Monomolecular (a), autocatalytic or logistic (b), Gompertz (c), and Richards (d) functions and their relation to mean equation of Heinrichs and Hargrove (1987).

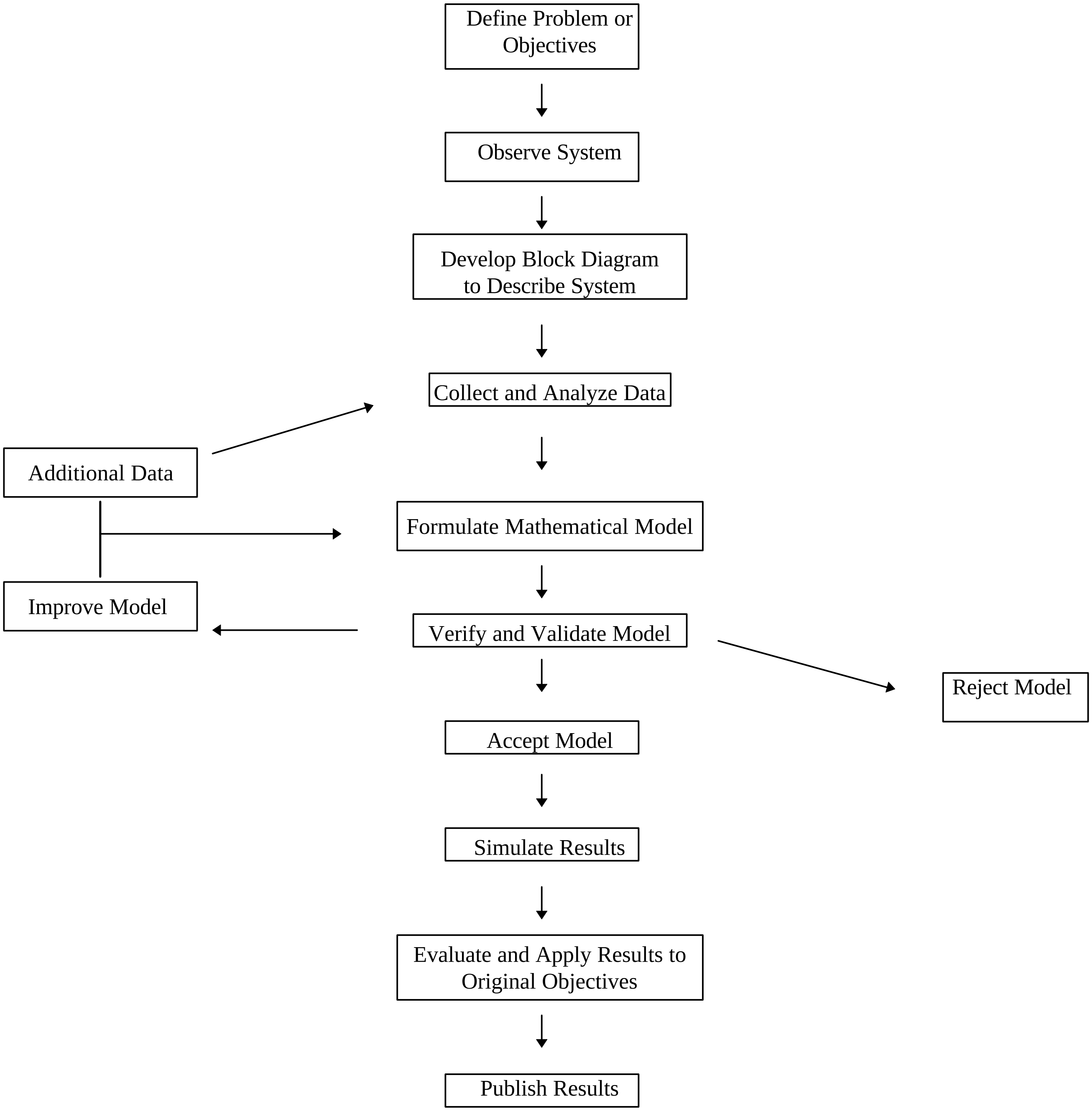


Figure 6. Steps in modeling process (Brown et al., 1981)

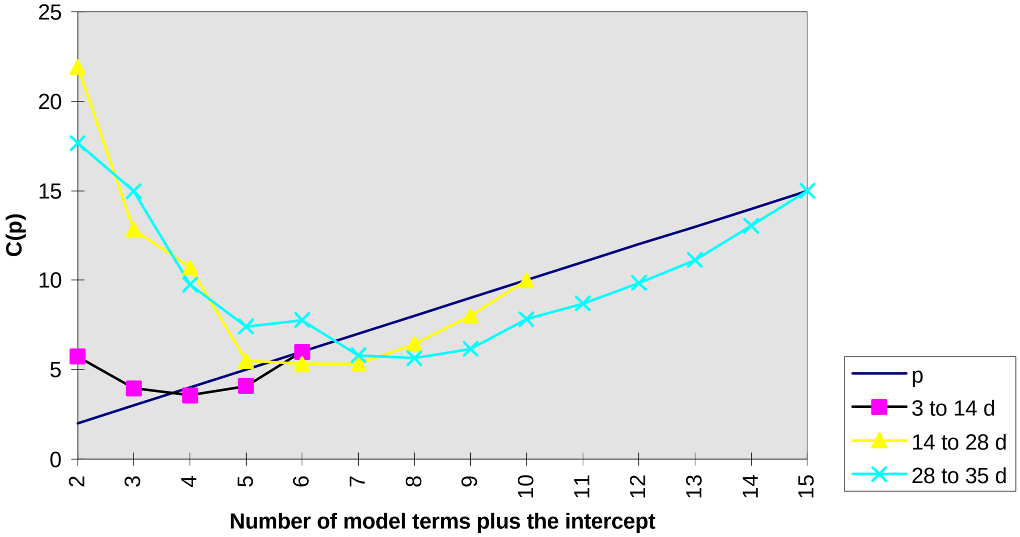


Figure 7. C(p) against *p* plots for equations predicting starter DMI for 3 to 14, 14 to 28, and 28 to 35 d old Holstein heifers.

Linear line represents where C(p)=p.

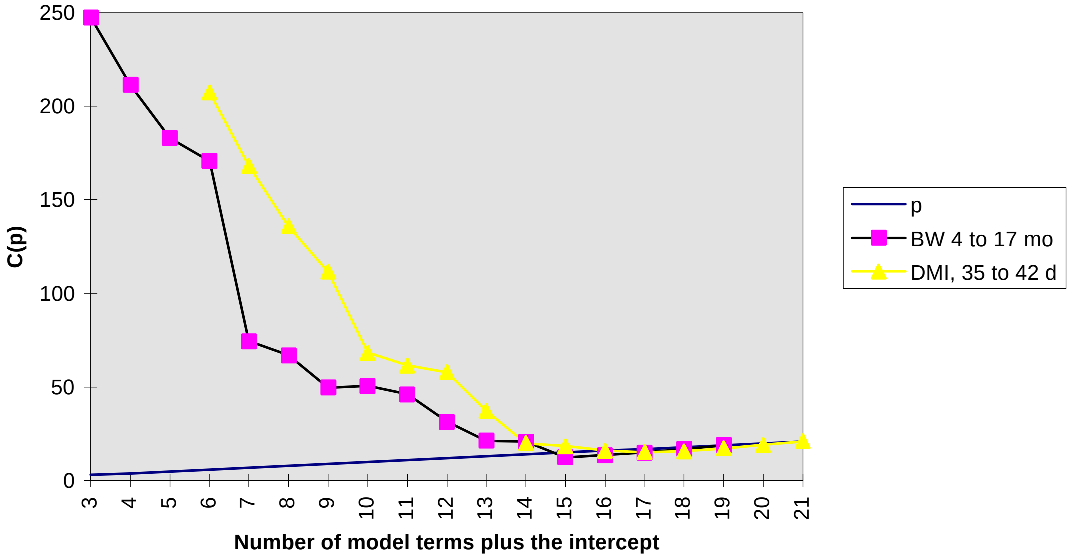


Figure 8. C(p) against *p* plots for equations predicting starter DMI for 35 to 42 d old Holstein heifers and BW for 4 to 17 mo old heifers.

Linear line represents where C(p)=p.

.

```
                      Histogram                          #
490+*                                                    2
   .*                                                    2
450+**                                                   8
   .****                                                15
410+*********                                           34
   .*************                                       49
370+*******************                                 76
   .*******************************                    124
330+************************************               144
   .*************************************              146
290+**************************************             152
   .*****************************************          161
250+***************************************            156
   .***********************************************    187
210+************************************************   189
   .*****************************************          162
170+************************************               141
   .*************************                           97
130+************                                        48
   .***                                                 11
 90+*                                                    2
    ----+----+----+----+----+----+----+----+----+---
    * may represent up to 4 counts
```

Figure 9. Histogram for BW (kg) of Holstein heifers from 4 to 17 mo of age.

```
    BW, kg             Normal Probability Plot
      490+                                                 *
         |                                                 *
      450+                                                 *
         |                                              ***
      410+                                           ****
         |                                        ***+
      370+                                     ****
         |                                  ****
      330+                               ****
         |                             ***+
      290+                           ***
         |                         ***
      250+                      ****
         |                   +***
      210+                +****
         |              ****
      170+          *****
         |      *****
      130+ ******++
         |*  +++
       90+*+++
         +----+----+----+----+----+----+----+----+----+----+
             -2        -1         0        +1        +2
                                SD Units
```

Figure 10. Normal probability plot for BW (kg) of Holstein heifers from 4 to 17 mo of age.

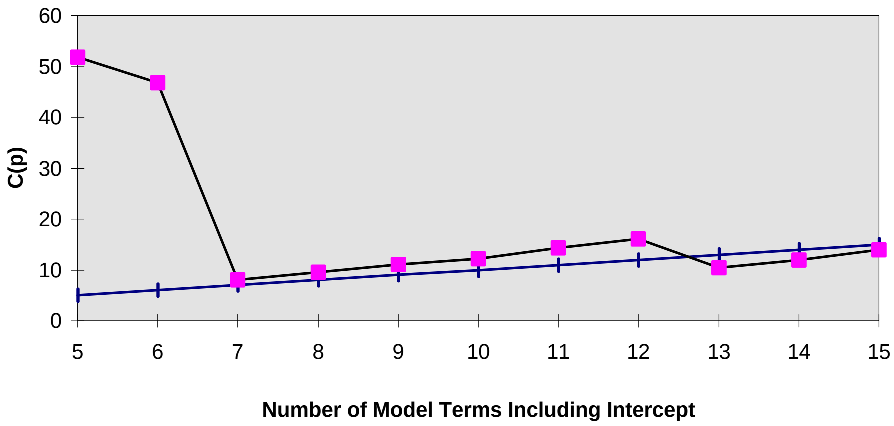


Figure 11. C(p) against *p* plot for equations predicting BW of 16 to 28 month old Holstein heifers. Linear line represents where C(p)=p.

```
Histogram                                        #
      770+*                                              1
         .*                                              2
         .*                                              3
         .***                                           12
         .********                                      29
         .**************                                53
         .**********************                        88
      630+****************************                 111
         .***********************************          137
         .************************************         143
         .**************************************       151
         .******************************************   166
         .************************************         144
         .***************************************      155
      490+************************************         143
         .*****************************                116
         .***************************                  106
         .********************                          79
         .**********                                    37
         .****                                          15
         .*                                              3
      350+*                                              1
          ----+----+----+----+----+----+----+----+--
        •  may represent up to 4 counts
```

Figure 12. Histogram for BW (kg) observations for 16 to 28 month old Holstein heifers.

```
BW, kg              Normal Probability Plot
 770+                                                  *
    |                                                  *
    |                                                 +*
    |                                               +***
    |                                            *****
    |                                         ****
    |                                     *****
 630+                                  ****
    |                                ***+
    |                             ***+
    |                           ***
    |                        ****
    |                      ***
    |                   +***
 490+                 ****
    |              ****
    |           ****
    |       *****
    |  ******
    |***+++
    |*++
 350+*
     +----+----+----+----+----+----+----+----+----+----+
         -2        -1         0        +1        +2
                            SD Units
```

Figure 13. Normal probability plot for BW (kg) observations for 16 to 28 month old Holstein heifers.

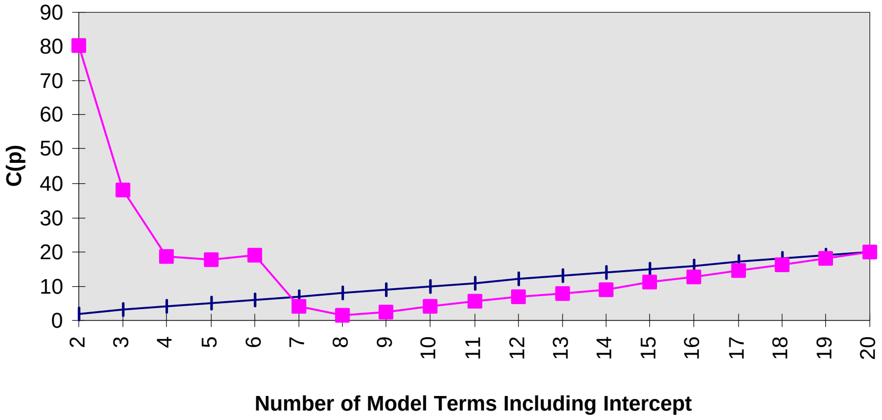


Figure 14. C(p) against *p* plot for equations predicting DMI of 16 to 28 month old Holstein heifers. Linear line represents where C(p)=p.

```
                   Histogram                        #
21.5+*                                                1
    .*                                                1
    .*                                                3
    .*                                                8
    .*                                                9
    .**                                              14
    .*****                                           37
    .**********                                      88
    .****************                               139
12.5+*********************************              291
    .********************************************   392
    .**************************************         337
    .**********************                         193
    .********                                        71
    .*****                                           39
    .**                                              12
    .*                                                3
    .*                                                2
 3.5+*                                                1
     ----+----+----+----+----+----+----+----+----
     * may represent up to 9 counts
```

Figure 15. Histogram for DMI (kg) observations for 16 to 28 month old Holstein heifers.

```
BW, kg           Normal Probability Plot
21.5+                                                  *
    |                                                  *
    |                                                  *
    |                                                 **
    |                                               ***
    |                                             ***+++
    |                                          ****++
    |                                      *****
    |                                 +*****
12.5+                            +******
    |                       *******
    |                *******
    |           ******+
    |       *****+
    |  ******
    |***
    |*
    |*
 3.5+*
     +----+----+----+----+----+----+----+----+----+----+
         -2        -1         0        +1        +2
```

Figure 16. Normal probability plot for DMI (kg) observations for 16 to 28 month old Holstein heifers.

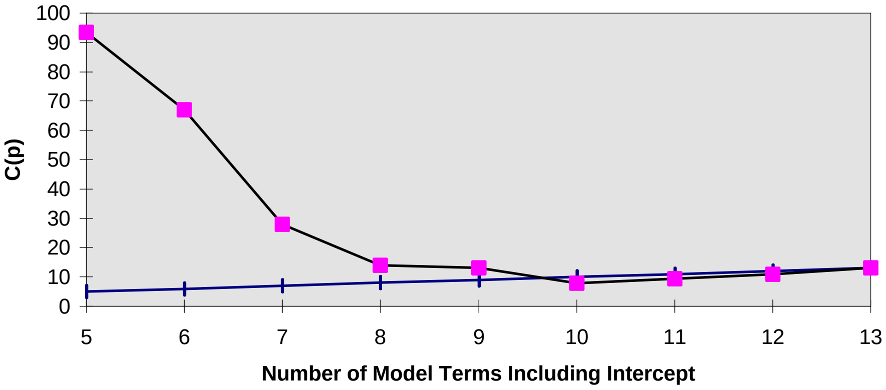


Figure 17. C(p) against *p* plot for equations predicting 305 d first lactation milk yield for Holstein cows. Linear line represents where C(p)=p.

```
                        Histogram                           #
13750+*                                                     1
     .*                                                     3
     .*                                                     2
     .*                                                    20
     .*                                                    66
     .**                                                  164
     .***                                                 336
     .*****                                               755
     .**********                                         1444
     .*****************                                  2611
     .***************************                        4152
     .*************************************              5670
     .**********************************************     7052
     .************************************************   7354
     .***********************************************    7121
     .*************************************              5580
     .***************************                        4118
     .****************                                   2409
     .*********                                          1324
 4250+****                                                563
      ----+----+----+----+----+----+----+----+----+---
      * may represent up to 154 counts
```

Figure 18. Histogram for first lactation 305 day milk yield (kg) observations.

```
Milk Yield, kg           Normal Probability Plot
    13750+                                                  *
         |                                                  *
         |                                                  *
         |                                                  *
         |                                                  *
         |                                                  *
         |                                                ***
         |                                            *****
         |                                         ****+
         |                                     *****
         |                                  ****
         |                              *****
         |                           ****
         |                       *****
         |                   *****
         |               *****
         |           *****
         |       *****
         |  ******
     4250+***+
          +----+----+----+----+----+----+----+----+----+----+
              -2        -1         0        +1        +2
                                 SD Units
```

Figure 19. Normal probability plot for first lactation 305 day milk yield (kg) observations.

```
                         Histogram                        #
9500+*                                                   18
    .**                                                 220
    .*                                                   83
    .******                                             753
    .****                                               510
    .************                                      1549
    .***************                                   1869
    .***************************                       3553
    .*******************************                   4031
    .******************************************        5530
    .************************************************  6311
    .*************************************             4757
    .*********************************************     5913
    .******************************                    3899
    .*******************************                   4083
    .*********************                             2726
    .***************                                   1924
    .*********                                         1161
    .*****                                              629
    .*****                                              593
    .***                                                370
    .**                                                 177
    .*                                                   39
4900+*                                                   47
     ----+----+----+----+----+----+----+----+----+---
     * may represent up to 132 counts
```

Figure 20. Histogram for herd average first lactation 305 day milk yield (kg) observations.

```
Milk yield, kg          Normal Probability Plot
    9500+                                                  *
        |                                                  *
        |                                                 +*
        |                                             ******
        |                                           +**
        |                                        *****
        |                                      ***
        |                                   ****
        |                                ****
        |                             ****
        |                         *****
        |                       ***+
        |                    ****
        |                  ***
        |               ****
        |            ****
        |         ****
        |       ***
        |    +***
        | ++***
        |****
        |*
        |*
    4900+*
         +----+----+----+----+----+----+----+----+----+----+
             -2        -1         0        +1        +2
                            SD Units
```

Figure 21. Normal probability plot for herd average first lactation 305 day milk yield (kg).

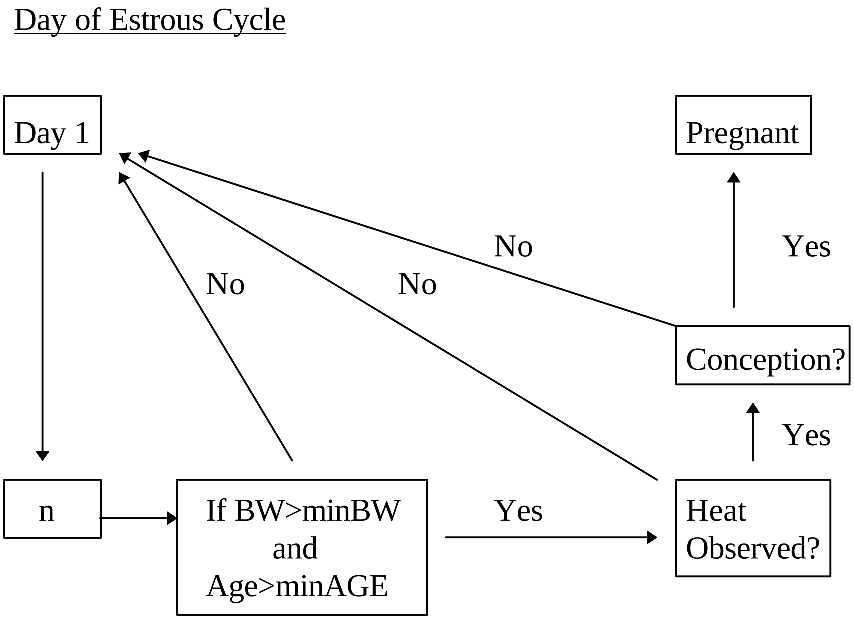


Figure 22. Events leading to conception of a heifer in the simulation.

Where minBW = minimum BW for breeding, minAGE = minimum age for breeding, and n = estrous cycle length.

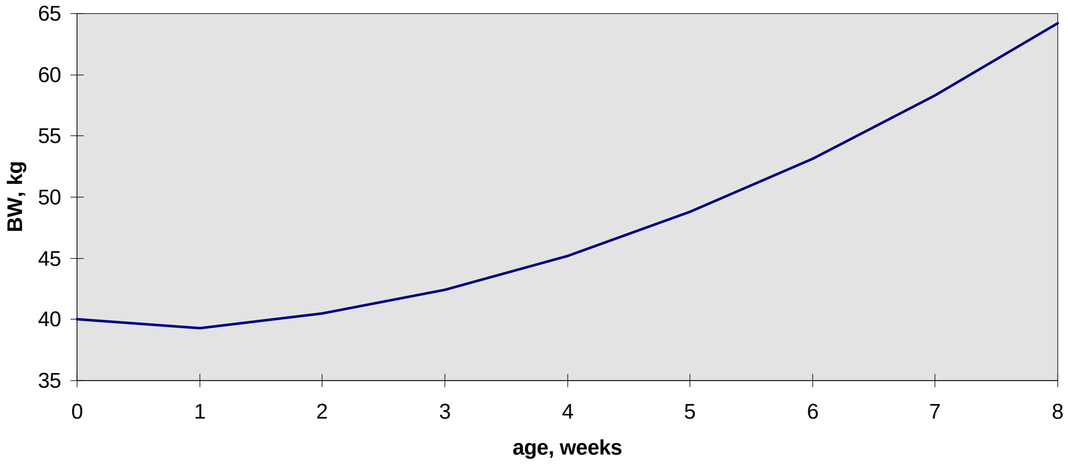


Figure 23. Body weight prediction equation for Holstein heifers from 0 to 42 days of age.

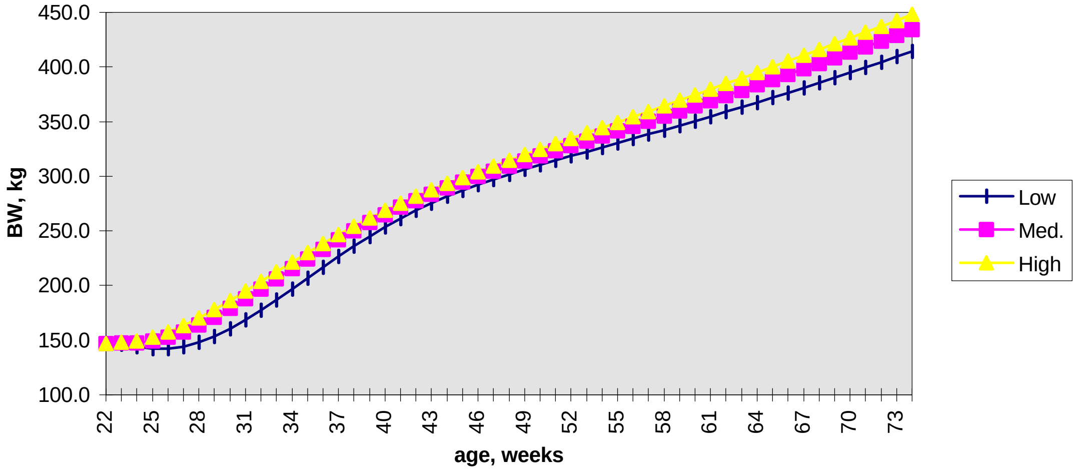


Figure 24. Body weight prediction for 5 to 17 month old Holstein heifers.

High (68% TDN, 28% ADF), medium (64% TDN, 30% ADF), and low (60% TDN, 32% ADF) energy diets where BW at 22 weeks = 147 kg and DMI predicted by equation of Quigley et al., 1986.

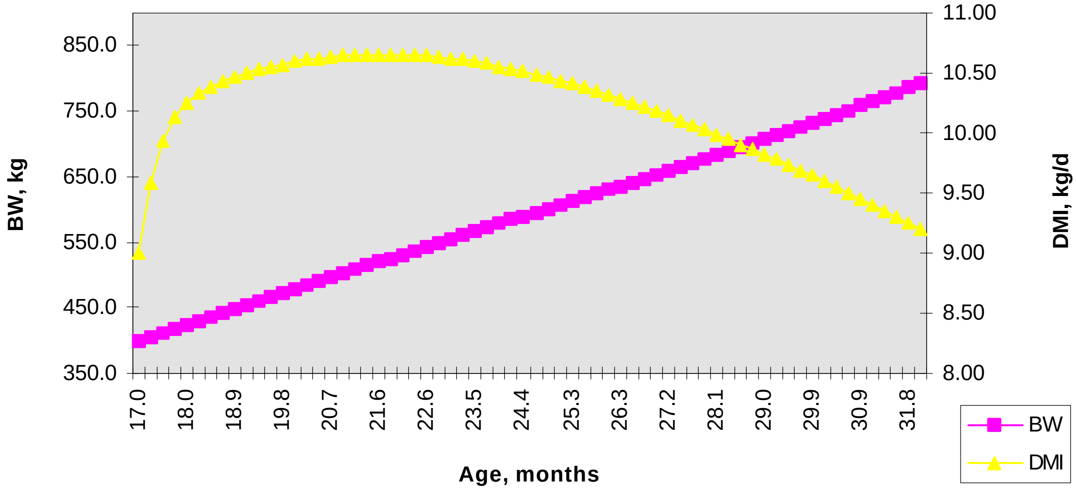


Figure 25. Body weight and DMI for Holstein heifers from 17 to 32 months of age.

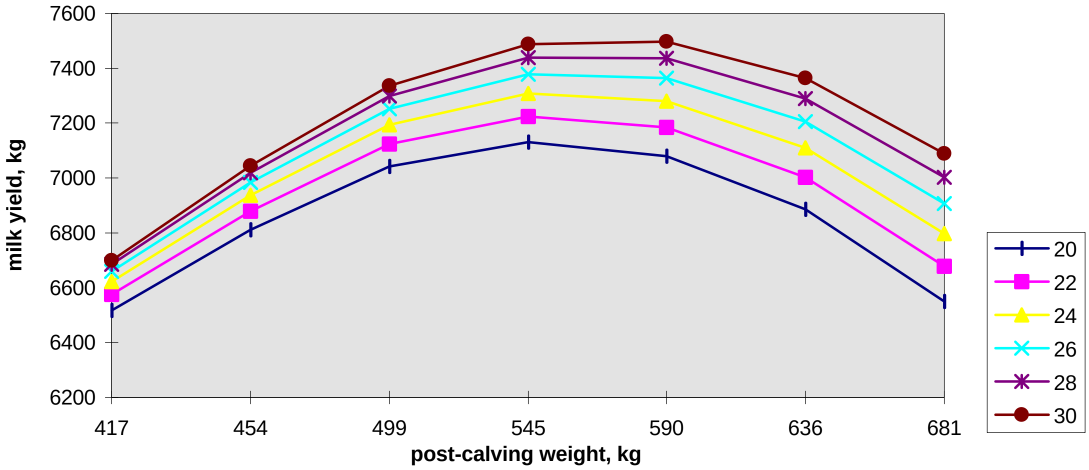


Figure 26. Prediction of first lactation milk yield for Holstein heifers at varied BW for 20, 22, 24, 26, 28, and 30 month age at first calving.

Milk yield (305 d) and BW of third and later lactation animals equal to 8329 kg and 642 kg, respectively.

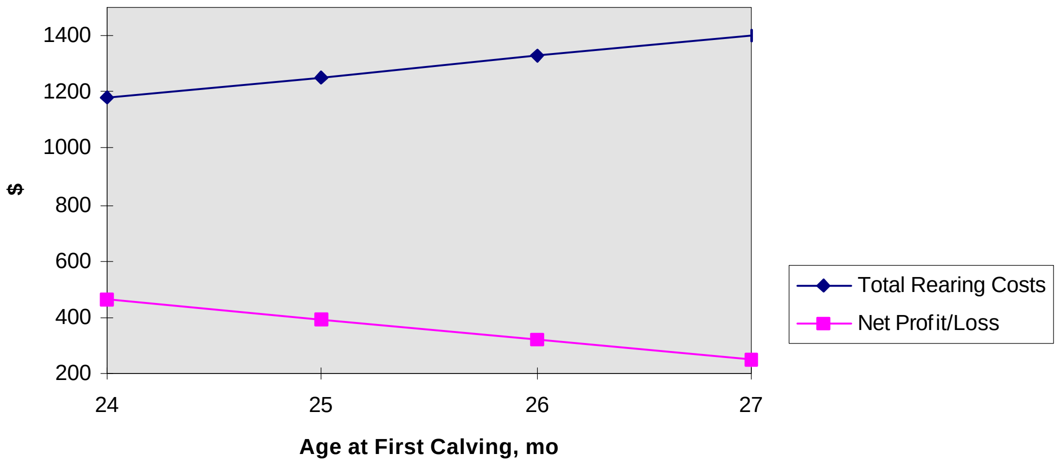


Figure 27. Relationship between age at first calving and total rearing costs ($R^2 = 0.97$) and net profit/loss ($R^2 = 0.95$).

CONCLUSIONS

The replacement enterprise is dynamic, with many variables influencing total cost and profitability. Hence, analyzing economics of the replacement enterprise is not easy, and requires more than a simple calculator, pencil, and paper. The goal of this research was to develop a dynamic simulation of the heifer enterprise that represents real life to a reasonable extent. This goal was achieved, as the simulation provided solutions that appear to mimic real life. The research conducted with the simulation is only a small portion of the possible research that can be accomplished with this research tool.

The equations developed to predict BW, DMI, and first lactation milk yield for use in the simulation were empirical and not mechanistic, thus they may not represent biological processes. Future modeling of dairy heifer growth may delve into mechanistic models of biological growth. The equations developed, however, accounted for most of the variation in the data sets, and accurately predicted DMI and BW of growing dairy heifers. A weakness of these models was that all heifers in the data sets were confinement-reared, therefore it was impossible to evaluate pasture or dry lot housing (loafing lots or the similar) as management alternatives. Empirical growth models for pasture-reared heifers are scarce because of the lack of data. Mechanistic models may be the only available approach to analyzing pasture systems for dairy heifers.

The equation to predict first lactation milk yield produced results similar to previous researchers (Keown and Everett, 1986). Reduced calving age diminished milk yield slightly, but the effects were minimal provided BW was adequate (545-590 kg). The primary weakness of the equation was that BW measurements were producer estimates, not scale weights. A large data set with actual BW is needed to determine precisely the relationship between post-calving BW and first lactation milk yield. However, producer estimates were assumed to be ranked appropriately, providing a valid equation. It is clear that BW influences first lactation milk yield, thus producers should strive to achieve adequate but not excessive calving BW. In addition, heifers with adequate BW at calving may enter second lactation with better condition and more BW, possibly avoiding a “sophomore slump” during second lactation. Hoffman (1997) discussed the difficulties of using BW as criteria for heifer size at calving, suggesting that some combination of body length, hip height, wither height, BW, and body condition score may be more appropriate. Future modeling of size and first lactation milk yield relationships should consider these variables.

The results of the growth rate analysis suggest that modest growth rates (0.75 to 0.80 kg/d) with reduced age at first calving (<24 mo) are most profitable. The Control:ACC (23.1 mo age at first calving, 0.78 kg/d BW gain from birth to calving) and Slow:ACC (23.1 mo age at first calving, 0.80 kg/d BW gain from birth to calving) treatments had the lowest total rearing costs and highest net profit at calving. This suggests that slow or average growth rates prior to breeding accompanied by accelerated growth during gestation are least costly. Accelerated pre-pubertal growth rates (>0.90 kg/d) are risky, as mammary development may be compromised (Foldager and Sejrsen, 1982; Sejrsen et al, 1982; Sejrsen and Purup, 1997; Swanson, 1960). Heifers that calve with excessive BW (>635 kg) or are over-conditioned may be predisposed to postpartum metabolic disorders (Grummer, 1995). In addition, accelerated growth rates are not needed to achieve desired post-calving BW in 22 to 24 mo. Although most producers do not achieve these goals (1996 DHIA average in Virginia: 28 mo age at first calving) with their replacement program, it is possible provided heifers are managed intensively. Intensive management includes monitoring growth rates and testing feeds to adequately formulate and deliver rations to achieve desired growth rates.

Analysis of the impact of death loss, abortion rate, and heat detection efficiency reveal that they comprise a modest but significant portion of total rearing costs. Managers that control these variables will substantially reduce heifer rearing costs. The combination of high death loss and abortion rate and poor heat detection can increase rearing costs up to $200 per heifer. Among these items, abortion rate has the largest impact on total rearing costs.

This research did not reveal any new or innovative approaches to raising dairy replacements. Rather, it reinforced previous recommendations for early calving and modest growth rates. It also identified specific costs of poor heat detection, death loss, and abortion rate. These marginal costs can be used as a decision aid for evaluating new or existing technologies that may reduce death loss and abortions or improve heat detection efficiency.

Dairy producers today that survive and prosper into the future will be those that reduce the cost of producing milk. The international marketplace may be a significant avenue of expanding the United States milk market beyond it’s current state. Domestic markets may increase, but the growth will likely be slow. The current United States milk price is not competitive on the global market without subsidies; therefore, United States dairy producers must continually improve efficiency and reduce costs to develop foreign markets for dairy products. Aside from adopting new technologies and controlling costs and improving production of the milking herd, the replacement enterprise offers a means to reduce costs of producing milk. Traditionally, the replacement enterprise has not been targeted for improvement or cost reduction, as many of the replacement costs are hidden, i.e. they do not have an immediate cash impact or are buried in the cow costs. Dairy producers that manage the replacement enterprise as an enterprise and not a sunk cost will better position themselves to profit in the future marketplace.

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APPENDIX

Appendix Table A. Models[1] selected by backward and forward Stepwise regression analysis for BW prediction of pre-weaned Holstein heifers.

	Backward		Forward	
Variable	parameter estimate	*P*	parameter estimate	*P*
Intercept	40.17183	0.0001	40.00418	0.0001
AGE, days				
AGE^2	0.00798	0.0001	0.00865	0.0001
AGE^3				
AGE^4				
AGE^5			-0.00000001	0.4773
p	2		3	
C(p)	-0.951		0.546	
R-squared	0.535		0.536	
Adjusted R-squared	0.534		0.533	

[1] Full model = AGE + AGE^2 + AGE^3 + AGE^4 + AGE^5.

Appendix Table B. The best one, two, and three variable models[1] selected by MAXR Stepwise regression analysis for BW prediction of pre-weaned Holstein heifers.

Variable	One Variable Model parameter estimate	One Variable Model *P*	Two Variable Model parameter estimate	Two Variable Model *P*	Three Variable Model parameter estimate	Three Variable Model *P*
Intercept	40.17182	0.0001	40.00418	0.0001	40.190354	0.0001
AGE, days					-0.105556	0.6209
AGE^2	0.00798	0.0001	0.00865	0.0001	0.014663	0.1689
AGE^3					-0.000097	0.4813
AGE^4						
AGE^5			-0.00000001	0.4773		
p	2		3		4	
C(p)	-0.952		0.546		2.36	
R-squared	0.535		0.536		0.536	
Adjusted R-squared	0.534		0.533		0.532	

[1] Full model = AGE + AGE^2 + AGE^3 + AGE^4 + AGE^5.

Appendix Table C. The best four and five variable models[1] selected by MAXR Stepwise regression analysis for BW prediction of pre-weaned Holstein heifers.

	Four Variable Model		Five Variable Model	
Variable	parameter estimate	*P*	parameter estimate	*P*
Intercept	40.24579	0.0001	40.38524	0.0001
AGE, days	-0.17810	0.6531	-0.46418	0.4734
AGE^2	0.02222	0.5413	0.07137	0.4531
AGE^3	-0.00034	0.7624	-0.00310	0.5402
AGE^4	0.000002	0.8278	0.000065	0.5632
AGE^5			-0.0000005	0.5759
p	5		6	
C(p)	4.314		6.000	
R-squared	0.536		0.537	
Adjusted R-squared	0.530		0.529	

[1] Full model = AGE + AGE^2 + AGE^3 + AGE^4 + AGE^5.

Appendix Table D. Mean square error, root mean square error, and R-squared from model BW = CALF + AGE[2] for various ages of pre-weaned Holstein heifers[1].

Age Range	Mean Square Error	Root Mean Square Error	Model R-squared
Birth to 14 d	4.1078	2.0268	0.935
14 d to 28 d	3.4746	1.8640	0.965
28 d to 42 d	3.5643	1.8879	0.977

[1] Data from Ziegler et al., 1996

Appendix Table E. Within-heifer estimates of daily starter DMI variation for a given week.

Equation	Within-heifer variation, or root MSE
DMI from 3 to 14d:	0.07327
DMI from 14 to 28d:	0.10301
DMI from 28 to 35d:	0.20714
DMI from 35 to 42d:	0.05009

Appendix Table F. Root mean square error and R-squared from various models[1] predicting BW for 5 to 17 mo old Holstein heifers.

	Model A		Model B		Model C	
Age Range, mo	Root Mean Square Error	Model R-squared	Root Mean Square Error	Model R-squared	Root Mean Square Error	Model R-squared
<6	12.86	0.75	9.98	0.90	9.55	0.87
6 to 7	7.83	0.87	4.26	0.98	4.88	0.98
7 to 8	9.32	0.92	7.43	0.96	7.30	0.98
8 to 9	17.77	0.83	5.76	0.98	5.99	0.99
9 to 10	23.79	0.72	6.28	0.99	6.29	0.99
10 to 11	24.08	0.68	12.34	0.95	12.21	0.95
11 to 12	19.22	0.81	5.12	0.99	5.10	0.99
12 to 13	21.43	0.81	4.94	0.99	4.96	0.99
13 to 14	19.03	0.85	7.69	0.99	7.79	0.99
14 to 15	10.46	0.94	5.34	0.99	5.72	0.99
15 to 16	29.24	0.79	5.15	0.99	5.10	0.99
> 16	8.02	0.99	4.15	0.99	3.95	0.99

[1] Model A: BW = PBW + PDMI + AGEW + PBW^2 + $PBW75^2$ + $PDMI^2$ + $AGEW^2$ + $PADFI^2$ + PBW*PDMI + PBW*AGEW + PDMI*AGEW + AGEW*PADFI + PBW75*PDMI + PBW75*AGEW; Model B: BW = HEIFER + AGEW + PBW; Model C: BW = HEIFER + AGEW; where PBW = previous BW, kg; PBW75 = $PBW^{.75}$, kg; PDMI = previous DMI, kg/d; PADFI = previous ADF intake, kg/d; AGEW = age in weeks.

Appendix Table G. Root mean square error and R-squared from various models[1] predicting BW for 4 to 17 mo old Holstein heifers from one data set (Bethard et al., 1995).

	Model A		Model B	
Age Range, mo	Root Mean Square Error	Model R-squared	Root Mean Square Error	Model R-squared
< 6	7.65	0.87	7.19	0.85
6 to 7	3.87	0.97	3.75	0.97
7 to 8	7.32	0.87	7.22	0.87
8 to 9	6.28	0.93	6.27	0.93
9 to 10	4.62	0.97	4.59	0.97
10 to 11	4.94	0.97	4.92	0.97
11 to 12	4.60	0.98	4.57	0.98
12 to 13	4.70	0.98	4.69	0.98
13 to 14	7.77	0.96	7.90	0.96
14 to 15	5.36	0.99	5.79	0.98
15 to 16	5.19	0.99	5.21	0.99
> 16	4.15	0.99	3.95	0.99

[1] Model A: BW = HEIFER + AGEW + PBW; Model B: BW = HEIFER + AGEW; where PBW = previous BW, kg; AGEW = age in weeks.

Appendix Table H. Root mean square error and R-squared for DMI for various ages of Holstein heifers from one data set (Bethard et al., 1995) using various models[1].

	Model A		Model B	
Age Range, mo	Root Mean Square Error	Model R-squared	Root Mean Square Error	Model R-squared
< 6	0.959	0.70	1.008	.65
6 to 7	0.511	0.89	0.548	0.87
7 to 8	0.778	0.77	0.774	0.77
8 to 9	0.693	0.80	0.700	0.79
9 to 10	0.614	0.82	0.616	0.82
10 to 11	0.854	0.68	0.855	0.68
11 to 12	0.927	0.68	0.926	0.68
12 to 13	0.978	0.76	0.972	0.76
13 to 14	0.998	0.65	1.00	0.65
14 to 15	0.788	0.73	0.782	0.73
15 to 16	0.829	0.78	0.820	0.78
> 16	0.519	0.95	1.060	0.70

[1] Model A: DMI = HEIFER + AGEW + BW; Model B: BW = HEIFER + AGEW; where AGEW = age in weeks.

Appendix Table I. Root MSE and R-squared from models[1] predicting DMI of Holstein heifers from 17 to 28 months of age.

Age Range, months	Root MSE	Model R-squared
< 17	0.7679	0.810
17 to 18	0.9755	0.772
18 to 19	1.0778	0.797
19 to 20	1.0701	0.768
20 to 21	0.9510	0.818
21 to 22	1.1426	0.792
22 to 23	1.0109	0.843
23 to 24	1.2125	0.766
24 to 25	1.2810	0.736
≥ 25	0.9667	0.724

[1] Model: DMI = HEIFER + MONTH + AGEW; where MONTH = month 1..12, AGEW = age in weeks.

Appendix Table J. Standard errors of least squares means from simulation results evaluating various growth rates[1] of Holstein heifers.

Item[2]	Control: Control	ACC: ACC	Slow: Slow	Control: ACC	ACC: Control	Slow: ACC
ADG I, kg/d	0.002	0.002	0.002	0.002	0.002	0.002
ADG II, kg/d	0.006	0.006	0.006	0.006	0.006	0.006
ADG overall, kg/d	0.002	0.002	0.002	0.002	0.002	0.002
DMI I, kg/d	0.013	0.013	0.013	0.013	0.013	0.013
DMI II, kg/d	0.028	0.028	0.028	0.027	0.028	0.028
DMI overall, kg/d	0.013	0.013	0.013	0.013	0.013	0.013
Services	0.024	0.024	0.024	0.023	0.024	0.024
Age at conception, mo	0.055	0.055	0.055	0.054	0.055	0.055
Age at calving, mo	0.055	0.055	0.055	0.054	0.055	0.055
BW at conception, kg	1.33	1.33	1.34	1.32	1.34	1.34
Post calving BW, kg	2.16	2.16	2.17	2.15	2.16	2.17
First lactation milk yield, kg	36.38	36.43	36.53	36.17	36.47	36.64
Feed costs I	1.82	1.82	1.83	1.81	1.83	1.83
Feed costs II	0.85	0.85	0.85	0.84	0.85	0.85
Feed costs overall	2.35	2.35	2.36	2.33	2.36	2.36
Operating costs I	0.32	0.32	0.32	0.32	0.32	0.32
Operating costs II	0.065	0.065	0.065	0.065	0.065	0.066
Operating costs overall	0.38	0.38	0.38	0.38	0.38	0.38
Ownership costs I	0.089	0.089	0.090	0.089	0.089	0.090
Ownership costs II	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Ownership costs overall	0.089	0.089	0.089	0.089	0.089	0.090
Breeding Costs	0.37	0.37	0.38	0.37	0.37	0.38
Total cash rearing costs[3]	3.01	3.02	3.03	3.00	3.02	3.04
Interest costs	0.47	0.47	0.47	0.47	0.47	0.48
Death and abortion costs[4]	4.96	4.96	4.98	4.93	4.97	4.99
Total rearing costs[5]	5.89	5.90	5.92	5.86	5.91	5.94
Monthly costs[6]	0.191	0.191	0.192	0.190	0.192	0.192
Annual costs[7]	2.37	2.37	2.38	2.36	2.37	2.39
Net Profit/Loss at Calving[8]	12.97	13.00	13.04	12.91	13.01	13.07

[1] Control:Control = normal growth, birth to calving; ACC:ACC = accelerated growth, birth to calving; Slow:Slow = slow growth, birth to calving; Control:ACC = normal growth 5 wk to 14 mo, accelerated growth 14 mo to calving; ACC:Control = accelerated growth 5 wk to 14 mo, normal growth 14 mo to calving; Slow:ACC = normal growth 5 wk to 14 mo, slow growth 14 mo to calving.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Includes feed, ownership, operating, and breeding costs.

[4] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[5] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[6] Total rearing costs adjusted to a monthly basis using 8% interest.

[7] Total rearing costs adjusted to an annual basis using 8% interest.

[8] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Appendix Table K. General Linear Model[1], Tukey's pairwise comparison, and NESTED analysis for simulation results evaluating various growth rates of Holstein heifers (SAS, 1985).

Item[2]	MSE[3]	Tukey's Critical Value	Treatment	Herd	Error
			------- percent of total variance -------		
ADG I, kg/d	0.003	0.008	82.6	0.1	17.3
ADG II, kg/d	0.030	0.024	31.2	0	68.8
ADG overall, kg/d	0.003	0.008	71.6	0	28.4
DMI I, kg/d	0.16	0.056	28.1	0	71.9
DMI II, kg/d	0.68	0.115	50.3	0	49.7
DMI overall, kg/d	0.15	0.054	54.4	0	45.6
Services	0.50		0	0	100
Age at conception, mo	2.68	0.228	48.1	0	51.9
Age at calving, mo	2.68	0.228	48.1	0	51.9
BW at conception, kg	1593	5.565	23.9	0	76.1
Post calving BW, kg	4193	9.029	30.4	0	69.6
First lactation milk yield, kg	1191081	152.179	0.4	0	99.6
Feed costs I	2983.71	7.617	29.23	0	70.8
Feed costs II	645.71	3.543	51.4	0	48.6
Feed costs overall	4959.70	9.820	19.3	0	80.7
Operating costs I	92.05	1.338	48.0	0	52.0
Operating costs II	3.83	0.273	43.5	0	56.5
Operating costs overall	130.55	1.593	47.7	0	52.3
Ownership costs I	7.16	0.373	48.1	0	51.9
Ownership costs II	0.00	0.001	36.0	0	64.0
Ownership costs overall	7.13	0.372	48.1	0	51.9
Breeding Costs	125.65	1.563	0	0	100
Total cash rearing costs[4]	8182.96		17.8	0	82.2
Interest costs	200.85	1.976	33.6	0	66.4
Death and abortion costs[5]	22108.85		7.0	92.9	0.1
Total rearing costs[6]	31280.90	24.662	20.3	1.2	78.5
Monthly costs[7]	32.85	0.799	71.6	6.3	22.0
Annual costs[8]	5050.50	9.909	71.9	6.3	21.8
Net Profit/Loss[9]	151666.10	54.304	1.6	0	99.4

[1] Model: y = treatment + herd(treatment); treatment significant ($P < 0.05$) for all variables except services and breeding costs, Tukey's Critical Value not computed for these.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] From herd(tmt) model term (used to test treatments).

[4] Includes feed, ownership, operating, and breeding costs.

[5] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[6] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

7 Total rearing costs adjusted to a monthly basis using 8% interest.

[8] Total rearing costs adjusted to an annual basis using 8% interest.

[9] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Appendix Table L. Standard errors of least squares means from simulation results evaluating various heat detection rates[1] at 40, 38, and 38% conception for first, second, and third services for Holstein heifers.

	Heat Detection Efficiency, %		
Item[2]	40	50	60
ADG I, kg/d	0.001	0.001	0.001
ADG II, kg/d	0.005	0.005	0.005
ADG overall, kg/d	0.002	0.002	0.002
DMI I, kg/d	0.016	0.016	0.016
DMI II, kg/d	0.020	0.020	0.020
DMI overall, kg/d	0.009	0.009	0.009
Services	0.043	0.043	0.043
Age at conception, mo	0.062	0.062	0.062
Age at calving, mo	0.062	0.062	0.062
BW at conception, kg	1.67	1.67	1.67
Post calving BW, kg	1.73	1.73	1.73
First lactation milk yield, kg	35.37	35.38	35.34
Feed costs I	2.22	2.22	2.22
Feed costs II	0.607	0.607	0.606
Feed costs overall	2.18	2.19	2.18
Operating costs I	0.363	0.363	0.363
Operating costs II	0.089	0.089	0.089
Operating costs overall	0.451	0.451	0.451
Ownership costs I	0.101	0.101	0.101
Ownership costs II	0.0002	0.0002	0.0002
Ownership costs overall	0.101	0.101	0.101
Breeding Costs	0.715	0.715	0.714
Total cash rearing costs[3]	3.25	3.25	3.24
Interest costs	0.57	0.57	0.57
Death and abortion costs[4]	5.57	5.57	5.56
Total rearing costs[5]	6.52	6.52	6.51
Monthly costs[6]	0.191	0.191	0.191
Annual costs[7]	2.37	2.37	2.37
Net Profit/Loss[8]	17.09	17.10	17.08

[1] Fourth and later services were natural with 85% heat detection efficiency and conception.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Includes feed, ownership, operating, and breeding costs.

[4] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[5] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[6] Total rearing costs adjusted to a monthly basis using 8% interest.

[7] Total rearing costs adjusted to an annual basis using 8% interest.

[8] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Appendix Table M. Standard errors of least squares means from simulation results evaluating various heat detection rates[1] at 65, 62, and 62% conception for first, second, and third services for Holstein heifers.

	Heat Detection Efficiency, %		
Item[2]	40	50	60
ADG I, kg/d	0.0012	0.0011	0.0012
ADG II, kg/d	0.0053	0.0053	0.0054
ADG overall, kg/d	0.0019	0.0019	0.0020
DMI I, kg/d	0.0166	0.0165	0.0167
DMI II, kg/d	0.0268	0.0266	0.0269
DMI overall, kg/d	0.0137	0.0136	0.0137
Services	0.0261	0.0259	0.0262
Age at conception, mo	0.0666	0.0660	0.0668
Age at calving, mo	0.0666	0.0660	0.0668
BW at conception, kg	1.713	1.699	1.719
Post calving BW, kg	2.443	2.424	2.452
First lactation milk yield, kg	38.967	38.660	39.101
Feed costs I	2.355	2.337	2.364
Feed costs II	0.832	0.825	0.835
Feed costs overall	2.745	2.723	2.754
Operating costs I	0.392	0.389	0.393
Operating costs II	0.0943	0.0937	0.0947
Operating costs overall	0.486	0.482	0.488
Ownership costs I	0.109	0.108	0.109
Ownership costs II	0.0002	0.0002	0.0002
Ownership costs overall	0.1086	0.1077	0.1090
Breeding Costs	0.3906	0.3876	0.3920
Total cash rearing costs[3]	3.540	3.513	3.553
Interest costs	0.600	0.594	0.601
Death and abortion costs[4]	3.85	3.82	3.86
Total rearing costs[5]	5.326	5.284	5.344
Monthly costs[6]	0.138	0.137	0.138
Annual costs[7]	1.71	1.70	1.72
Net Profit/Loss[8]	13.20	13.09	13.24

[1] Fourth and later services were natural with 85% heat detection efficiency and conception.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Includes feed, ownership, operating, and breeding costs.

[4] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[5] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[6] Total rearing costs adjusted to a monthly basis using 8% interest.

[7] Total rearing costs adjusted to an annual basis using 8% interest.

[8] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Appendix Table N. Standard errors of least squares means from simulation results evaluating various heat detection rates[1] at 80, 78, and 78% conception for first, second, and third services for Holstein heifers.

	Heat Detection Efficiency, %		
Item[2]	40	50	60
ADG I, kg/d	0.001	0.001	0.001
ADG II, kg/d	0.005	0.005	0.005
ADG overall, kg/d	0.002	0.002	0.002
DMI I, kg/d	0.013	0.013	0.013
DMI II, kg/d	0.026	0.026	0.026
DMI overall, kg/d	0.012	0.012	0.012
Services	0.021	0.021	0.021
Age at conception, mo	0.054	0.054	0.055
Age at calving, mo	0.054	0.054	0.055
BW at conception, kg	1.25	1.25	1.26
Post calving BW, kg	2.16	2.16	2.18
First lactation milk yield, kg	39.12	39.16	39.45
Feed costs I	1.82	1.82	1.83
Feed costs II	0.80	0.80	0.81
Feed costs overall	2.30	2.30	2.32
Operating costs I	0.32	0.32	0.32
Operating costs II	0.39	0.39	0.40
Operating costs overall	0.39	0.39	0.40
Ownership costs I	0.089	0.089	0.089
Ownership costs II	0.0002	0.0002	0.0002
Ownership costs overall	0.089	0.089	0.089
Breeding Costs	0.32	0.32	0.32
Total cash rearing costs[3]	2.97	2.98	3.00
Interest costs	0.48	0.48	0.48
Death and abortion costs[4]	5.08	5.09	5.12
Total rearing costs[5]	6.05	6.06	6.10
Monthly costs[6]	0.19	0.19	0.19
Annual costs[7]	2.34	2.35	2.36
Net Profit/Loss[8]	13.64	13.65	13.75

[1] Fourth and later services were natural with 85% heat detection efficiency and conception.

[2] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[3] Includes feed, ownership, operating, and breeding costs.

[4] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[5] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[6] Total rearing costs adjusted to a monthly basis using 8% interest.

[7] Total rearing costs adjusted to an annual basis using 8% interest.

[8] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Appendix Table O. Standard errors of least squares means from simulation results evaluating various death loss rates at birth for Holstein heifers.

	Death Loss at Birth, %		
Item[1]	5	10	15
ADG I, kg/d	0.002	0.002	0.002
ADG II, kg/d	0.006	0.006	0.007
ADG overall, kg/d	0.002	0.002	0.002
DMI I, kg/d	0.015	0.015	0.016
DMI II, kg/d	0.031	0.032	0.033
DMI overall, kg/d	0.014	0.014	0.015
Services	0.022	0.023	0.024
Age at conception, mo	0.059	0.061	0.063
Age at calving, mo	0.059	0.061	0.063
BW at conception, kg	1.59	1.64	1.70
Post calving BW, kg	2.42	2.49	2.57
First lactation milk yield, kg	33.98	35.07	36.27
Feed costs I	2.02	2.09	2.16
Feed costs II	0.96	0.99	1.03
Feed costs overall	2.51	2.59	2.68
Operating costs I	0.35	0.36	0.37
Operating costs II	0.082	0.085	0.087
Operating costs overall	0.43	0.44	0.46
Ownership costs I	0.097	0.100	0.103
Ownership costs II	0.0002	0.0002	0.0002
Ownership costs overall	0.096	0.100	0.103
Breeding Costs	0.32	0.33	0.34
Total cash rearing costs[2]	3.19	3.30	3.41
Interest costs	0.52	0.53	0.55
Death and abortion costs[3]	4.61	4.76	4.92
Total rearing costs[4]	6.52	6.73	6.96
Monthly costs[5]	0.17	0.18	0.18
Annual costs[6]	2.11	2.18	2.25
Net Profit/Loss[7]	12.08	12.46	12.89

[1] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[2] Includes feed, ownership, operating, and breeding costs.

[3] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[4] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[5] Total rearing costs adjusted to a monthly basis using 8% interest.

[6] Total rearing costs adjusted to an annual basis using 8% interest.

[7] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Appendix Table P. Standard errors of least squares means from simulation results evaluating various death loss rates from birth to weaning for Holstein heifers.

	Death Loss From Birth to Weaning, %		
Item[1]	1	10	15
ADG I, kg/d	0.001	0.001	0.001
ADG II, kg/d	0.007	0.007	0.007
ADG overall, kg/d	0.003	0.003	0.003
DMI I, kg/d	0.016	0.017	0.017
DMI II, kg/d	0.035	0.037	0.038
DMI overall, kg/d	0.018	0.019	0.019
Services	0.029	0.031	0.031
Age at conception, mo	0.061	0.064	0.065
Age at calving, mo	0.061	0.064	0.066
BW at conception, kg	1.56	1.63	1.66
Post calving BW, kg	3.02	3.17	3.22
First lactation milk yield, kg	46.84	49.11	49.93
Feed costs I	2.19	2.29	2.33
Feed costs II	1.10	1.15	1.17
Feed costs overall	2.99	3.14	3.19
Operating costs I	0.36	0.38	0.38
Operating costs II	0.086	0.090	0.092
Operating costs overall	0.45	0.47	0.47
Ownership costs I	0.100	0.105	0.107
Ownership costs II	0.0002	0.0002	0.0002
Ownership costs overall	0.100	0.105	0.107
Breeding Costs	0.48	0.50	0.51
Total cash rearing costs[2]	3.89	4.08	4.14
Interest costs	0.57	0.60	0.61
Death and abortion costs[3]	5.46	5.72	5.82
Total rearing costs[4]	5.64	5.92	6.02
Monthly costs[5]	0.19	0.20	0.21
Annual costs[6]	2.40	2.51	2.56
Net Profit/Loss[7]	12.91	13.53	13.76

[1] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[2] Includes feed, ownership, operating, and breeding costs.

[3] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[4] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[5] Total rearing costs adjusted to a monthly basis using 8% interest.

[6] Total rearing costs adjusted to an annual basis using 8% interest.

[7] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

Appendix Table Q. Standard errors of least squares means from simulation results evaluating various abortion rates for Holstein heifers.

	Abortions, %		
Item[1]	1	5	10
ADG I, kg/d	0.001	0.001	0.001
ADG II, kg/d	0.006	0.006	0.007
ADG overall, kg/d	0.002	0.002	0.002
DMI I, kg/d	0.014	0.014	0.015
DMI II, kg/d	0.029	0.030	0.031
DMI overall, kg/d	0.013	0.014	0.014
Services	0.027	0.028	0.029
Age at conception, mo	0.054	0.055	0.057
Age at calving, mo	0.054	0.055	0.058
BW at conception, kg	1.33	1.35	1.40
Post calving BW, kg	2.30	2.33	2.43
First lactation milk yield, kg	41.39	41.95	43.68
Feed costs I	1.93	1.96	2.04
Feed costs II	0.91	0.92	0.96
Feed costs overall	2.32	2.36	2.45
Operating costs I	0.32	0.32	0.34
Operating costs II	0.076	0.077	0.080
Operating costs overall	0.39	0.40	0.42
Ownership costs I	0.089	0.090	0.094
Ownership costs II	0.0002	0.0002	0.0002
Ownership costs overall	0.089	0.090	0.094
Breeding Costs	0.43	0.44	0.46
Total cash rearing costs[2]	2.99	3.04	3.16
Interest costs	0.49	0.49	0.51
Death and abortion costs[3]	9.18	9.31	9.69
Total rearing costs[4]	9.47	9.60	9.99
Monthly costs[5]	0.33	0.33	0.35
Annual costs[6]	4.09	4.15	4.32
Net Profit/Loss[7]	15.10	15.31	15.94

[1] I = birth to conception, II = conception to calving, overall = birth to calving. Costs are on a $/heifer basis.

[2] Includes feed, ownership, operating, and breeding costs.

[3] Total costs of all dead and aborted animals/number of heifers that calved, adjusted to day of calving using 8% interest.

[4] Includes cash rearing expenses, value of heifer at birth, interest, and death and abortion costs.

[5] Total rearing costs adjusted to a monthly basis using 8% interest.

[6] Total rearing costs adjusted to an annual basis using 8% interest.

[7] Total rearing costs plus feed and non-feed costs during lactation, milk income, value of calf born to heifer, and value of heifer at end of first lactation all adjusted to day of calving using 8% interest.

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