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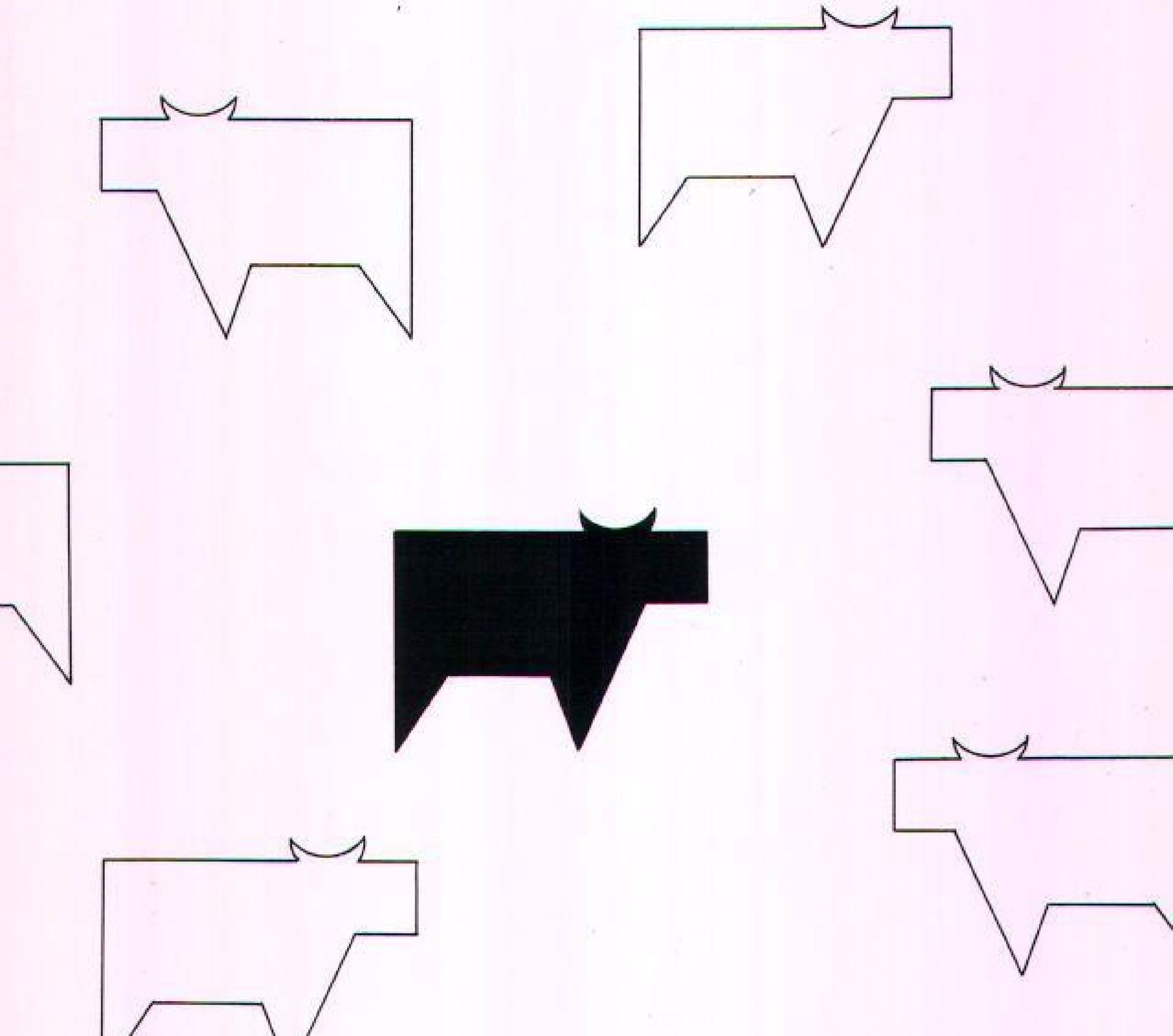
Economic optimization of decisions with respect to dairy cow health management



E.H.P. Houben

NN08201, 1910

Stellingen

1. Voor een economisch optimale ondersteuning van vervangingsbeslissingen bij individuele koeien met klinische mastitis kan het meenemen van historische informatie hieromtrent beperkt blijven tot de lopende lactatie *(dit proefschrift)*.

2. Het in de praktijk vaak toegepaste interval van melkmeting van drie tot vier weken is te groot om tot een juiste inschatting van een door ziekte veroorzaakte melkproduktiederving te komen (*dit proefschrift*).

3. Omdat optimalisatiemodellen in tegenstelling tot de partial budgeting methode onder gewijzigde omstandigheden automatisch de optimale beslissingen volgen, zijn zij bij uitstek geschikt om de maximaal toelaatbare kosten van preventieve ziektemaatregelen te bepalen (*dit proefschrift*).

4. Een hybride systeem waarbij met een genetisch algoritme de korte termijn belangen geoptimaliseerd worden en met dynamische programmering de lange termijn belangen blijkt een goede methode te zijn om in zeer complexe situaties tot de juiste beslissingen te komen (*dit proefschrift*).

5. Voor een verantwoord gebruik van een beslissingsondersteunend systeem is het kennen van de beperking minstens zo belangrijk als het kennen van de werking.

6. Het ontbreken van een varkenscyclus in de melkveehouderij zal tot gevolg hebben dat de melkveehouderij met een relatief hoge kostprijs geconfronteerd wordt.

7. Het ontbreken van de organisatiegraad van de rundveehouderij in de varkenshouderij zal tot gevolg hebben dat de varkenshouderij met een relatief lage opbrengstprijs geconfronteerd wordt.

8. Het is weliswaar goed te verklaren maar moeilijk te verdedigen dat voor het uitvoeren van vaccinaties in de veehouderij een universitaire scholing vereist is.

9. De in de praktijk vaak geconstateerde overmatige belangstelling voor de betrouwbaarheid van een fokwaarde wordt vooral veroorzaakt doordat men de schattingsmethode niet betrouwbaar vindt.

10. Wetenschap beoogt vernieuwend te zijn, maar veel wetenschappers voelen zich op hun gemak als hun resultaten overeenkomen met het onderzoek van hun voorgangers.

11. Voor onervaren zeilers worden de kosten van een zeilweekend veelal in sterkere mate bepaald door de borgsom dan door de huurprijs van de boot.

E.H.P. Houben
Economic optimization of decisions with respect to dairy cow health management
Wageningen, 5 april 1995

Economic optimization of decisions with respect to dairy cow health management

ontvangen

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NN08201, 1910

E.H.P. Houben

Economic optimization of decisions with respect to dairy cow health management

Proefschrift
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in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
dr. C.M. Karssen,
in het openbaar te verdedigen
op woensdag 5 april 1995
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Dit onderzoek maakte deel uit van een project van:
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Fullwood b.v.

Omslag: Pepijn Schakenraad

Abstract

Economic optimization of decisions with respect to dairy cow health management.
Economomische optimalisatie van beslissingen gericht op gezondheidsmanagement bij melkvee.
Houben, E.H.P., 1995.

The research described in this thesis was directed towards decision support in dairy cow health management. Attention was focused on clinical mastitis, in many countries considered to be the most important dairy health problem. First a statistical analysis was carried out to obtain biological and economic parameters with respect to clinical mastitis which fitted in the state space definition of the stochastic dynamic programming model. This optimization model was based on the hierarchic Markov process technique. An extensive sensitivity analysis of key parameters in optimizing decisions on individual cows was carried out. The economic value of information on clinical mastitis in making insemination and replacement decisions was determined for a broad range of mastitis incidences. The effect of income maximization per unit of physical output (i.e. milk) instead of maximization per cow and including the opportunity costs of labour and housing was determined. Finally, a method was developed to optimize decisions for individual animals within herd level restrictions, such as exceeding of milk quota, shortage of replacement heifers, and disease transmission between animals. The methods described are general of nature and can be used for other diseases and species.

PhD-thesis, Department of Farm Management, Wageningen Agricultural University, Hollandseweg 1, 6706 KN Wageningen, The Netherlands.

Voorwoord

Al met al betekent de openbare verdediging van dit proefschrift voor mij de afsluiting van een mooie periode. Ik heb de afgelopen jaren vaak toe moeten lichten wat er mij toe gebracht heeft om 'iets met koeien' te doen. Die vraag werd steevast gesteld, omdat men mij om de een af andere reden altijd associeerde met varkens. Gelukkig kon ik de betreffende personen meestal wel geruststellen door te melden dat het vooral om de bedrijfseconomische invalshoek ging en dat de gebruikte methoden veel breder inzetbaar waren. Dáárom hebben de koeien op de omslag een ietwat abstracte vorm: met een beetje fantasie kun je er varkens in herkennen. Maar wat was nu de reden om AIO te worden? Het salaris was niet zo fantastisch, dus daar zal het wel niet aan gelegen hebben. Militaire Dienst? Ja, dat heeft inderdaad een beetje meegespeeld. Maar het was vooral de uitdaging om in een bepaalde periode met een sterke mate van vrijheid een onderwerp van begin tot eind uit te werken. Boven alles gaf het de doorslag dat mijn directe begeleiders - prof.dr.ir. Aalt Dijkhuizen en dr.ir. Ruud Huirne - in de periode die ik als toegevoegd onderzoeker een half jaar op de vakgroep werkte, zeer inspirerend waren. Aalt en Ruud, bedankt dat jullie die voortreffelijke aanpak vast bleven houden tijdens mijn AIO-periode. Een woord van dank gaat tevens uit naar de overige leden van de begeleidingscommissie, prof.dr.ir. J.A. Renkema, prof.dr.ir. A. Brand en dr.ir. J.A.M. van Arendonk. Tijdens de bijeenkomsten van de commissie werden alle zaken nog eens belicht vanuit ieders vakspecifieke invalshoek en dat heeft ook zeker bijgedragen aan het resultaat.

Reeds in een vroeg stadium moest een beslissing genomen worden welke optimalisatietechniek gebruikt zou worden. De tijd die dr. Anders Kristensen tijdens mijn bezoek in Kopenhagen voor mij vrijmaakte, om de hierarchic Markov techniek toe te lichten heeft er toe geleid dat ik snel van start kon gaan met een veel belovende methode. Dear Anders, thank you very much for the time you spent on me while I was visiting you in Copenhagen. Also many thanks for your quick and comprehensive responses to my questions later on.

Mijn onderzoek was een onderdeel van een groter opgezet onderzoeksproject: het Melk Produktie Project. Ik wil mijn collega-onderzoekers, projectleiding en projectondersteuning hartelijk danken voor de plezierige manier waarop kennis uitgewisseld werd.

De vakgroep Agrarische Bedrijfseconomie is tijdens mijn periode flink, tegen de verdrukking in, gegroeid. De sfeer op de vakgroep was erg goed en ik heb mede daardoor altijd met veel plezier op de Leeuwenborch gewerkt (en taart gegeten). De AIO-onderzoeksbesprekingen leverde altijd weer nuttige suggesties en nieuwe ideeën

op. Tevens maakten deze besprekingen het mogelijk om op een veel breder vlak kennis op te doen. Een formule die jullie vast moeten blijven houden!

Een woord van dank gaat uit naar SKBS en Landbouwuniversiteit Wageningen als zijnde de financiers van mijn onderzoek, Fullwood b.v. voor de financiële bijdrage in de drukkosten van dit proefschrift, vakgroep Bedrijfsdiergeneeskunde & Voortplanting van de Faculteit Diergeneeskunde in Utrecht voor het beschikbaar stellen van hun dataset, Diny Dijkhuizen voor de correctie van de Engelse teksten en Pepijn Schakenraad voor het ontwerp van de omslag.

Verder wil ik mijn ouders bedanken voor de mogelijkheid die zij mij boden om te gaan studeren en hun belangstelling tijdens deze Wageningse periode.

Tot slot gaat een mieters woord van dank uit naar Marika. Vooral tijdens de laatste fase van mijn onderzoek bleken er steeds meer zaken te zijn die mijn tijd opslokten en ik vind het dan ook fantastisch Marika op welke manier jij begrip toonde en mij steunde.

Contents

Chapter 1

General introduction

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1. Introduction

The replacement policy of dairy cows greatly influences profitability of the herd (Van Arendonk, 1985). The major reasons for culling cows are low production, failure to conceive, and mastitis. Decisions to replace cows are mainly based on economic rather than on biological considerations, i.e., the farmer expects to improve profits by replacing the cow. The inherent biological cycles of reproduction and lactation make dairy cow management decisions dynamic, recursive, and stochastic. Decisions are time-dependent. In multi-stage optimization problems, dynamic programming (DP) has the advantage of determining optimal decisions without requiring exhaustive enumeration of all sequences of production possibilities (DeLorenzo et al., 1992). Jenkins and Halter (1963), Giaever (1966) and Smith (1971) already used the DP approach in their studies on optimal dairy cow replacement policies. Before the mid-1980s, however detailed DP models were not available because of the lack of computer capacity. Subsequently, several DP models have been developed to optimize replacement decisions for individual animals (cows and sows) based on production capacity and reproductive state (Van Arendonk, 1985; Huirne, 1990; Kristensen, 1993). Only Stott and Kennedy (1993) included clinical mastitis, which is, in many countries, considered to cause major losses (Schepers and Dijkhuizen, 1991). In the model of Stott and Kennedy (1993), however, replacement during a lactation was not possible and mastitis status was treated as a binomial variable rather than a multilevel one. The way clinical mastitis was modelled, therefore, was not detailed enough to come to sound economic conclusions.

The objectives of this thesis were to develop an optimization model for dairy cow replacement which includes clinical mastitis in a detailed way. The model should allow decisions to be taken frequently, e.g., each month within a lactation and taking into account monthly transitions between production classes. Another objective was to determine the sensitivity of farm results to suboptimal culling policies. Furthermore, a method had to be developed to include herd level restrictions, such as milk quota, in the decision-making process.

2. Background

This research was part of a larger project: the Milk Production Project, MPP (Brée et al., 1992). The aim of the MPP was to develop a prototype of an integrated management decision support system for dairy farms, focusing on mastitis management. Three modules related to mastitis management were developed: 1) automatic mastitis detection (Nielen, 1994; Spigt, 1994), 2) automatic diagnosis and therapy selection at cow level, as well as automatic mastitis problem analysis at herd level (Hogeveen, 1994), and 3) automatic economic evaluation of insemination and replacement decisions with special emphasis on mastitic cows (this thesis).

Within the MPP, a basic architecture for a decision support system was developed (Van den Broek and Schreinemakers, 1993). Using this architecture, automatic detection of clinical mastitis, automatic pathogen diagnosis, and economic evaluation were implemented in the MPP prototype. Data from the milking parlour are entered into the detection module, to search for affected quarter of the cows (Nielen, 1994). Next, these cows are automatically presented to the pathogen diagnosis module of the prototype system (Hogeveen, 1994). The third module (economic evaluation) calculates the insemination and replacement value for the cows concerned (this thesis).

3. Outline of the thesis

Chapter 2 describes a statistical analysis of obtaining biological and economic parameters with respect to clinical mastitis which fit in the state space definition of the stochastic dynamic programming model. This optimization model was based on the hierarchic Markov process structure and is fully described in Chapter 3, including the results of an extensive sensitivity analysis of the key parameters. Chapter 4 determines the economic value of information on clinical mastitis in making insemination and replacement decisions for a broad range of mastitis incidences. The effect of maximization per unit of physical output (i.e. milk) instead of maximization per cow in the context of inclusion of opportunity costs of labour and housing is described in Chapter 5. A method was developed to include the effects of decisions for individual animals within herd level restrictions, such as exceeding of milk quota, shortage of replacement heifers, and disease transmission between animals. This method is described in Chapter 6.

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Chapter 2

Short- and long-term production losses and repeatability of clinical mastitis in dairy cattle

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Abstract

A study of 5313 lactations between 1985 and 1990 was carried out in 2477 Black and White cows. A stepwise least squares method was used to obtain unbiased estimates of milk, fat, and protein losses that were due to clinical mastitis and the carry-over effect from the previous lactation. Logistic regression was used to estimate the probabilities that a cow would have clinical mastitis in the next month.

The effect of clinical mastitis on production within one lactation was estimated at 527 kg of milk (8.1%), 22.7 kg of fat (8.0%) and 13.7 kg of protein (6.2%) for 3 or more clinical cases in the second lactation. One or two clinical cases in a lactation did not significantly affect the production in the next lactation. The negative carry-over effect of 3 or more clinical cases was estimated at 381 kg of milk (5.9%), 23.7 kg of fat (8.4%), and 10.1 kg of protein (4.6%) up to and including mo 8 of the second lactation. The fat content in milk produced after the onset of mastitis decreased, and protein content increased.

The risk of clinical mastitis infection in the following month was influenced by month of lactation (a higher risk early in lactation), lactation number (risk increased with lactation number), production level (higher risk for high producing cows), number of clinical quarter cases in the previous lactation, number of clinical quarters in the previous months of the current lactation, and occurrence of clinical mastitis in the current month.

Key words: clinical mastitis, production, repeatability

Abbreviation key: **CQ** = accumulated number of diagnosed clinical quarter cases in current lactation from the beginning of the lactation (t = 0) through month t - 1 (four levels: 0, 1, 2, and 3+), **DQ** = binary variable indicating that clinical mastitis was diagnosed in at least 1 quarter (1+) or in none of the quarters (0) in month t of the current lactation, **PQ** = accumulated number of clinical quarter cases in the previous lactation (four levels: 0, 1, 2, and 3+).

1. Introduction

Mastitis causes major losses in dairy cattle. Various attempts have been made to quantify the reduction in milk production in relation to clinical and subclinical mastitis as mentioned in recent reviews (Janzen, 1970; Rowlands et al., 1986; Deluyker, 1991; Schepers and Dijkhuizen, 1991) and to quantify the risk factors for clinical mastitis (Bunch et al., 1984; Dohoo and Martin, 1984; Rowlands et al., 1986; Morse et al., 1987; Schukken et al., 1991). Differing methods and origins of (field) data are considered to be major reasons for the observed differences in losses (Schepers and Dijkhuizen, 1991).

Only a few recent studies (Deluyker, 1991) reported the effect of clinical mastitis on fat and protein production. Moreover, most estimates in the literature are biased downward by culling based on production level and mastitis. These estimates are also mostly based on a few observations of short duration. Estimation of production losses may also be biased because highly productive cattle run a higher risk of contracting mastitis (Bunch et al., 1984; Heuven, 1987; Bartlett et al., 1991; Deluyker, 1991). No study has considered the effect of mastitis on milk, fat, and protein production and the risk factors of mastitis on a short-term basis. Therefore, the objective of this research is to obtain reliable estimates of production losses caused by clinical mastitis and to obtain estimates of the occurrence and reoccurrence probabilities of clinical mastitis on a monthly basis.

A special technique is used to estimate the effect of mastitis on milk, fat, and protein production (i.e., excluding discarded milk, treatment costs, replacement costs, and other costs) by the least squares method. This technique corrects for the effect of culling and the correlation between the risk of contracting clinical mastitis and production level. The major costs caused by clinical mastitis can be determined with those estimates for a specific cow in a specific situation. Logistic regression is used to estimate the probabilities that a cow will contract mastitis in the next month.

2. Materials and methods

2.1. Study Population

Between June 1985 and November 1990, data were collected from 25 farms with Black and White cows. The farms were located in the center of The Netherlands near the Veterinary Faculty. At a 3- or 4-wk interval, the milk, fat, and protein production data were recorded and analyzed by the Dutch milk recording organization. All cases of clinical mastitis observed by the farmer were reported to the Veterinary Faculty veterinarian. Moreover, all of the farms were visited by veterinarians of the Department of Herd Health and Reproduction of the Veterinary Faculty at least once a month. Information about mastitis, such as the date of diagnosis, infected quarters, bacteria, and treatments were recorded in the VAMPP computerized management information system (Noordhuizen and Buurman, 1984). Three farms were excluded from the analysis because veterinarians were not satisfied with the completeness of the recording. Moreover, data were excluded when cows were older than 3 yr at first calving; when a clinical case was observed in the dry period, but only before the last week of the dry period; or when the first production record was measured more than 40 d after calving. For those reasons 698 lactations were excluded and a total of 5313 lactations of 2477 cows remained for analysis.

2.2. Calculation of Accumulated Production

Production was measured at irregular intervals within each month, but monthly intervals were used for the analysis. Production on the days on which no measurements took place was estimated by linear interpolation of those points. To determine the milk production and fat and protein percentages, extra attention should be paid to mo 1 of the lactation because no observations are available until at least 20 d after calving. Therefore, a Wood curve (Wood, 1967) was used to estimate production on d 1, 5, and 15. Accumulated production was estimated by taking the surface below the graph formed by 1) estimates of the production on d 1, 5, and 15 based on the first production record; 2) regularly recorded production data; and 3) interpolation points of these observations at monthly intervals. Formula [1] shows how average production on d 1, 5, and 15 was estimated using the Wood curve (Heuven, 1987):

$$\hat{y}_d = \hat{y}_p \left(\frac{d}{\hat{d}_p} \times e^{\frac{\hat{d}_p - d}{\hat{d}_p}} \right)^{\hat{c}} \qquad [1]$$

where

$\hat{y}_d$ = estimated production on day d,

d = days in production,

$\hat{y}_p$ = estimated peak production,

$\hat{d}_p$ = estimated day of peak production, and

$\hat{c}$ = estimated slope.

Maximum production of milk and minimum production of fat and protein were fixed on d 58 in the first lactation, d 43 in the second lactation, and d 50 in the later lactations (Congleton and Everett, 1980). Slope and peak production were estimated for the first, second, and third or higher lactations from the data set (Table 1). Those estimates were based on production records up to d 200 and indicate a sizeable lactation effect, especially for milk production (Table 1). Peak milk production was greater for higher lactations, but production after the peak decreased more rapidly.

Average production was estimated from Formula [1]. Subsequently, individual production was estimated by multiplying average production on days 1, 5, and 15 by observed production on the day of the first production record divided by the average production on that day.

Table 1. Estimated peak production ($\hat{y}_p$) and estimated slope ($\hat{C}$) for milk, fat and protein production.

	Lactation					
	1		2		3+	
Production	$\hat{y}_p$	$\hat{C}$	$\hat{y}_p$	$\hat{C}$	$\hat{y}_p$	$\hat{C}$
Milk	22.9 kg/d	.1674 d^{-1}	29.6 kg/d	.1809 d^{-1}	32.6 kg/d	.2446 d^{-1}
Fat	4.20 %	-.0688 d^{-1}	4.16 %	-.0449 d^{-1}	4.10 %	-.0618 d^{-1}
Protein	3.21 %	-.1044 d^{-1}	3.23 %	-.0642 d^{-1}	3.16 %	-.0896 d^{-1}

Further analysis was carried out on the basis of kilograms rather than percentages because the distribution of ratios may not be normal.

2.3. Diagnoses and Definition of Mastitis

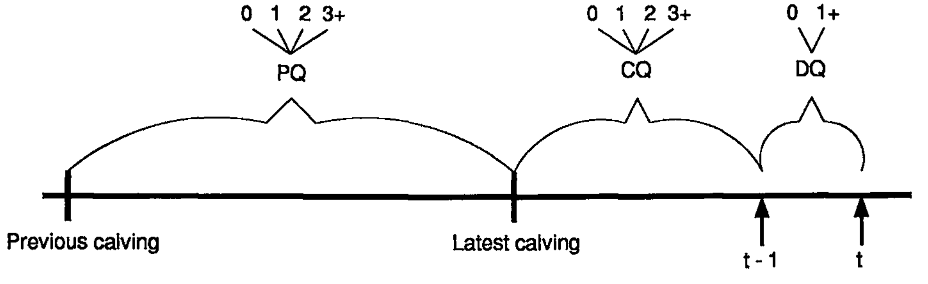


Figure 1. Graphical representation of the clinical mastitis states and the possible levels for DQ (binary variable indicating that clinical mastitis was diagnosed in at least 1 quarter or in none of the quarters in month t of the current lactation), CQ (accumulated number of diagnosed clinical quarter cases in current lactation from the beginning of the lactation through previous month), and PQ (accumulated number of clinical quarter cases in the previous lactation).

Three variables were introduced that describe the mastitis state of an individual cow: the accumulated number of clinical quarter cases diagnosed by a farmer or veterinarian in the previous lactation (PQ) (four levels: 0, 1, 2, and 3+), the accumulated number of diagnosed clinical quarter cases in the current lactation (CQ) from the beginning of the lactation (t = 0) through month t - 1 (four levels: 0, 1, 2, and 3+), and the binary variable indicating that clinical mastitis was diagnosed (DQ) in at least 1 quarter (1+) or in none of the quarters (0) in month t of the current lactation. A clinical case refers to all quarters in which the farmer or veterinarian considered an inflammation severe enough to warrant treatment with antibiotics. In Figure 1, the definition of mastitis states is depicted graphically.

Period t = 0 includes the period from 7 d before to 7 d after calving. Subsequently, period t = 1 is 1 wk shorter than the following periods with regard to the mastitis definition. The following are periods of 30.5 d. In these definitions, infection of the same quarter twice is considered to be comparable to 2 different infected quarters. If the same quarter was found infected within 3 d, however, it was not considered to be a new quarter case.

2.4. Production

Formula [2] shows the additive model of milk production, where the random variable Y_{nt} is the accumulated production (kilograms) of milk, fat and protein of the 1st t months of lactation n.

$$Y_{ijklmnopqrt} = mu_{nt} + h_{int} + ys_{jnt} + a_{knt} + g_{lnt} + f_{mnt} + c_{ont} + PQ_{pnt} + CQ_{qnt} + DQ_{rnt} + U_{nt} \qquad [2]$$

where
- Y = accumulated production (milk, fat, and protein);
- mu_{nt} = overall mean production in lactation n up to and including month t;
- h_{int} = effect of herd i (i = 1,...,23);
- ys_{jnt} = effect of year/season j (j = 1,...,34);
- a_{knt} = effect of breed k (k = 1,...,4);
- g_{lnt} = effect of age at calving l (l = 1,...,10);
- f_{mnt} = effect of day of first production record m (m = 1,...,8);
- c_{ont} = effect of expected calving interval o (o = 1,...,10);
- PQ_{pnt} = effect of no. of clinical quarters in previous lactation (p = 1,...,4);
- CQ_{qnt} = effect of no. of clinical quarters infected up to and including month t − 1 (q = 1,...,4);
- DQ_{rnt} = effect of infected quarter(s) in month t (r = 1, 2); and
- U_{nt} = measure of Y corrected for $_{nt}$, h_{int}, ys_{jnt}, a_{knt}, g_{lnt}, f_{mnt}, c_{ont}, PQ_{pnt}, CQ_{qnt} and, DQ_{rnt}.

The estimates are restricted to n in {1,...,3} and t in {1,...,10} because the method of analysis requires that the whole production history of a cow be available. Only a few cows with greater than three lactations met this requirement and were, therefore, excluded.

Similar to Wilmink (1987), 10 age classes were defined, corresponding to 22 to 24, 25 to 27, 28 to 32, 33 to 37, 38 to 44, 45 to 56, 57 to 68, 69 to 92, 93 to 104, and more than 104 mo at calving. The season classes were defined for 2-mo periods from June to July until April to May of the subsequent year.

The day of the first measurement of the production record falls into one of eight groups of 5 d each (i.e., 1 to 5, 6 to 10,..., 36 to 40).

The anticipated calving interval on day t in lactation is calculated as the interval from calving until conception plus 40 wk. If conception occurred < 3 wk previously, the anticipated calving interval is assumed to be unknown (class 0; this class also includes open cows). The 10 classes of calving interval were 0, 44 (< 322 d), 48 (322 d until 350 d), 52,..., and 76 (> 517 d) wk.

Among the Black and White cows, four breeds are distinguished, i.e., Holstein-Friesian, Dutch Friesian, Dutch Friesian x Holstein Friesian, and Dutch Friesian crossed with another breed.

The residual vector $(U_{1,1},...,U_{3,10})'$ is assumed to be multidimensionally normally distributed with the mean vector **O** and covariance matrix **C**. According to Kristensen (1986), the covariance matrix **C** is assumed to have the property that the simultaneous regression coefficients of U_{nt} with respect to $U_{1,10},...,U_{n,t-1}$ (i.e., all previous observations of U_{nt}), where $t > 1$, are all zero, except those concerning $U_{n-1,10}$ (when $n > 1$) and $U_{n,t-1}$. Therefore, in the prediction of U_{nt} only the last observation of the preceding lactation and the last observation of the current lactation are included. Correspondingly, when $t = 1$ and $n > 1$ only the regression coefficients of U_{nt} concerning $U_{n-2,10}$ (when $n > 2$) and $U_{n-1,10}$ are assumed to deviate from zero. Thus, to predict the first U_{nt} of a lactation, only the last observation of each of the two preceding lactations must be included. These assumptions are in agreement with Smith (1971), who concluded that knowledge of milk production during the two most recent lactations is sufficient to predict milk production during the following period. However, in the present study, a slightly different approach was used. Instead of $U_{n-1,10}$ and $U_{n-2,10}$, $U_{n-1,6}$ and $U_{n-2,6}$ have been used, respectively, because too many cows in the data set (about 65%) did not have production records from 6 through 10 mo in lactation, and they would therefore have been excluded if the former approach had been used. The error introduced by this approach is small because the correlation between $U_{n,10}$ and $U_{n,6}$ is high (> .95).

Mainly low producing cows are subjected to culling. In the analysis of variance, therefore, a special technique is used to account for culling. This technique has been used for a similar purpose by Giaever (1966) and Kristensen (1986). In the present study, the method has an additional advantage because results are unbiased, even when the occurrence of mastitis is correlated with production level, assuming that this correlation is absent in mo 1 of the first lactation.

Because of culling, the covariance matrix **C** is biased unless an indirect approach is used. It is assumed that no culling occurs before mo 1 after first calving. Thus, the parameters for (n,t) = (1,1) (including the variance of $U_{1,1}$) can be estimated directly by the ordinary least squares method. For other values of n and t, the parameters are estimated step by step by Formula [3], which is an extension of Formula [2]:

$$Y_{ijklmnopqrt} = mu_{nt} + h_{int} + ys_{jnt} + a_{knt} + g_{lnt} + f_{mnt} + c_{ont} + PQ_{pnt} + CQ_{qnt} + DQ_{rnt} + \beta1_{nt}U_{n,t-1} + \beta2_{nt}U_{n-1,6} + \varepsilon_{nt} \quad [3]$$

where

$\beta1_{nt}$ = regression coefficient of U_{nt} on $U_{n,t-1}$,

$\beta2_{nt}$ = regression coefficient of U_{nt} on $U_{n-1,6}$, and

ε_{nt} = residual, $N(0,\sigma^2)$.

From Formula [3], U_{nt} can be determined as

$$U_{nt} = \beta1_{nt}U_{n,t-1} + \beta2_{nt}U_{n-1,6} + \varepsilon_{nt}. \quad [4]$$

U_{nt} (Formula [4]) can be used to estimate parameters in the following month.

The extended model (Formula [4]) represents a situation in which t > 1 and n > 1. Analogous formulas are used for other combinations; the parameters of the extended model are estimated by ordinary least squares.

2.5. State Transition Probabilities

The estimation of transition probabilities concerning mastitis can be determined by Formula [5]:

$$p_{ijklmt} = \frac{e^{(mu + m_t + l_i + p_j + PQ_k + CQ_l + DQ_m)}}{1 + e^{(mu + m_t + l_i + p_j + PQ_k + CQ_l + DQ_m)}} \quad [5]$$

The maximum likelihood procedure of CATMOD (SAS, 1988) was used to fit logistic models; binary variable DQ at month t + 1 was the dependent variable.

The basic variables in the model were lactation (1, 2, 3, 4, and 5+), month in lactation (1,..,10), production level (+, 0, and -) at month t, PQ (0, 1, 2, and 3+), CQ (0, 1, 2, and 3+) at month t and, DQ (0, 1+) at month t. With the estimates of the regression coefficients, conditional probabilities can be calculated when Formula [5] is used.

where

p_{ijklmt} = conditional probability of at least 1 infected quarter in month t + 1,

mu = intercept,

m_t = effect of month t (t = 1,...,10),

l_i = effect of lactation i (i = 1,...,5),

p_j = effect of production level j (j = 1,...,3),

PQ_k = effect of no. of quarters infected in previous lactation (k = 1,...,4),

CQ_l = effect of no. of quarters infected up to and including month t - 1 (l = 1,...,4), and

DQ_m = effect of infected quarters in month t (m = 1, 2)

Accumulated production of each cow is compared with production levels corrected for lactation and month of lactation, and then divided into three production classes (production is 1 sd less than average (-), 1 sd higher than average (+), and average (0)). Using this definition of production class instead of the corrected production from the previous section, the possibility is offered to include all cow records for the calculation of transition probabilities instead of a limited number only.

In the results of the logistic analysis, the estimates of the regression coefficients, standard error and odds ratios were presented. The last class value was taken as a reference class for the regression coefficients and the odds ratios. Mean coding was used by CATMOD (SAS, 1988) to obtain solutions. Thus, the sum of all regression coefficients in a class, including the reference class, was zero. The odds ratios are calculated as $\exp(\beta-\beta_{ref})$ (see Appendix 1).

A separate analysis was carried out for mo 1 of lactation; no information was available in that period on CQ, and the length of period DQ was 1 wk shorter than in other periods.

3. Results

3.1. Incidence of Clinical Mastitis

Incidence rates per 10,000 cow-days at risk were calculated from absolute values (Table 2). The incidence rates of clinical mastitis in the period from 1 wk before calving until 10 mo after calving were 6.6, 9.0, and 14.7 cases per 10,000 cow days at risk for first, second, and third lactation, respectively. For example, the incidence rate of 6.6 was calculated as

$$\frac{10000 * (83 + 33 + ... + 2 + 5)}{1332 * 14 + 1332 * 23.5 + (1278 + ... + 423) * 30.5} = \frac{10000 * 220}{334301.5}.$$

Table 2. Observations (Obs.), average accumulated milk production (Prod.), average percentages of fat and protein in accumulated milk (Prod.), unadjusted standard deviations (SD), and incidence of diagnosed clinical mastitis quarter cases[1] for each month in lactation (Lact.) 1, 2, and 3.

		Milk			Fat			Protein			
		Obs.	Prod.	SD	Obs.	Prod.	SD	Obs.	Prod.	SD	
Lact.	Month	(no.)	(kg)	(kg)	(no.)	(%)	(%)	(no.)	(%)	(%)	Incidence
1	1	1332	626	109	1279	4.59	.56	1278	3.40	.25	33
	2	1278	1354	224	1210	4.41	.46	1209	3.27	.21	27
	3	1238	2065	337	1166	4.35	.43	1164	3.27	.21	18
	4	1219	2747	449	1129	4.34	.42	1125	3.29	.21	9
	5	1182	3411	553	1084	4.34	.42	1080	3.31	.21	10
	6	1132	4046	663	1027	4.35	.42	1024	3.34	.21	16
	7	1082	4667	768	953	4.38	.42	950	3.36	.20	15
	8	1009	5266	872	867	4.40	.42	865	3.38	.20	2
	9	760	5869	975	639	4.43	.43	637	3.40	.20	5
	10	423	6433	1066	349	4.44	.41	348	3.42	.19	2
2	1	689	860	157	607	4.50	.60	605	3.41	.27	23
	2	680	1821	318	589	4.33	.49	587	3.29	.22	19
	3	670	2729	471	576	4.29	.46	574	3.28	.21	18
	4	656	3580	604	549	4.28	.45	547	3.30	.20	18
	5	643	4369	739	527	4.29	.44	525	3.33	.20	9
	6	624	5128	851	502	4.31	.44	501	3.35	.20	13
	7	605	5827	970	479	4.34	.44	478	3.38	.20	10
	8	562	6470	1087	436	4.37	.44	435	3.40	.19	8
	9	409	7071	1217	321	4.41	.44	321	3.42	.20	5
	10	220	7632	1324	169	4.42	.39	169	3.44	.19	1
3	1	357	939	151	287	4.53	.57	287	3.37	.26	20
	2	327	2012	310	255	4.32	.45	255	3.23	.20	27
	3	318	3023	470	243	4.26	.40	243	3.22	.19	21
	4	314	3949	616	238	4.25	.40	237	3.24	.19	18
	5	307	4825	738	225	4.26	.40	224	3.26	.20	5
	6	297	5631	875	213	4.28	.41	212	3.29	.20	3
	7	288	6378	980	205	4.31	.42	204	3.32	.20	6
	8	266	7040	1111	183	4.34	.42	182	3.34	.20	4
	9	196	7704	1237	136	4.38	.42	135	3.38	.21	4
	10	88	8286	1359	64	4.47	.44	63	3.40	.21	0

[1] Clinical quarter cases that occur in wk 1 after calving are excluded from mo 1 but included in a separate class mo 0; an additional 83, 39, and 19 clinical quarter cases are diagnosed in lactations 1, 2, and 3 respectively, between 7 d before and 7 d after calving (i.e. mo = 0)

In the week before and after calving the incidence rates were 44.5, 40.4 and 38.0 per 10,000 cow days at risk for first, second and third lactation, respectively. In the period from 1 wk before calving until 2 mo after calving, the incidence rates were 16.1, 17.4, and 28.3 per 10,000 cow days at risk for first, second, and third lactation, respectively.

Bacterial examination of the milk samples was carried out for 77% of the clinical cases and showed that *Escherichia coli* occurred in 20.9% of infections, *Streptococcus dysgalactiae* in 6.3%, *Streptococcus uberis* in 8.5%, *Streptococcus agalactiae* in 2.4%, *Staphylococcus aureus* in 7.4%, *Actinobacillus pyogenes* in 2.8%, and other genera in 2.5%. In 49.2% of infections no significant organism were reported.

3.2. Production Parameters

The average accumulated milk production was 6433 kg (sd = 1066) on 305 d (10 mo) in the first lactation, 7632 kg (sd = 1324) in the second lactation, and 8286 kg (sd = 1359) in the third lactation (Table 2). The percentage of fat in the accumulated milk production in mo 10 was almost the same for first, second, and third lactations (4.45%), although the pattern during lactation differed. The standard deviation of percentages of fat and protein in accumulated milk was very stable over months and lactation number, i.e., .43 and .21, respectively. The percentage of protein in accumulated milk was highest in the second lactation and second highest in the first lactation (Table 2). In mo 10, the percentage of protein was 3.42 in the first lactation, 3.44 in the second lactation, and 3.40 in the third lactation. The pattern of percentages of fat and protein over months shows that the fat content in accumulated milk started to increase in mo 5; protein contents started to increase 1 mo earlier.

In the statistical analysis, the model with only main effects was used (Formula [3]) because preliminary results showed no consistent significant two-way interactions. Although DQ and the regression coefficient $\beta2$ were most often not significant and therefore excluded for statistical reasons, they were retained in the analysis for biological reasons. The expected calving interval was included in the analysis from mo 4 for statistical and biological reasons only.

The research was primarily focused on the effect of mastitis on production. Therefore no further attention was paid to the other main effects of Formula [3]. Estimates were only presented for first, second, and third lactations because too few observations were available for higher lactations.

In Table 3, the effect of mastitis on milk production (kilograms) are presented for the first 10 mo of three lactations: each row is a result of a separate analysis. To obtain unique solutions, the restriction PQ(0) = 0, CQ(0) = 0, and DQ(0) = 0 was introduced.

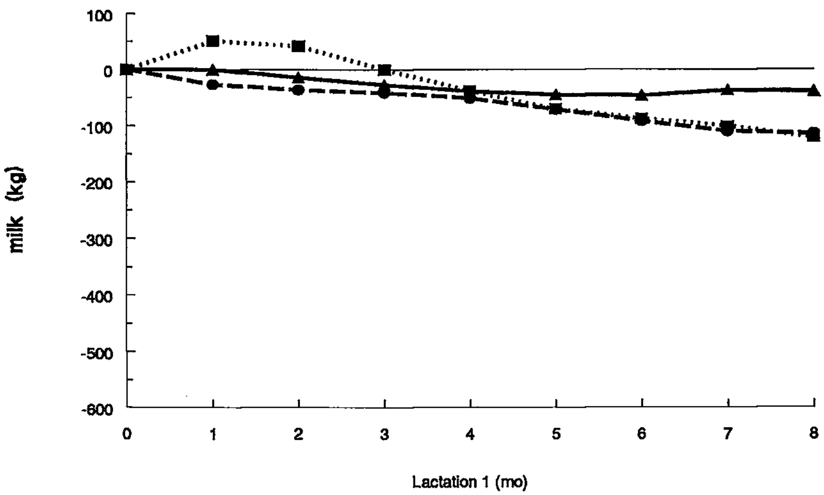
Table 3. The effect of mastitis class on the accumulated milk production. PQ (he number of clinical quarter cases in previous lactation), CQ (the number of clinical quarter cases in current lactation up to and including previous month) and DQ (the number of clinical quarter cases in current month). Lactation is Lact. and number of observations is Obs.

			DQ		CQ				PQ			
Lact.	Month	Obs.	0	1	0	1	2	3+	0	1	2	3+
1	1	1332	0	-20	0	0	-26	51	...	...	...	...
	2	1278	0	-21	0	-14	-36	42[bc]	...	...	...	...
	3	1238	0	-46[a]	0	-27[a]	-41	0	...	...	...	...
	4	1219	0	-32	0	-39[a]	-51[a]	-38	...	...	...	...
	5	1182	0	-25	0	-45[a]	-71[a]	-70[a]	...	...	...	...
	6	1132	0	0	0	-47[a]	-92[ab]	-88[a]	...	...	...	...
	7	1082	0	-10	0	-37[a]	-110[ab]	-101[ab]	...	...	...	...
	8	1009	0	-68	0	-39[a]	-114[ab]	-121[ab]	...	...	...	...
	9	760	0	11	0	-47[a]	-121[ab]	-132[ab]	...	...	...	...
	10	423	0	-12	0	-31	-106[ab]	-128[ab]	...	...	...	...
2	1	689	0	-33	0	-39	-88	-85	0	27	-30	-50
	2	680	0	-41	0	-71[a]	-177[a]	-193[ab]	0	38[a]	-31[b]	-110[abc]
	3	670	0	-11	0	-108[a]	-167[a]	-322[abc]	0	40[a]	-9	-171[abc]
	4	656	0	-43	0	-132[a]	-192[a]	-444[abc]	0	43[a]	-7	-206[abc]
	5	643	0	-22	0	-155[a]	-194[a]	-469[abc]	0	32	-15	-258[abc]
	6	624	0	56	0	-166[a]	-208[a]	-511[abc]	0	18	10	-286[abc]
	7	605	0	-34	0	-147[a]	-193[a]	-544[abc]	0	2	40	-336[abc]
	8	562	0	45	0	-161[a]	-214[a]	-527[abc]	0	-4	63[ab]	-381[abc]
	9	409	0	73	0	-160	-220	-429[abc]	0	-12	102[ab]	-429[abc]
	10	220	0	12	0	-155[a]	-172[a]	-448[abc]	0	-24	152[ab]	-459[abc]
3	1	357	0	-86[a]	0	-35	-31	...	0	53	66	1
	2	327	0	-28	0	-121[a]	-235[ab]	-116	0	77[a]	118[a]	-14[c]
	3	318	0	-66[a]	0	-137[a]	-215[a]	-235[a]	0	78[a]	157[a]	-85[bc]
	4	314	0	-15	0	-170[a]	-212[a]	-244[a]	0	83[a]	214[ab]	-152[abc]
	5	307	0	-26	0	-188[a]	-196[a]	-194[a]	0	74[a]	259[ab]	-196[abc]
	6	297	0	-9	0	-203[a]	-123[a]	-167[a]	0	32	298[ab]	-265[abc]
	7	288	0	27	0	-200[a]	9[b]	-133[a]	0	-10	328[ab]	-293[abc]
	8	266	0	15	0	-159[a]	62[b]	-91[a]	0	-68[a]	348[ab]	-274[abc]
	9	196	0	28	0	-116[a]	45	-26	0	-134[a]	377[ab]	-296[ac]
	10	88	0	...	0	-136	40	58	0	-128	329[ab]	-324[ac]

[a] 1, 2, 3+ versus 0 ($P < .01$)
[b] 2, 3+ versus 1 ($P < .01$)
[c] 3+ versus 2 ($P < .01$)

The analysis was carried out separately for milk, fat, and protein production. In Table 3 and Figure 2, the results of the effect of mastitis state variables on milk production are presented. Fat and protein estimates are presented only graphically in Figures 3 and 4. Comments on the patterns of fat and protein production over months are made only if they differ from milk production. The percentages of fat and protein are calculated as kilograms divided by uncorrected averages of Table 2.

The effect of one or more mastitis cases on the accumulated production of milk, fat, and protein is most often not significant during the month of occurrence (DQ) and is therefore excluded from Figures 2 to 4. However, the effect of a mastitis case on the production during the rest of the lactation (CQ) is much clearer and depends on the number of quarter cases. When only one quarter case has been observed, the effect on milk production appears to be temporary because the estimated effect is, on average, 40 kg in the first lactation and 140 kg in the second lactation and does not increase with the number of months in lactation (Table 2, Figure 2). Moreover, the effect of a mastitis case does not appear to depend on the stage of lactation in this situation but has a long-term effect on fat production. For example, the accumulated fat production was reduced by 1.7 kg (1.9%) in mo 3 and 4.3 kg (1.9%) in mo 8 in the first lactation (Figure 3), and the reduction in fat production in the second lactation was slightly higher (3.3 kg (2.8%) in mo 3 and 5.1 kg (1.8%) in mo 8). This pattern is different from that of protein production; few effects were significant for one quarter case in the first lactation. In the second lactation, this effect was relatively stronger than for fat production [4.5 kg (2.0%) reduction in month 8; Figure 4] which was proportionally larger than the reduction for fat production. Two and, especially, three or more cases of mastitis during a lactation seem to have a long-term effect on milk and fat production, in contrast to protein production, which does not decrease continuously during the months in lactation. Accumulated milk production at mo 8 of the first lactation was reduced by 121 kg (2.3%) when three or more mastitis infections occurred (Table 3). However, this reduction was not significantly different from a double infection. In the second lactation, milk production was significantly more reduced when three or more mastitis cases were observed in contrast to two mastitis cases. In mo 8 of the second lactation, the reduction in milk production was 527 kg (8.1%) and 214 kg (3.3%) when three or two cases were observed respectively (Table 3). Until mo 6 in the first lactation, more than one mastitis case did not have a significantly different effect on production in comparision with only one case. From that point on, two and more cases had a significantly higher reduction than did one case. The effects of CQ and DQ in the third lactation seem to be the same as in the second lactation.



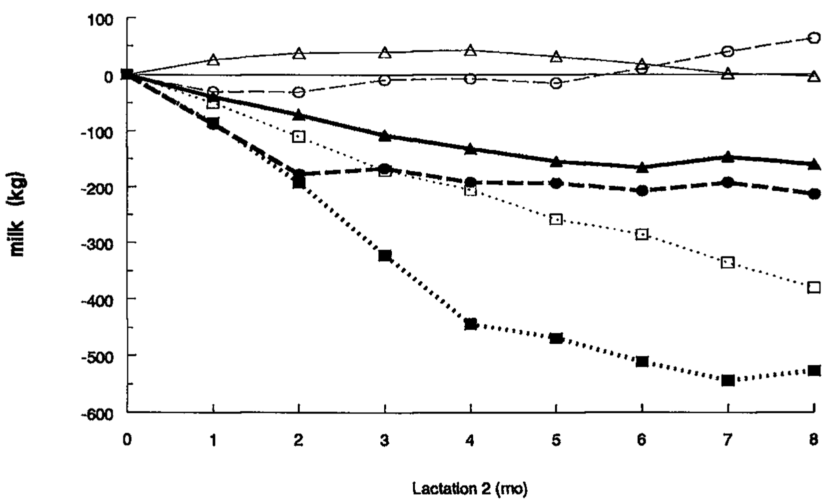


Figure 2. The effect of 1 (▲), 2 (●), or 3 or more (■) accumulated number of clinical quarter cases in current lactation through previous month (CQ) and 1 (△), 2 (○), or 3 or more (□) accumulated number of clinical quarter cases in previous lactation (PQ) on accumulated milk production in first lactation (top) and second lactation (bottom).

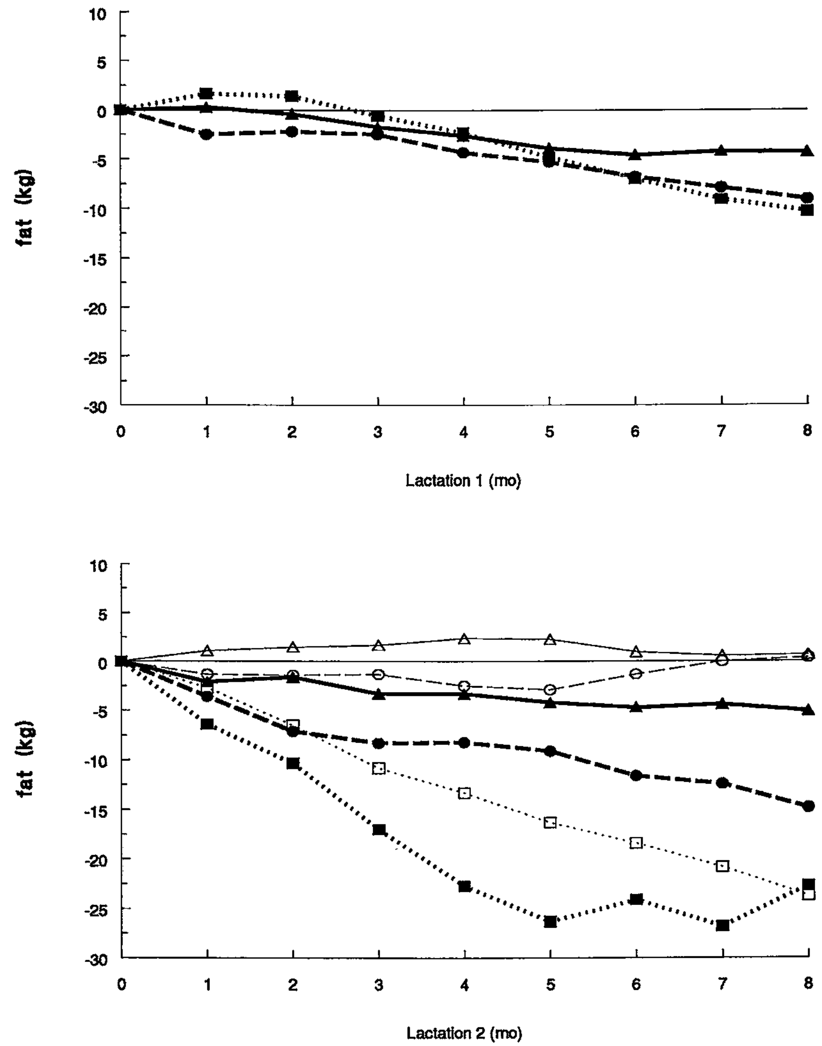
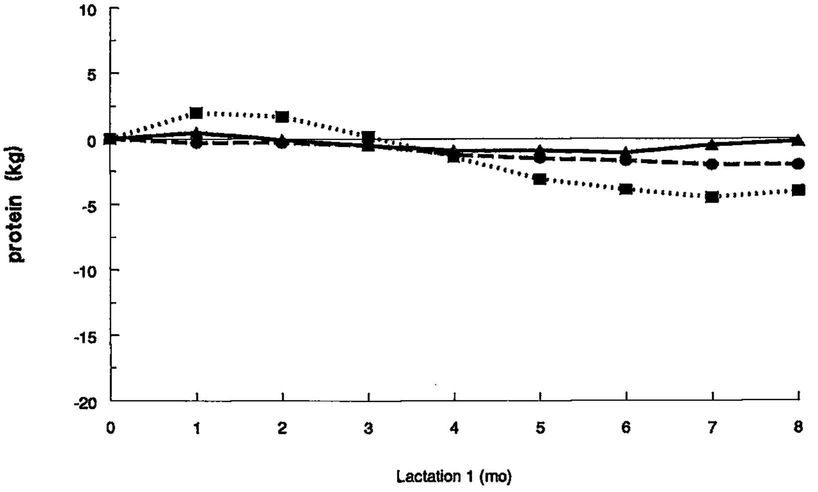


Figure 3. The effect of 1 (▲), 2 (●), or 3 or more (■) accumulated number of clinical quarter cases in current lactation through previous month (CQ) and 1 (△), 2 (○), or 3 or more (□) accumulated number of clinical quarter cases in previous lactation (PQ) on accumulated fat production in first lactation (top) and second lactation (bottom).



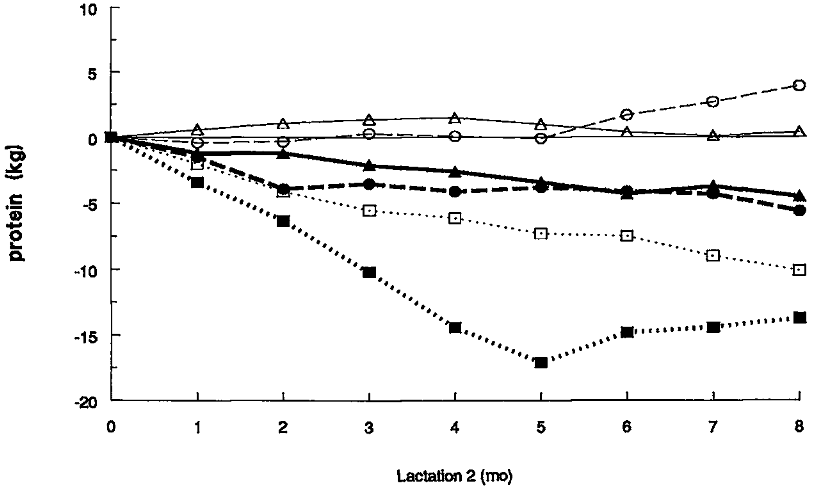


Figure 4. The effect of 1 (▲), 2 (●), or 3 or more (■) accumulated number of clinical quarter cases in current lactation through previous month (CQ) and 1 (△), 2 (○), or 3 or more (□) accumulated number of clinical quarter cases in previous lactation (PQ) on accumulated protein production in first lactation (top) and second lactation (bottom).

The effects of one or more mastitis cases in the previous lactation (PQ) on production in the current lactation differed from the effects of mastitis during the current lactation. The effect of one or two mastitis cases in the previous lactation was seldom significant for accumulated milk, fat, and protein production during the second lactation and appeared to be positive even in the third lactation. However, when three or more mastitis cases were observed in the first lactation, accumulated milk production decreased by 171 kg in mo 3 (6.3%) and 381 kg (5.9%) in mo 8 of lactation two (Table 3). The accumulated fat production decreased by 10.8 kg (9.2%) in mo 3 and 23.7 kg (8.4%) in mo 8 (Figure 3). The effect on accumulated protein production was less than on fat production but was still significant at 5.5 kg (6.1%) and 10.1 kg (4.6%) in mo 3 and 8, respectively (Figure 4). Three or more clinical cases in the first lactation showed a constant negative additive effect on milk, fat, and protein production in the second lactation, as suggested from almost linear trends of PQ(t) = (3+) in Figures 2, 3, and 4.

As expected, production decreased for cows with three or more mastitis cases during the first lactation and three or more cases during the second lactation. Until mo 8 of the second lactation, the production for this subset of cows with chronic infections decreased with 909 kg (381 + 527; Table 3) (14.0%), 46.4 kg (23.7 + 22.7) (16.0%), and 23.8 kg (10.1 + 13.7) (10.8%) for milk, fat, and protein production, respectively.

Because production capacity (U_{nt}) was included in the model, very high R-squares were obtained. In mo 1 of each lactation, R-squares were lowest and ranged from 23.2% in the first lactation to 55.6% in the third lactation. In higher months, when the production capacity was estimated more accurately, the R-squares were more than 94% in mo 2 and even higher than 99% in mo 5 and onward. The correlations of residuals between accumulated production in mo 6 of the first lactation and mo 6 of the second lactation were .54, .49 and .50 for milk, fat, and protein production, respectively. Between the second and third lactation, the correlation of residuals were .65, .65, and .63, and .54, .50, and .52 between the first and third lactation.

3.3. State Transition Probabilities

The applied model of the logistic analysis from mo 2 to 10 fitted the data with a deviance of 1007 with 1405 df (Table 4). A mastitis case in the current month increased the probability of a clinical quarter case in the next month by 4.8. Especially until mo 4, the risk of mastitis infection was high. Table 4 indicates that cows had a higher risk of infection as lactation number increased. For cows that produce 1 sd more than average in the previous month, the risk of mastitis in the next month increased by 2.6 in comparison with cows that produce less than 1 sd

Table 4. Multivariate regression coefficients (β), standard errors and odds ratios (OR) of model parameters excluding mo 1 of lactation.

Effect	Class	β	SE	OR
Intercept		-2.4239	.0906	
Month	2	.7495	.0877	4.1
	3	.5333	.0914	3.4
	4	.3082	.0985	2.7
	5	.0509	.1070	2.1
	6	.1390	.1078	2.2
	7	-.0837	.1175	1.8
	8	-.5127	.1414	1.2
	9	-.5131	.1430	1.2
	10	-.6714	Reference	1
Lactation	1	-.5370	.0892	.4
	2	-.0359	.0806	.6
	3	.0788	.0800	.7
	4	.0825	.0835	.7
	>=5	.4116	Reference	1
Production level	+	.4630	.0646	2.6
	o	.0349	.0549	1.7
	-	-.4979	Reference	1
PQ[1]	>=3	.3975	.1269	2.9
	2	.2705	.1150	2.6
	1	.0042	.0935	2.0
	0	-.6722	Reference	1
CQ[2]	>=3	.2942	.1589	2.5
	2	.3189	.1331	2.6
	1	.0218	.0984	1.9
	0	-.6349	Reference	1
DQ[3]	1	.7814	.0564	4.8
	0	-.7814	Reference	1

[1] PQ = accumulated number of clinical quarter cases in the previous lactation

[2] CQ = accumulated number of clinical quarter cases in current lactation from the beginning of the lactation through previous month

[3] DQ = binary variable indicating that clinical mastitis was diagnosed in at least 1 quarter or in none of the quarters

below average. The factor of the increased risk of mastitis infections because of infections in the previous lactation ranged from 2.0 (one mastitis case) to 2.9 (three or more cases); i.e., this effect was about the same as the effect of accumulated mastitis cases until the previous month in the current lactation. Apparently, occurrence of clinical mastitis in the current lactation (CQ(t) > 0) was more important than the number of clinical cases because those odds ratios were similar and indicated that the probability had approximately doubled.

The applied model for calculating the risk of mastitis in mo 1 of lactation was fitted with a deviance of 1.9 on 3 df (Table 5). Production level and lactation number are not included in Table 5 because they were not significant. The effect of PQ was almost the same as for other months in làctation. One or more mastitis cases from 7 d before calving until 7 d after calving (DQ) increased the risk of a mastitis case by 4.7 during the rest of mo 1 after calving.

Table 5. Multivariate regression coefficients (β),standard errors and odds ratios (OR) of model parameters for mo 1 of lactation.

Effect	Class	β	SE	OR
Intercept		-2.2713	.1724	
PQ[1]	>=3	.3410	.3459	2.6
	2	.1037	.3226	2.0
	1	.1548	.2347	2.1
	0	-.5995	Reference	1
DQ[2]	1	.7751	.1130	4.7
	0	-.7751	Reference	1

[1] PQ = accumulated number of clinical quarter cases in the previous lactation

[2] DQ = binary var iable indicating that clinical mastitis was diagnosed in at least 1 quarter or in none of the quarters in the week before and the week after calving

The state transition probabilities were calculated using Formula [5]. For example, the probability that a high producing cow in mo 4 of the third lactation will be clinically infected with mastitis providing that she had two quarter cases in the second lactation, one quarter infected in mo 3, and none in the first 2 mo, was

$$\frac{e^{(-2.4239\ +\ .3082\ +\ .0788\ +\ .4630\ +\ .2705\ -\ .6349\ +\ .7814)}}{1\ +\ e^{(-2.4239\ +\ .3082\ +\ .0788\ +\ .4630\ +\ .2705\ -\ .6349\ +\ .7814)}} = .24.$$

Such a cow had a 24% probability of contracting clinical mastitis in mo 5 of the third lactation.

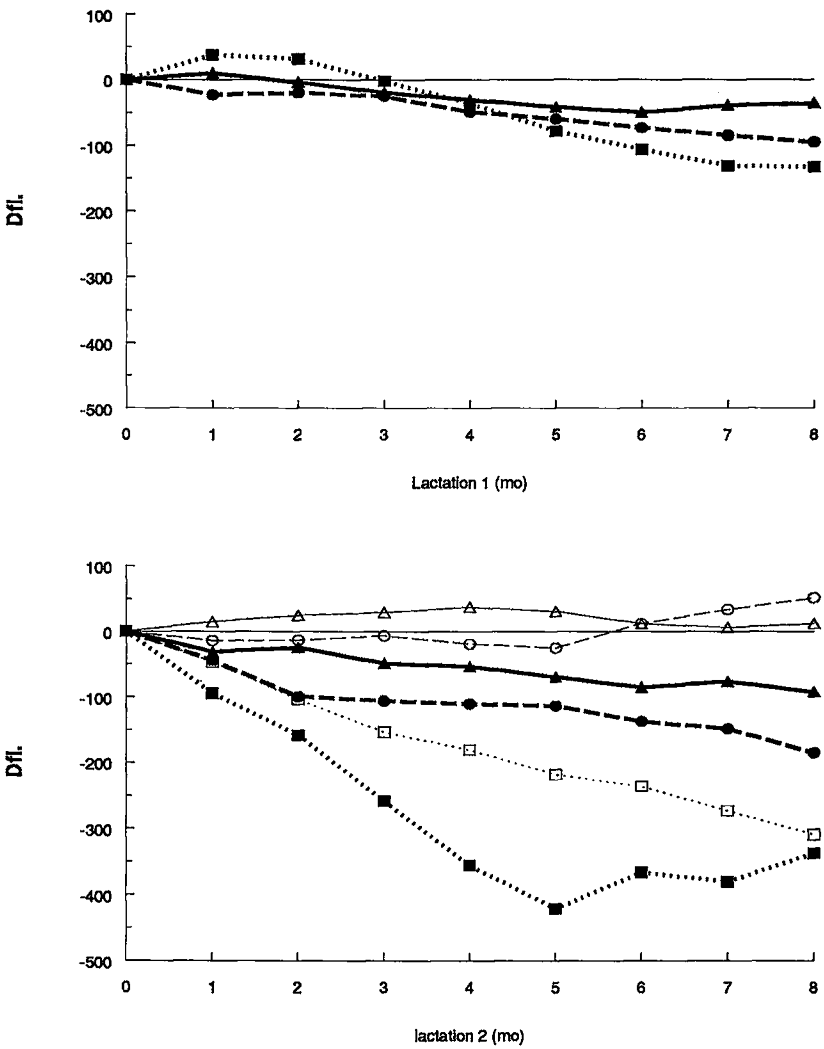


Figure 5. The effect of 1 (▲), 2 (●), or 3 or more (■) accumulated number of clinical quarter cases in current lactation through previous month (CQ) and 1 (△), 2 (○), or 3 or more (□) accumulated number of clinical quarter cases in previous lactation (PQ) on economic return (Dutch florin (Dfl.) = -.09 x kg milk + 8.5 x kg fat + 14 x kg protein) in first lactation (top) and second lactation (bottom).

4. Discussion

4.1. Production Parameters

The technique used in this study was a reliable method to calculate unbiased estimates of production losses, although cows were culled, and mastitis was more frequently observed in high producing cows. The major disadvantage of this stepwise estimation method was the requirement of the complete history of a cow. Estimates were based on the presence of records for all lactations until lactation n and month t in the data set. Consequently, estimates in higher lactations and higher months in a lactation were based on only a few records and were therefore less accurate. In the future, estimates for older cows can only be unbiased when production data are stored on a long-term basis, which should not present a problem for available computer systems.

Although culling and correlation between milk production and occurrences of mastitis no longer bias the estimates, these estimates are affected because they are based on the distribution of mastitis types in the dataset. This distribution cannot be expected to be the same as if no culling had occurred. For example, cows that died from acute mastitis are less likely to have been used as samples, and cows suffering from *Actinobacillus pyogenes* are most often culled immediately. Therefore, the effect of this type of mastitis on production was not included in the estimates. Estimates for each type of mastitis would have been preferable, but the size of the data set did not allow the division of mastitis into more classes. According to Lucey and Rowlands (1984), both King (1969) and Natzke et al. (1972) demonstrated that the severity of mastitis varies substantially with the pathogens involved, which could have an overall bearing on the magnitude of observed reduction in milk production. The limitation in number of mastitis classes was also the reason for representing the mastitis history of a cow with only three variables (PQ, CQ, and DQ); within each of those three variables, the time of occurrence was assumed not to have a separate effect.

Estimates of lactation production have been based on testing at monthly intervals. However, within a 1 mo period, a cow may contract mastitis, suffer substantial milk losses, completely recover, and reach her previous production level (Bartlett et al., 1991). Depending on the production testing schedule, some or all of this mastitis experience may even be omitted from the production record. For these reasons, the effect of mastitis on the production can be expected to be underestimated because the lowest production has most often not been measured. Dohoo and Martin (1984) reported that the percentage loss determined from individual test day data was substantially higher than the loss determined from lactation mean. Lucey et al. (1986)

concluded that monthly frequency of sampling was insufficient for studying short-term effects on milk quality. The long-term effects of mastitis on production, represented by PQ (carry-over) and CQ, were estimated more adequately in our study because more measure points were available, which made interpolation possible. The underestimation of a short-term effect (DQ) and the exclusion of the time of occurrence may be the reason that the short-term effect of mastitis most often has no significant effect on production, which is in disagreement with Bartlett et al. (1991), who reported decreased production of 92 kg during the 60 d after clinical onset. This effect is also in disagreement with Deluyker et al. (1991), who found a significant reduction of 7.3% and 8.1% in accumulated production for the periods of 1 to 21 and 50 to 119 d in milk, respectively, when mastitis was diagnosed in subsequent periods. Lucey et al. (1986) reported decreased production even before the onset of clinical mastitis.

The long-term impact (more than 1 mo) of mastitis on production is shown in Figures 2, 3, and 4 for milk, fat, and protein production respectively. Although DQ (short-term effect) was rarely significant, the mastitis state had clear long-term impact on production level. As expected, the carry-over effect from the previous lactation (PQ) of 3 or more clinical infected quarters on production was considerable. Compared with production of completely healthy cows, production until mo 8 of the second lactation decreased 381 of kg milk (5.9%), 23.7 kg of fat (8.4%), and 10.1 kg of protein (4.6%). In the third lactation cows with 3 or more clinical infected quarters in previous lactation produced 274 kg of milk (3.9%), 12.5 kg of fat (4.1%) less, but change in protein production was not significant. Therefore, fat content in milk produced after the onset of mastitis decreased and protein content increased. According to Deluyker (1991), several studies reported that milk fat percentage was reduced in clinical mastitis. Deluyker (1991) also reported that most researchers found increased protein concentration, although total protein production and milk volume decreased. These results are in agreement with our study.

The estimates of PQ show that 1 or 2 infected quarters in the previous lactation have no clear effect. Raubertas and Shook (1982) reported that a unit of increase in total lactation average $\log_2$ SCC (which reflects clinical and subclinical mastitis) resulted in an estimated milk loss in the following lactation of between 81 and 111 kg, but their findings were not statistically significant. Moreover, Fetrow et al. (1991) reported also results of a carry-over effect of subclinical mastitis and they found that this effect of a high SCC over lactations was generally statistically significant but small (less than 20% of the direct effect of increased SCC). Lucey and Rowlands (1984) subdivided their population, to examine the effect of clinical mastitis in the previous lactation on milk production in the current lactation, showing no significant effect in milk production in the current lactation when cows were free from infection but clinical mastitis had occurred in the preceding lactation. Dohoo and Martin (1984) reported a minor beneficial effect of clinical mastitis on milk production after controls for the negative effect of subclinical mastitis. They suspected that the positive effect of clinical mastitis may have been due to the effects of mastitis therapy, which probably eliminated subclinical infection successfully. According to Deluyker (1991) this positive effect after treatment was also reported by Wood and Booth (1983). In our study, no correction was made for treatment effect because 25% missing values for treatment would reduce the data set too much. Nevertheless, most of the clinical cases were expected to be treated (according to the existing values, 99% of the clinical cases were treated parenterally, locally, or both); therefore, an effect similar to that suggested by Dohoo and Martin (1984) could be the reason for the slightly positive effect of single or double infection in the previous lactation.

The lower graph in Figures 2 to 4 shows that the direct effect of mastitis (CQ) on production in the second lactation was much clearer. Each infected quarter had a negative additive effect on the milk, fat, and protein production. However, those curves apparently flattened after mo 5 in lactation, which means that no effect of clinical mastitis occurred on daily production later in the lactation. Accumulated production, however, did not return to its normal level. Also, Lucey and Rowlands (1984) reported that clinical mastitis had no effect on production later in the lactation.

In most European countries, the milk price depends on fat and protein contents; therefore the effects of mastitis on milk, fat, and protein production were analyzed in our study. In the Dutch payment system, for example, the value of 1 kg of milk, fat, and protein is -.09, 8.5, and 14 Dutch florins (Dfl.) respectively (Anonymous, 1991). In the first lactation, each clinically infected quarter reduced the accumulated gross returns on milk, fat, and protein production by 40 Dfl. until mo 8 (Figure 5). Three or more infections in the first lactation reduced the gross returns by approximately 40 Dfl. in each month of the second lactation. Three or more infections in the second lactation reduced the gross return by about 80 Dfl. monthly until mo 5, after which gross returns were stabilized and even compensated for somewhat. One or two clinically infected quarters in the second lactation reduced the gross returns on milk, fat, and protein production by approximately 10 and 20 Dfl., respectively.

Only a relatively small group of farmers was represented in the data set. Although randomness was attempted, the sample of the Dutch dairy cows was not random [in 1990, average 305-d production of all Dutch Black and White cows was 6997 kg (Anonymous, 1991), which is 845 kg less than the corresponding average in our study]. All producers were from the center of The Netherlands; their general management (breed and soil type), therefore, differed from that of a typical Dutch farmer. Schukken et al. (1991) found, for example, that breed and dry soil in summer was associated with the incidence of *Escherichia coli*, but not with the incidence of *Staphylococcus aureus*.

4.2. State Transition Parameters

Bunch et al. (1984) found that 45% of the first cases of mastitis occurred during the first 60 d of lactation. Probability of mastitis infection was highest in the first part of the lactation (Table 4). Bunch et al. (1984) also observed that the incidence of mastitis was slightly higher in winter and spring than in summer and autumn. In our study, such an effect was not significant, probably because of the size of the data set.

One or two clinical cases of clinical mastitis in the previous lactation in the present study had no consistent impact on milk production in the current lactation. Although usually not significant, one or two clinical mastitis cases in the previous lactation tended to have a positive effect on production, provided that a cow was healthy in the current lactation. In spite of the slightly positive effect of a moderate infection in the previous lactation, future production is expected to be reduced, because the logistic regression shows that, for cows with mastitis in the previous lactation, the risk of mastitis in the current lactation increased by 1.8, 2.3, and 2.8 for one, two, and more than two diagnosed clinical cases, respectively. Mastitis had a strong negative effect on production in the current lactation; therefore, those cows were expected to produce less in the future. Rowlands et al. (1986) reported that mastitis occurred in 38% of the cows that experienced the disease in the previous lactation as opposed to 23% of those that had not. Similar tendencies to infection were found by Bunch et al. (1984) and Dohoo and Martin (1984). According to Rowlands et al. (1986), this effect may be due to two factors: an increased susceptibility to further outbreaks or prolongation of a subclinical infection through the dry period and into the next lactation.

The risk of mastitis infection increased with production level, which is in agreement with others (Bartlett et al., 1991; Bunch et al., 1984; Deluyker, 1991; Heuven, 1987; Schukken et al., 1991). Moreover, incidence of mastitis increased with lactation number, which is in agreement with literature (Bunch et al., 1984; Lucey and Rowlands, 1984). However, no lactation effect occurred for incidence of mastitis in mo 1. For this reason, inclusion of an interaction effect was not necessary. A separate analysis had to be carried out because of a different period in length of mo 1 (i.e., wk 1 after calving is excluded) and because of the inclusion of the period around calving. When clinical mastitis was observed from wk 1 before until wk 1 after calving, the risk of mastitis in the remaining part of mo 1 increased by 4.7 (Table 5).

In logistic regression, effects of treatment (such as local or parenteral treatment) could not be included in the statistical model directly because of missing values in the VAMPP data set. These effects, therefore, should be estimated separately or gathered from the literature.

According to Curtis et al. (1988), problems arise when logistic regression for analysis of data from field studies is used, because the sampling unit is often a livestock premise, whereas the individual animal is the unit of interest and analysis. The use of multiple logistic regression requires the assumption that animals with the same covariate vectors (identical set of risk factors) are independently and identically distributed. However, Curtis et al. (1988) compared several more advanced logistic regression techniques and concluded that, in general, the parameter estimates were similar for the model types but that the significance levels were greater, and the confidence intervals wider, for the more advanced techniques. Because significance levels in our study clearly showed that included effects were significant, a more advanced technique cannot be expected to change the presented results.

In contrast to estimation of production parameters, production level in logistic regression was based on the uncorrected production of the cow; otherwise, too many mastitis observations would have been excluded. For this reason, estimates of the effect of production on transition probabilities were biased and should be interpreted carefully.

Outlook

The whole complex of costs, returns, and probabilities can be evaluated by dynamic programming (Van Arendonk and Dijkhuizen, 1985; Kristensen, 1987; Huirne, 1990). Results can be used to determine the impact for economically optimal treatment and replacement decisions. In that analysis, other effects of mastitis will also be included, e.g., treatment costs, costs of discarded milk, and other costs.

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Appendix 1

This Appendix describes the deduction of odds ratio (OR) = $\exp(\beta - \beta_{ref})$. The OR(level 1 vs. level 3) is determined in an example of an analysis in which the occurrence of disease depends on one class variable with three levels. Estimation of the parameter of the last level is not needed because CATMOD constrains the three parameters to sum to zero (SAS, 1988). The design matrix is

level	β_1	β_2
1	1	0
2	0	1
3	-1	-1

Logistic regression uses a loglinear model to describe the risk of the development of disease. The probability of disease is

$$p = \pi(x) = \frac{e^{\beta_0 + \beta_1 x_1 + \beta_2 x_2}}{1 + e^{\beta_0 + \beta_1 x_1 + \beta_2 x_2}}$$

where β_0 (intercept), β_1, and β_2 are parameters to be estimated from the data set, x is the specific value from the design matrix. The main idea behind logistic regression is the logit transformation of $\pi(x)$, which is defined as

$$g(x) = \ln\left(\frac{\pi(x)}{1 - \pi(x)}\right) = \ln\left(\frac{\dfrac{e^{\beta_0 + \beta_1 x_1 + \beta_2 x_2}}{1 + e^{\beta_0 + \beta_1 x_1 + \beta_2 x_2}}}{\dfrac{1}{1 + e^{\beta_0 + \beta_1 x_1 + \beta_2 x_2}}}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2.$$

The odds between probability of being ill and not ill for level 1 of the class variable is $\pi(1) = \pi(x_1 = 1, x_2 = 0)$:

$$\frac{\pi(1)}{1 - \pi(1)}.$$

The odds between probability of being ill and not ill for level 3 of the class variable is $\pi(3) = \pi(x_1 = -1, x_2 = -1)$:

$$\frac{\pi(3)}{1 - \pi(3)}.$$

Odds ratio is the ratio between both odds. Ln(OR) is

$$\ln(OR) = \ln\left(\frac{\dfrac{\pi(1)}{1 - \pi(1)}}{\dfrac{\pi(3)}{1 - \pi(3)}}\right) = g(1) - g(3).$$

In this example is

$$g(1) = \beta_0 + \beta_1 * 1 + \beta_2 * 0$$
$$g(3) = \beta_0 + \beta_1 * -1 + \beta_2 * -1.$$

If β_{ref} [reference level (3)] is defined as (i.e., mean coding):

$$\beta_{ref} = -\beta_1 - \beta_2,$$

OR (level 1 vs. level 3) is

$$OR = e^{g(1) - g(3)} = e^{(\beta_0 + \beta_1) - (\beta_0 + \beta_{ref})} = e^{\beta_1 - \beta_{ref}}.$$

Chapter 3

Optimal replacement of mastitic cows determined by a hierarchic Markov process

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Abstract

Farmers frequently have to decide whether to keep or to replace cows that suffer from clinical mastitis. A dynamic programming model was developed to optimize these decisions for individual cows within the herd, using the hierarchic Markov process technique. It provides a method to model a wide variety of cows, differing in age, productive performance, reproductive status, and clinical mastitis occurrence. The model presented was able to support decisions related to 63% of all replacements. Results - for Dutch conditions - showed a considerable impact of mastitis on expected income of affected cows. Nevertheless, in most cases, the optimal decision was to keep and treat the cow rather than to replace her. Clinical mastitis occurring in the previous lactation showed a negligible influence on expected income. Clinical mastitis in current lactation, especially in the current month, however, had a significant effect on expected income.

Total losses caused by clinical mastitis were $83[1] per cow per year. Farm level treatments which reduces incidence by 25%, on a farm with 10 clinical quarter cases per 10,000 cow days, may cost $27 at maximum per cow per year.

(**Key words**: economics, dynamic programming, mastitis, replacement)

Abbreviation key: CQ = accumulated number of diagnosed clinical quarters in the current lactation from the beginning of the lactation (t = 0) through month t - 1 (four levels: 0, 1, 2, and ≥3), **DP** = dynamic programming, **DQ** = binary variable indicating that clinical mastitis was diagnosed in at least one quarter (≥1) or in none of the quarters (0) in month t of the current lactation, **HMP** = hierarchic Markov process, **PQ** = accumulated number of clinical quarters in the previous lactation (four levels: 0, 1, 2, and ≥3).

1. Introduction

A farmer's replacement policy of dairy cows greatly influences profitability (Renkema and Stelwagen, 1979; Congleton and King, 1984). According to Morris and Marsh (1985) and Van Arendonk (1988), major reasons for culling cows are low production, failure to conceive, and mastitis. Mastitis has a large economic impact and is considered to be the most important health problem in many countries (Schepers and Dijkhuizen, 1991). Houben et al. (1993) analyzed a 5313 lactation data set of 2477 Dutch Black and White cows, and described estimated production parameters and reoccurrence probabilities with regard to clinical mastitis. Over a

[1] 1$ = Dfl. 1.80 in this research

mid- and long-term period (>1 mo) clinical mastitis reduced milk production by 2.3 to 6.2%. Clinical mastitis appears to be repetitive across lactations and, therefore, has important economic implications, which in turn affects decision making. Decisions to replace cows are mainly based on economic rather than biological considerations; i.e., the farmer expects to improve profits by replacing the cow (Van Arendonk, 1988). The inherent biological cycles of reproduction and lactation make dairy cow management decisions dynamic, recursive, and stochastic. Replacement decisions are in the first place time-dependent. In recursive stochastic multistage optimization problems, dynamic programming (DP) has the advantage of determining optimal decisions without requiring exhaustive enumeration of all sequences of transition possibilities (DeLorenzo et al., 1992).

Jenkins and Halter (1963), Giaever (1966), and Smith (1971) used the DP approach in their comprehensive studies to optimize dairy cow replacement policies. Before the 1980s, detailed DP models were not available to support decisions because of the lack of computer capacity. Subsequently, several DP models were developed to optimize decisions to replace individual animals (cows and sows) based on production capacity, reproductive status, or both (Van Arendonk and Dijkhuizen, 1985; Van Arendonk, 1986; Kristensen, 1987; Kristensen, 1989; Stott and Kennedy, 1990; DeLorenzo et al., 1992; Huirne et al., 1993).

Stott and Kennedy (1990) included clinical mastitis as a state variable in their replacement model. Replacement within a lactation was not possible in their model, and mastitis state was treated as a binomial variable rather than a multilevel variable. The way clinical mastitis was modelled was not detailed enough to come to sound economic conclusions.

In the Netherlands, the main reasons for culling cows are poor production and appearance (35%), poor fertility (20%), and mastitis (8%) (1987). If these factors were successfully included in a replacement model, the system would support about 63% of all replacement decisions in dairy cattle management. Because risk factors for clinical mastitis include production, age, month in lactation, and mastitis history (1993), and because of the stochastic nature of mastitis, addition of clinical mastitis to replacement and insemination models appears to be worthwhile.

One objective of this paper was to develop a DP model for dairy cow insemination and replacement decisions that include, in a detailed way, clinical mastitis as a state variable. Another objective was to carry out a sensitivity analysis to gain insight into the relationship between mastitis-related parameters and losses caused by clinical mastitis. Methods used provide a means of determining actual costs of clinical mastitis, and maximum cost of farm level treatments on an average farm.

2. Material and methods

2.1. Markov Decision Theory

The general description of Markov decision theory and the basic formulation of the hierarchic Markov process as presented in this and the next section were mainly based on Kristensen (1988).

Consider a time dependent Markov decision process with a finite state space U at each stage t and a finite decision set D. Policy s is a map assigning to each state i at stage t a decision $d(i,t) \in D$. The time interval between two transitions is called a stage (t). Let $p_{ij}(t,d)$ be the transition probability from state i to state j if decision d is taken at stage t. If in state i at stage t a decision d is chosen, then (according to the Markovian property), regardless of the history of the system, 1) an immediate expected reward $r_i(t,d)$ is obtained, and 2), at the next stage, the system will be in state j with probability $p_{ij}(t,d)$. According to the Markovian property, the immediate expected reward obtained from the decision made in state i at stage t, is not dependent upon the next state j. This general Markov decision process is reviewed at equidistant points in time t. However, in semi-Markov decision theory it is assumed that, if state i is observed and decision d is made, a physical quantity (e.g. time or milk) of $m_i(t,d)$ is involved in the transition of the system.

An optimal policy is defined as a policy that maximizes (or minimizes) some predefined objective function. The objective function can maximize the total expected discounted rewards over the planning horizon (discounting criterion) or the expected average reward per unit of time (average criterion). To solve general Markov decision problems by DP, value and policy iteration can be used as optimization techniques. With value iteration, the optimal policy is determined sequentially using the recurrent equations of Bellman (1957). Value iteration is exact when optimization occurs under a finite planning horizon. Under an infinite planning horizon, however, the value iteration method can be used to approximate the optimal policy, especially in case of cyclic production. Value iteration makes it possible to handle large models. With policy iteration, a set of linear simultaneous equations are solved (Howard, 1960). By discounting criteria, policy iteration determines the total present value of the expected future rewards of a process starting in a certain state under a given policy. When an average criterion is used, the set of simultaneous equations determines the relative value of each state and moreover the average reward per unit of time (gain) under a certain policy. With this information, a new policy is chosen, which maximizes the objective function. Those steps are performed iteratively until the policy does not change anymore. Policy iteration can only be used for optimization under an infinite planning horizon and is in that case exact. Because of the more complicated mathematical formulation involving a solution of large systems of simultaneous linear equations, the method can only handle rather small models (Kristensen, 1993).

Kristensen (1988) developed an alternative structure of a Markov process, called the hierarchic Markov process (HMP) that includes both value iteration and policy iteration in one model. In our study, the HMP approach was used.

2.2. HMP

One of the reasons that replacement models, formulated as a general Markov decision process are usually very large is that the age of the animal in question is included as a separate state variable (Kristensen, 1988). As a result, most elements of the transition matrix equal zero, because these transitions are not feasible (e.g., immediate transition from the second to the fifth lactation is not possible). The HMP omits age as a state variable and, moreover, takes advantage of the fact that, when a replacement occurs the process (life cycle of the replacement animal) is restarted. In the traditional Markov decision model, a replacement is represented as a transition just like all others from one state to another. In an HMP, the general Markov decision process is split into one main process and subprocesses. Each state in the main process represents a separate Markov decision process (a subprocess) with a finite number of stages (i.e., the maximum lifespan of a cow). The structure of the transition matrix of an HMP is shown in Figure 1. The number of subprocesses equals the number of states in the main process. State variables of the main process concern states of the cow that do not change during its life time (e.g., age at first calving). The immediate expected rewards (net revenue from a single stage) in the main process are calculated from the rewards of the subprocesses. The timestep (stage duration) in the main process equals the total length of the corresponding subprocess (Kristensen, 1987).

One advantage of an HMP over a general Markov decision process is that the number of transition probabilities is reduced by a factor equal to the square of the number of aging states. If, for instance, 12 lactations are distinguished in the model, the number of transition probabilities is reduced by 12^2. However this reduction is not really a reduction of the number of transition probabilities because these probabilities are all zero in a general Markov decision process. In other words, the HMP especially refers to the nonzero part of the transition matrix of a general Markov decision process.

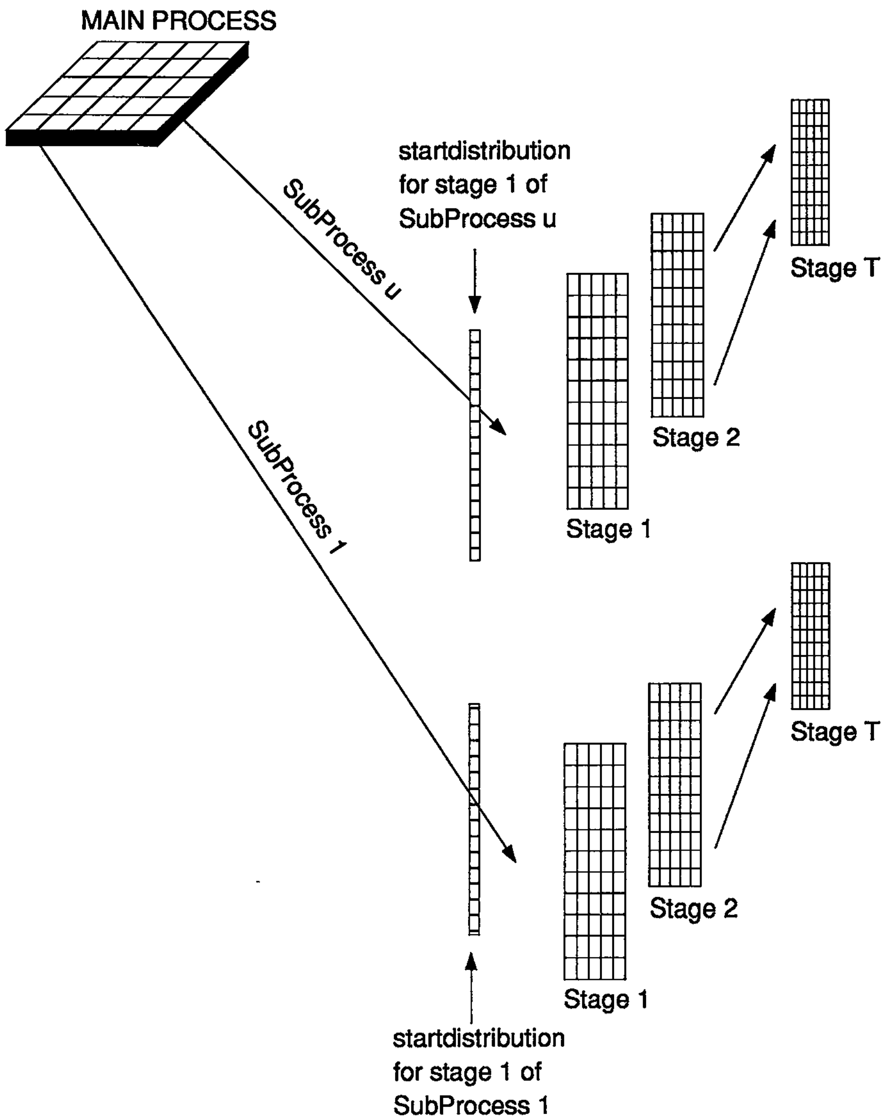

Figure 1. Transition probability structure of a hierarchic Markov process (T is the maximum age of a cow).

The main advantage of the HMP is directly related to its structure. A subprocess has a well-defined finite planning horizon (lifespan of cow). This and its large state space make value iteration the ideal optimization method to use. The main process has a small state space and an infinite planning horizon; therefore, policy iteration can be applied without computation problems. It can be proven mathematically that the complete HMP should be regarded as a general Markov decision process optimized with policy iteration (Kristensen, 1988). Applying the value iteration method in the subprocesses with a finite planning horizon and policy iteration in the main process with an infinite planning horizon results in a sound optimization technique which is fast, exact, and able to handle very large models (Kristensen, 1988; Kristensen, 1991).

In our study, a special case of the HMP was used with only one state in the main process (i.e., one type of subprocess). The objective function in the current cow replacement model was to maximize average net revenues per time unit. Discounting of net revenues was not applied because previous work (Kristensen, 1991) had shown that discounting had no effect on the optimal strategy.

2.3. Optimization of the HMP

The iterative optimization procedure of the HMP starts with the choice of an arbitrary policy. In the second step this policy is used to calculate the total expected reward and total expected output from the remaining part of the process for each state at each stage in a subprocess. Weighing of the total expected reward and output at stage 1 with the start distributon of a subprocess produces the total expected reward and total expected output for each state in the main process. With this information, the relative value of each state in the main process and the gain can be calculated by using matrix algebra. In the last step of the procedure the gain is used to determine the new improved policy. Steps 2 and 3 are repeated until the policy is stable, i.e. does not change with further iterations. These steps are described in formula form within the following paragraphs, and are based on Kristensen (1991).

In the notation, α and β are used to denote states of the main processs and i and j to denote states of subprocesses. A policy for a subprocess is denoted s and the map of policies of subprocesses is denoted σ (i.e. $s = \sigma(\alpha)$). The three steps of the iteration cycle are

Step 1), Choose an arbitrary policy σ. Go to step 2.

Step 2), Solve the following set of u + 1 linear simultaneous equations for $g(\sigma)$ and $F_\alpha(\sigma)$ by using matrix algebra:

$$g(\sigma)h_\alpha(\sigma) + F_\alpha(\sigma) = f_\alpha(\sigma) + \sum_{\beta=1}^{u} P_{\alpha\beta}F_\alpha(\sigma), \quad \alpha = 1,\ldots,u \qquad [1]$$

$$F_u(\sigma) = 0$$

where

$g(\sigma)$ = gain (i.e. reward per physical output) under policy σ,

$F_\alpha(\sigma)$ = relative value of state α under policy σ,

$P_{\alpha\beta}$ = transition probability from state α to state β in the main process,

u = number of subprocesses,

$f_\alpha(\sigma)$ = the reward in state α of the main process

$$= \sum_{i=1}^{I_{t=1}} p_i(0) f_i(1,s)$$

(the right-hand side of this equation belongs to subprocess α),

$h_\alpha(\sigma)$ = the physical output in state α of the main process

$$= \sum_{i=1}^{I_{t=1}} p_i(0) h_i(1,s)$$

(the right hand side of this equation belongs to subprocess α),

$p_i(0)$ = probability of starting at state i in a subprocess α,

$f_i(t,s)$ = total expected reward from the remaining part of the process under policy s if present state and stage are i and t, respectively,

$$= \begin{cases} r_i(t,s), & t = T \\ r_i(t,s) + \sum_{j=1}^{I_{t+1}} p_{ij}(t,s) f_j(t+1,s), & t = T-1,\ldots,1 \end{cases}$$

$r_i(t,s)$ = immediate expected reward in state i at stage t under policy s,

$p_{ij}(t,s)$ = transition probability from state i to state j where i is the state of the stage t, j is the state of the following stage, and s is the policy,

I_t = number of states at stage t,

$h_i(t,s)$ = total expected output from the remaining part of the process under policy s when present state and stage are i and t, respectively,

$$= \begin{cases} m_i(t,s), & t = T \\ m_i(t,s) + \sum_{j=1}^{I_{t+1}} p_{ij}(t,s) h_j(t+1,s), & t = T-1,\ldots,1 \end{cases}$$

$m_i(t,s)$ = immediate physical output in state i at stage t under policy s,

Go to step 3.

Step 3), For each subprocess α, find by means of the recurrence equations a policy s′ of the subprocess:

$$V_{\alpha i}(t) = \begin{cases} \max\limits_{d}\left\{r_i(t,d) - m_i(t,d)g(\sigma)\right\}, & t = T \\ \max\limits_{d}\left\{r_i(t,d) - m_i(t,d)g(\sigma) + \sum\limits_{j=1}^{I_{t+1}} p_{ij}(t,d)V_{\alpha j}(t+1)\right\}, & t = T-1,\ldots,1 \end{cases} \qquad [2]$$

where $V_{\alpha i}(t)$ = maximum relative value at subprocess α, state i, and stage t.

The decision d′(t,i) maximizes the right hand side of the recurrence equation of state i at stage t. Those decisions determine the new policy s′. Put σ′(α) = s′ for α = 1,...,u. If the new policy equals the old policy, stop, because then an optimal policy has been found. Otherwise, redefine the old policy according to the new policy and go back to step 2.

Note that in our special case of only one subprocess, Equation [1] can be reduced to Equation [3]:

$$g(\sigma) = \frac{f_\alpha(\sigma)}{h_\alpha(\sigma)}. \qquad [3]$$

2.4. Stage and State Variables and Decisions

In the replacement model, the maximum age of a cow is 12 lactations, and the maximum calving interval is 17 mo, which results in a total of 12 x 17 = 204 stages. In each stage, the cow is described by the following state variables (number of classes between brackets): production level in current lactation [(15); < 74%, 74 to 78%, . . ., 122 to 126%, and ≥ 126%], production level in previous lactation [(15); < 74%, 74 to 78%, . . ., 122 to 126%, and ≥ 126%)], calving interval [(8); 11 . . . 17 mo and open cows)], clinical mastitis in current month [(2); yes or no], accumulated number of mastitic quarters in current lactation up to and including previous month [(4); 0, 1, 2, and 3 ≥)] and accumulated number of mastitic quarters in previous lactation [(4; 0, 1, 2, and 3 ≥)]. Production level is defined relative to cows of the same age and month of lactation in absence of genetic improvement and voluntary culling and corrected for expected calving interval and mastitis status. For a calving interval of 11 mo, the number of days open is assumed to be between 45.75 and 76.25. For each subsequent class, an additional 30.5 d are added to days open to more accurately reflect the prolonged calving interval. The last class is defined for open cows. Not all states are accessible at each stage: e.g., in mo 17 a cow can only be open or have a calving interval of 17 mo. Exclusion of those states that are not feasible results in an HMP model with 6,821,724 different states a cow may enter during her life.

The model optimizes three decisions that can be made at each state and stage: 1) keep the cow at least one more month and do not inseminate her when in estrus (keep), 2) keep the cow at least 1 mo more and inseminate her when in estrus (insm), and 3) replace the cow immediately by a replacment heifer (repl). Treatment of a cow is not defined as a separate decision. For each decision d at each state i and stage t, the HMP algorithm (see Equation [2]) generates a relative value of expected net revenues, assuming optimal decisions in the future. With those relative values $V_i(t,d)$, the impact of the decision can be evaluated by two key figures: retention pay off (RPO) (also called the future profitability) and insemination value (IV) (Van Arendonk, 1988). Subscript α is omitted because in our case only one subprocess is defined.

$$RPO_i(t) = \max(V_i(t,keep),V_i(t,insm)) - V_i(t,repl)$$
$$IV_i(t) = V_i(t,insm) - V_i(t,keep).$$

Thus, RPO is the total extra profit to be expected in the future from keeping or inseminating a cow until her optimal lifespan, compared with immediate replacement, taking into account the risk of involuntary disposal of retained cows (Huirne et al., 1993). IV is the extra profit to be expected in the future from inseminating a cow, compared with leaving her open for at least 1 mo more, taking into account the risk of no conception and involuntary disposal. Keep and replace decisions have to be made in all states. Insemination is defined as possible between 3 to 9 mo in lactation only (i.e., calving interval of 11 through 17 mo). In the model the decision to replace results in an immediate replacement (i.e. at the beginning of the month). Cows are kept at least 1 mo more when the decision to keep or inseminate has been chosen. Involuntary replacement (e.g., due to lameness and death), can occur at the end of each month.

The components of a hierarchic Markov decision process to be defined further are (see also steps 2 and 3 of the optimization algorithm) the immediate expected rewards $r_i(t,d)$, physical output $m_i(t,d)$, and the transition probabilities $p_{ij}(t,d)$ and $p_i(0)$. In subsequent sections is described how the decision and stage dependent immediate expected rewards are calculated, using a gross margin model.

2.5. Gross Margin Model

The model that calculates gross margins from milk production, calf sales, feed costs and sundry costs was described by Van Arendonk (Van Arendonk, 1985). Regular fixed cost of labor supplied by the farmer was not included. In our study, housing costs were not included either and were considered to be fixed costs. Groen (Groen, 1988) and Jalvingh et al. (1993) slightly modified this gross margin model and updated the prices. Those modifications were also incorporated in our model.

For each month in lactation the gross margins from milk production were determined and based on fat and protein contents. Feed costs were calculated from consumption of roughage and concentrates, estimated from the energy requirements. Furthermore, the calf revenues were included. Parameters of, and prices in the model were chosen to represent the Black and White cows in The Netherlands at normalized price levels of 1989-1991. In Table 1, the basic prices and other parameters used in the gross margins model are shown.

Table 1. Basic prices and other parameters used in determining the optimal replacement policy.

Prices	(US$)
Milk fat, / kg	4.72
Milk protein, / kg	7.78
Base price of milk, / 100 kg	-1.61
Female calves, / kg	3.67
Male calves, / kg	5.86
Roughages, / MJ NE[1]	.021
Concentrates, / MJ NE[1]	.028
Carcass weight, / kg (for a heifer 7 mo in lactation)	3.33
Price of replacement heifer	1444
Insemination	11
Mature equivalent (8 yr) herd level	
Milk, kg	7750
Fat content, %	4.35
Protein content, %	3.39
Other	
Age at first calving, mo	24
Mature live weight, kg	650

[1]Megajoules of net energy

The gross margin model of Van Arendonk (1985) was extended to include effects of clinical mastitis. Houben et al. (1993) estimated the effects of clinical mastitis on production. Major results of that study were used to determine normalized monthly production effects from accumulated number of clinical quarter cases in current lactation up to and including the previous month (CQ) and the accumulated number of clinical quarter cases in the previous lactation (PQ). The effect of clinical mastitis in the current month (DQ) was estimated indirectly, because Houben et al. (1993) had concluded that this effect was underestimated in their study.

As can be concluded from the work of Houben et al. (1993), the typical pattern of the CQ effect, and to a lesser extent of the PQ effect, on accumulated production showed that accumulated production losses increased asymptotically until about 10 mo in lactation. This increase can be explained by the fact that most of the mastitis cases occur in the beginning of the lactation and those will only have a minor effect on production later in the lactation. Estimates of production losses by CQ and PQ are normalized by assuming that the maximum accumulated production losses are observed in mo 10 and then stay at that level and that production losses reach that maximum according to a second-degree polynomial, which starts in mo 1 with an acccumulated production loss of 0 kg. With those assumptions, it was possible to calculate the monthly production losses for each CQ (0, 1, 2, and ≥ 3) and PQ (0, 1, 2, and ≥ 3). Different parameters were used for the first lactation than for second and later lactations. Table 2 shows the maximum production losses for each CQ and PQ for lactations 1 and 2 ≥. Milk production losses caused by three or more clinical cases in current lactation were 132 kg in the first lactation and 544 kg in the second and later lactation (Table 2). One or two clinical cases in the previous lactation had only a minor effect on the production in current lactation (PQ in Table 2).

Table 2. Maximum accumulated production losses until mo 10 by number of clinical quarter cases in current lactation (CQ) and in previous lactation (PQ).

	CQ				PQ			
	0	1	2	≥3	0	1	2	≥3
Lactation 1								
Milk, kg	0	47	121	132	...	...	...	...
Fat , kg	0	5.1	10.0	11.2	...	...	...	...
Protein, kg	0	1.1	2.0	4.5	...	...	...	...
Lactation ≥ 2								
Milk, kg	0	166	220	544	0	24	31	459
Fat, kg	0	6.9	18.9	26.8	0	0	2.9	27.6
Protein, kg	0	4.5	6.0	17.1	0	0	.4	12.8

For background information and more details of the data in Table 2, the reader is referred to Houben et al. (1993).

In the gross margin model, a multiplicative effect of mastitis was used, and, therefore, the normalized monthly milk production losses were multiplied by a correction factor (corr) to accomplish this multiplicative effect.

where

$$corr = \left(\frac{RelProd}{100}\right)\left(\frac{305Prod_l}{305Ref_l}\right) \qquad [4]$$

corr = correction factor to obtain a multiplicative effect,
RelProd = relative production level of a cow (%),
$305Prod_l$ = average 305-day milk production according to the gross margin model in lactation l,
$305Ref_l$ = average 305 milk production of cows in lactation l (4824, 5724, and 6215 kg for lactation 1, 2, and ≥ 3, respectively) in Houben et al. (1993)

The production losses from clinical mastitis in the month that mastitis occurs (DQ) were calculated indirectly. According to Morris and Marsh (1985), several studies produced loss estimates to average 10% or more, assuming that each infected cow has, on average, one to two infected quarters. To obtain approximately the same production losses, we accordingly assumed for each clinical quarter case that 1) milk production in the month after mastitis had occurred was reduced by 40% in lactation 1 and 50% in later lactations, 2) fat production was reduced by 45% in lactation 1 and 55% in later lactations, and 3) protein production by 30% in lactation 1 and 40% in later lactations.

According to the data used by Houben et al. (1993), the average number of clinical cases per cow case is 1.29 in mo 1 to 4 and 1.18 in mo 5 ≥. Combination of this information with the estimated effect of DQ and CQ on production leads to an expected production loss for each cow case. Table 3 shows the expected total production loss in a lactation and relative production loss for a cow case diagnosed in a certain month and the percentage of the total production loss that appears in the month of diagnosis, for a cow with an average production and a calving interval of 12 mo. A clinical cow case in the 1st or 2nd mo of lactation ≥ 2 reduced milk production per lactation by about 10%, which agrees with the findings of Morris and Marsh (1985) (Table 3). At between 79 and 85% of production losses occurred in the month of infection (percentages of DQ in Table 3). In the first lactation, a maximum reduction in lactation milk production was observed when a cow contracted mastitis in the 2nd mo (7.3%). When mastitis occurred in mo ≥ 7, > 95% of the production losses were observed in the month of infection (Table 3).

Other effects of clinical mastitis included in the gross margin model are treatment costs, costs of discarded milk, and positive effect on feed consumption.

Table 3. Expected milk, fat, and protein production losses by lactation and month of clinical case. Based on average production (within cow class) and CI of 12 mo; month = month within lactation number, loss = expected losses in kilogram and as percentage of lactation production, and %DQ = percentage which appears in month of diagnosis.

Month	Milk			Fat			Protein		
	Loss		%DQ	Loss		%DQ	Loss		%DQ
Lactation 1	(kg)	(%)		(kg)	(%)		(kg)	(%)	
1	394	6.8	87.6	22.5	8.8	77.8	9.9	5.1	88.6
2	420	7.3	90.9	22.2	8.7	82.3	10.1	5.1	91.3
3	392	6.8	92.7	20.4	8.0	85.4	9.4	4.8	93.2
4	364	6.3	94.3	18.6	7.3	88.5	9.0	4.6	94.6
5	310	5.4	95.4	16.0	6.2	90.2	7.9	4.0	95.5
6	287	5.0	96.8	14.9	5.8	93.3	7.4	3.8	96.9
7	264	4.6	98.1	13.7	5.4	95.3	7.0	3.6	98.3
8	237	4.1	99.1	12.6	4.9	97.5	6.4	3.3	99.9
9	195	3.4	99.7	10.6	4.1	99.1	5.3	2.7	99.9
10	143	2.5	100.0	7.9	3.1	100.0	4.0	2.0	100.0
Lactation 2									
1	699	10.3	78.9	34.6	11.4	79.2	19.5	8.2	78.9
2	705	10.4	83.5	33.3	11.0	83.0	18.9	7.9	82.7
3	641	9.4	86.2	30.2	10.0	85.9	17.3	7.3	85.4
4	581	8.5	88.9	27.4	9.1	89.0	15.9	6.7	88.6
5	482	7.1	90.7	23.1	7.6	90.9	13.4	5.6	90.7
6	433	6.4	93.4	21.1	7.0	93.8	12.3	5.2	93.5
7	386	5.7	95.8	19.2	6.3	96.4	11.3	4.7	96.0
8	335	4.9	97.9	17.0	5.6	98.3	9.9	4.2	97.8
9	266	3.9	99.3	14.0	4.6	99.9	7.9	3.3	99.9
10	189	2.8	100.0	10.1	3.3	100.0	5.7	2.4	100.0
Lactation 3									
1	788	10.7	80.6	38.8	11.8	80.8	21.6	8.5	80.9
2	780	10.6	84.6	36.8	11.2	84.0	20.5	8.0	84.0
3	705	9.5	87.1	33.2	10.1	86.6	18.6	7.3	86.9
4	635	8.6	89.5	29.9	9.1	89.3	17.1	6.7	89.3
5	522	7.1	91.2	25.1	7.7	90.9	14.4	5.6	91.2
6	464	6.3	93.6	22.6	6.9	93.4	13.0	5.1	93.8
7	407	5.5	95.9	20.4	6.2	95.7	11.7	4.6	96.0
8	347	4.7	97.9	17.8	5.4	97.4	10.1	4.0	97.7
9	269	3.6	99.3	14.2	4.3	99.2	7.9	3.1	99.8
10	186	2.5	100.0	10.0	3.1	100.0	5.6	2.2	100.0

2.6. Treatment Costs

It was assumed that all cows with clinical mastitis that were not replaced voluntarily were treated according to the following distribution (based on data used by Houben et al. (1993)): milk stripping (1.2%), intramammary (31.5%), parenteral (3.6%), and both intrammair and parenteral (63.7%). For each intramammary treatment, 3 injectors were used at a price of $1.94 each, and each parenteral treatment cost $14. It was assumed that a veterinarian had to visit the farm for 25% of the clinical quarter cases at a cost of $22 per visit. Furthermore, a farmer was assumed to spend 2 h for each new quarter case at a price of $15.30 / h (note that only additional labor costs were included). Of the quarter cases, 8.4% occurred in the same cow on the same day, and, therefore, only 91.6% of the mastitic quarters needed extra labor and veterinary visits. These figures led to average treatment costs for each clinical quarter of $49 (only in case a cow was not culled).

2.7. Costs of Discarded Milk

Production losses from clinical mastitis do not only occur from reduced milk production but also because milk with antibiotics cannot be delivered to the milk factory. The number of days of no delivery depends on treatment: milk stripping (0 d), intramammary (6 d), parenteral (4 d), and both intramammary and parenteral (6 d). However, the cost of discarded milk is less than the normal value of milk because this milk can partly be used for calves, replacing milk powder. To ensure quality, milk could not be used to replace milk powder in the first 1.5 d, and so had no value during that period. The actual production of a cow was used (i.e., lower production because of mastitis) to determine the value and the alternative value of the discarded milk. Per kilogram, the alternative value of discarded milk was set at $.17.

2.8. Effect on Feed Consumption

Mastitis reduces milk production, and, hence, less feed consumption is neccessary. The reduced energy need because of less milk, fat, and protein production was considered in the gross margin model. Milk was assumed to be produced with the same efficiency as by healthy cows.

2.9. Immediate Expected Reward

With the information from the gross margin model, the immediate expected rewards $r_i(t,d)$ for state i (a combination of production, production in previous lactation, calving interval, DQ, CQ, and PQ) at stage t (a combination of lactation and month in lactation) and decision d (keep, inseminate or replace) were calculated as follows:

$$r_i(t,keep) = \begin{cases} GM_i(t) - HC - VC(t) + [pIR(t) * (SE_i(t) - RCV(t))], & t=1,\ i \neq I \\ GM_i(t) - VC(t) + [pIR(t) * (SE_i(t) - RCV(t))], \\ \qquad 2 \leq t \leq T-1,\ t \neq CI,\ i \neq I \\ GM_i(t) - VC(t) + [pIR(t) * (SE_i(t) - RCV(t))] + [(1 - pIRN) * PE_i(t)], \\ \qquad t = CI,\ i \neq I \\ GM_i(t) - VC(t) + SE_i(t) - [pIR(t) * RCV(t))], & t = T,\ i \neq I \\ 0, & i = I \end{cases} \quad [5]$$

where

$r_i(t,d)$ = immediate expected reward for state i at stage t and decision is to keep the cow for at least one more month,
$GM_i(t)$ = gross margin for state i at stage t,
HC = costs of replacement heifer,
VC(t) = veterinary costs at stage t,
pIR(t) = probability of involuntary replacement at stage (t) (see also section about transtion probabilities),
$SE_i(t)$ = carcass value for state i at end of stage t,
RCV(t) = reduction in carcass value because of involuntary culling,
pIRN = total probability of involuntary replacement during next lactation,
$PE_i(t)$ = production effect of length of calving interval,
CI = stage in which month is equal to calving interval,
T = last month in last lactation, and
I = replacement state

Equation [5] shows that in the last month of a lactation (t = CI), the production effect of the length of calving interval, weighed for the probability of realization of next lactation, is added to the immediate expected reward. It would have been preferable theoretically to add this effect in the next lactation. However, this month is the last in which the calving interval is known.

Regular veterinary costs (VC) were obtained from Van Arendonk (1985): \$17, 6, 6, and 3 in 1, 2, 3, and ≥ 3 in lactation, respectively.

$$r_i(t,insm) = \begin{cases} GM_i(t) - VC(t) - IC + [pIR(t) * (SE_i(t) - RCV(t))], & FI \le t \le LI,\ i \ne I \\ 0, & i = I \end{cases} \quad [6]$$

where

$r_i(t,d)$ = immediate expected reward for state i at stage t and decision is to inseminate the cow and to keep her for at least one more month,

IC = insemination costs,

FI = stage in which month is month of first insemination (i.e., stage 3),

LI = stage in which month is month of last insemination (i.e., stage 9)

$$r_i(t,repl) = \begin{cases} SE_i(t-1), & 1 \le t \le T,\ i \ne I \\ 0, & i = I \end{cases} \quad [7]$$

where

$r_i(t,d)$ = immediate expected reward for state i at stage t and decision is to replace the cow immediately with a replacement heifer

2.10. Physical Output

Within the HMP approach the physical output has to be defined. Physical output is the denominator of the object function (see Equation [3]). In our study, in which the optimization criteria were to maximize gross margin per time unit, length of a stage (time) is in HMP terms the immediate physical output: $m_i(t,d)$. Time unit is 30.5 d (1 mo). From the definition of each decision, follows:

$$m_i(t,keep) = \begin{cases} 1, & 1 \le t \le T,\ i \ne I \\ 0, & i = I \end{cases} \quad [8]$$

$$m_i(t,insm) = \begin{cases} 1, & FI \le t \le LI,\ i \ne I \\ 0, & i = I \end{cases} \quad [9]$$

$$m_i(t,repl) = 0,\ 1 \le t \le T,\ 1 \le i \le I \quad [10]$$

2.11. Transition Probabilities

The model was applied to situations in which cullings for age, low production, fertility status, and mastitis state were incorporated in the decision-making process of the HMP, which were also the stochastic elements of the model. The next state of the cow depended on the current state, the current stage, the decision to keep or cull, the probability of conception if inseminated, the probability of survival to the next stage, the probability of transition to a different production level, and the probability of clinical mastitis.

The type of cow disposal not subject to decision making processes was referred to as involuntary (Van Arendonk, 1985). The total marginal probabilities of disposal and the marginal probabilities of disposal because of production, reproduction, and udder/mastitis were taken from Dijkhuizen (1980). From those figures the marginal probability of involuntary disposal was calculated for lactations 1 to 12 (Table 4).

Table 4. Marginal probabilities of replacement (%).

Lactation	Total marginal probability (A)	Because of production (B)	Because of reproduction (C)	Because of udder/ mastitis (D)	Marginal probability of involuntary culling (A-B-C-D)
1	21	7	2.2	2.1	9.7
2	20	5	2.5	3.0	9.5
3	21	3	3.6	4.0	10.4
4	22	2	5.0	4.8	10.2
5	23	0	6.3	5.7	11.0
6	25	0	7.8	6.7	10.5
7	27	0	9.0	7.4	10.6
8	29	0	10.1	7.8	11.1
9	32	0	11.3	7.8	12.9
10	35	0	12.2	7.7	15.1
11	38	0	13.0	7.5	17.5
12	41	0	13.6	7.3	20.1

The proportions of disposal during each month of lactation are: 20, 8, 7, 7, 8, 9, 9, 9, 8, 7, 6, and 5% for mo 1 to 12, respectively, and 4% for higher months (Van Arendonk, 1985). The calculation of the probability of conception for mo 3 to 9 was obtained from Van Arendonk and Dijkhuizen (1985) and modified by Jalvingh et al. (1993). Rate of detection of estrus was set at 70%.

One of the objectives of the present study was to develop a DP model allowing monthly transitions to other production levels. Dommerholt (1975) found a coefficient of variation of 12% for lactation production, after correction for the effects of age and herd-year-season. In our study, we assumed a constant variation coefficient of accumulated production throughout the lactation. Using correlations between the milk production in the current and next month and between the milk production in the previous lactation and the next month, multiple regression factors and reliabilities of the transition probabilities were calculated analogously to Van Arendonk (1985). With those multiple regression factors, the accumulated production for the next month was estimated from the accumulated production in the current month and previous lactation. Correlations were calculated from data used by Houben et al. (1993). The correlations between the accumulated milk production in the next month and current month were .956, .979, .988, .911, .993, .994, .996, .996, and .997 for respectively mo 1 to 9, and 1 for mo ≥ 10. The correlations between the accumulated milk production in the next month and mo 10 in previous lactation were .391, .429, .478, .498, .535, .544, .545, and .547 for months 1 to 8 and .55 for mo ≥ 9. The correlation between the 1st mo in a lactation and last month in previous lactation was .327. Those correlations resulted in a repeatability of lactation production of .55 and .42 for a one- and two-lactation interval, respectively, which closely agrees with results of Van Arendonk (1985).

To reduce the amount of calculations needed during the optimization procedure, transitions were pruned when the transition probability was < .05 times the reliability of the regression factors in that month. For the cow replacement model with typical high repeatabilities between monthly accumulated production the pruning factor reduced the amount of calculations by almost 85%; 99% of all transitions were still covered.

The coefficients that calculate the probability that a cow will contract clinical mastitis in the next month were obtained from Houben et al. (1993). The risk of clinical mastitis in the following month was influenced by month of lactation (a higher risk early in lactation), lactation number (risk increased with lactation number), production (higher risk for high producing cows), number of clinical quarters in the previous lactation, number of clinical quarters in the previous months of the current lactation, and occurrence of clinical mastitis in the current month. In that study, the incidence rates of clinical mastitis in the period from 1 w before calving until 10 mo after calving were 6.6, 9.0, and 14.7 cases per 10,000 cow days at risk for first, second, and third lactations, respectively. Further analysis of the same data showed that the probability of clinical mastitis during the last month of the dry period was 9.4% when mastitis had occurred earlier in lactation and 4.4% in other cases. The probability that a cow contracts mastitis in the next stage was calculated according to the Equation [11]:

$$p(q(t+1) \mid i(t), d(t)) = \begin{cases} \dfrac{\exp\left(fh_i(t)\right)}{1 + \exp\left(fh_i(t)\right)}, & t = 1,\ldots,CI - 2 \\ pDP_{q(t)}, & t = CI - 1 \\ \dfrac{\frac{30.5}{23.5} \times \exp\left(ff_i(t)\right)}{1 + \left(\frac{30.5}{23.5} \times \exp\left(ff_i(t)\right)\right)}, & t = CI \end{cases} \quad [11]$$

where

$p(q(t + 1) \mid i(t), d(t))$ = conditional probability of at least one clinical quarter in stage t + 1, given current state i(t) and decision d(t);

$fh_i(t)$ = function of logistic regression coefficients obtained from Houben et al. (1993) for later months in lactation. Risk factors in this function are clinical mastitis in current month, in previous months, and in previous lactation, lactation number, month in lactation and production level;

$pDP_{q(t)}$ = probability of mastitis in last month of dry period depending on occurrence of mastitis in month before last month in dry period (q(t));

$ff_i(t)$ = function of logistic regression coefficients obtained from Houben et al. (1993) for first month in lactation, and risk factors in this function are: clinical mastitis in current month and in previous months.

As can be seen in Equation [11] a correction was made for the probability of mastitis in the 1st mo of lactation because those coefficients were based on a period of 23.5 d instead of 30.5 d.

Based on Houben et al. (1993), the following distribution of clinical cases in a month during whicht mastitis was observed was calculated to be 80%, 1 quarter case; 15%, 2 quarter cases; and 5% ≥ 3 quarter cases if mastitis was observed in the first 4 mo of lactation. Elsewhere, the distribution was: 86% one quarter case, 10% two quarter cases and 4% three or more quarter cases. The transition probabilities with regard to the CQ state in the next stage could be calculated with those figures.

The PQ state does not change within a lactation. In the 1st mo of a lactation the CQ state of the last month before the dry period was taken as new PQ state.

The transition probabilities $p_{ij}(t,d)$ were calculated as a multiplication of the transition probability of production class, calving interval class, DQ class, CQ class, PQ class and probability of involuntary culling. A cow entered the replacement state when the cow was voluntarily or involuntarily replaced. When i = I (i.e., replacement state), the cow remained in the replacement state until the last stage.

At the beginning of a subprocess the distribution over production classes is according to the standard normal distribution and the clinical mastitis state is obtained from the lower part of Equation [11]. With those two components the start distribution, $p_i(0)$, at the beginning of a subprocess was calculated.

3. Results

The gross margin model and optimization model were written in Pascal and run on SUN SparcStation 1[1] (UNIX[2]). The program first calculates the gross margins for all states, which takes about 10 min of computation time, and then it starts with the optimization. On average, this takes about 6 h of computation time.

This section shows the effect of using the optimal replacement and insemination policy on the farm results in the basic situation. Furthermore, the effect of the state of a cow on the retention pay off and insemination value are shown. To gain more insight into major model characteristics, a sensitivity analysis was carried out.

3.1. Basic Results

The optimal replacement and insemination policy in the basic farm resulted in a replacement rate of 29.2% annually, of which 18.3% voluntary (Table 5). In the basic situation, the model supported decisions related to 63% of all replacements. Furthermore, 12.7% (3.7 of 29.2) of the culled cows were infected with clinical mastitis at culling (i.e., 20.2% of voluntarily culled cows). This result does not mean, however, that mastitis was the only reason for culling. The gross margin in the basic situation was $2431 per cow per year (housing and fixed labor costs not included), and feed costs were $896 / yr per cow. Milk production corrected for fat and protein was 7735 kg / yr per cow. Mastitis occurred at an incidence rate of 9.7 clinical cases per 10,000 cow days.

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[1]Sun Microsystems, Inc. U.S.A.

[2]UNIX Systems Laboratories, Inc. U.S.A.

TABLE 5. The expected farm results when basic parameters are used in contrast to results for alternative parameters[1].

	Basic	Alternative[3]					
		rp = 0	rp = .5	rp = 2	rl = .5	rl = 2	notr
Gross margin, US$ / yr per cow	2431	83	48	-123	24	-28	10
Milk production, kg of FPCM[2] / yr per cow	7735	168	96	-219	77	-78	58
Feed costs, US$ / yr per cow	896	14	8	-19	6	-6	4
Number of calves / yr per cow	1.14	-.01	-.01	.05	0	.02	.02
Calving interval, d	370	1	0	0	0	0	1
Calving interval ≥14 mo, %	11.8	.3	.2	-.3	0	.1	.4
Mastitis incidence per 10,000 cow days	9.7	-9.7	-5.4	10.0	.6	-1.0	.2
Replacement rate, % / yr	29.2	-2.1	-1.5	8.4	-1.0	1.5	2.4
Voluntary replacement, % / yr	18.3	-2.2	-1.6	8.5	-1.1	1.5	2.4
Voluntary replacement with mastitis, % / yr	3.7	-3.7	-2.5	9.0	-1.5	2.9	0.1

[1]rp = Relative probability of mastitis, rl = relative production losses caused by clinical mastitis, and notr = no within lactation transitions of production level are assumed.
[2]FPCM = fat- and protein-corrected milk. FPCM = .349milk (kilogram) + 10.7fat (kilogram) + 6.7protein (kilogram).
[3]Values represent increase or decrease in basic model parameters.

Table 5 also shows results when no mastitis occurred (relative probability (rp) = 0). In that case it could be concluded that the gross margin increased by $83 / yr per cow, the total loss from of mastitis.

3.2. Changes in Incidence of Clinical Mastitis

Changes of the probability that clinical mastitis will occur had a major effect on the farm results. A 50% reduction of this probability (rp = .5) increased the gross margin by $48 / yr per cow and, when the probability of contracting mastitis had doubled (rp = 2), the gross margin decreased by $123 / yr per cow (Table 5). An increase of risk of mastitis infection leads to much more voluntary culling (+8.5%) according to the optimal policy. In turn the high replacement rate had a strong negative effect on the gross margin. Although many of the mastitic cows were culled when probability of mastitis was high (47% of all voluntarily replaced cows had clinical mastitis), the mastitis incidence had still doubled. Therefore, the effect of culling was minimal with regard to the mastitis incidence, probably because replacement heifers also run a high risk of mastitis infection. Table 5 shows that the relationship is linear between relative risk of mastitis (alternative rp) and mastitis incidence and to a lesser extent also between relative risk and gross margin. Because of the high rate of involuntary culling, according to the optimal policy for high relative risk of mastitis, the gross margin was expected to have been relatively more reduced. The relative risk of mastitis had a small effect on the insemination decisions, which can be inferred from the few changes in average calving interval and percentage of cows with a calving interval of > 13 mo.

3.3. Changes in Production Losses Caused by Clinical Mastitis

The effect of changing production losses caused by clinical mastitis is presented in Table 5. In contrast to the relative probability of clinical mastitis, the relative losses caused by clinical mastitis had no linear effect on the gross margin. Apparently culling was an effective way to reduce the losses relatively, since the decrease in gross margin when production losses were increased by 100% (Table 5; relative loss (rl) = 2) was only slightly higher than the increase in gross margin for the alternative when production losses were reduced by 50% (relative loss = .5). So, in contrast to relative probability, relative production losses did not have a linear effect on gross margin. Doubled relative production losses resulted in 33.3% of the voluntarily replaced cows having clinical mastitis in contrast to 20.2% in the basic situation and 12.8% in the situation in which production losses had been halved. Relative production losses had an even smaller effect on the insemination decisions as relative risk. Calving interval and percentage of cows with a calving interval of > 13 mo hardly changed.

3.4. Changes Within-Lactation Transitions of Production Class

To find out the effect of including within-lactation transitions of production class on farm results, an alternative situation in which those transitions were not included was defined (Table 5; without transitions (notr)). The repeatability of total lactation production for one and two lactation intervals was kept at the same level (.55 and .42, respectively).

The most remarkable finding for the alternative, without transitions within lactation, was the increase in voluntary replacement rate by 2.4%. Because the percentage of the voluntarily replaced cows with clinical mastitis was almost the same as in the basic situation, it can be concluded that the increase of voluntary replacements was only for reasons related to production. Low producing cows were culled more frequently when no within-lactation production transitions were allowed and when more cows had a calving interval of > 13 mo. The latter effect may be caused because high producing cows remain longer in the herd. Despite the increase in voluntary replacement by 2.4%, the gross margin was increased by $10 and milk production was corrected for fat and protein by 58 kg.

3.5. Calving Interval

In Figures 2 and 3, the effect of calving interval, month of gestation, and clinical mastitis state on retention pay off are shown for cows in first and second lactation, respectively. Cows in those two figures had no clinical mastitis cases in the past and milk production was at a relative level of 100%.

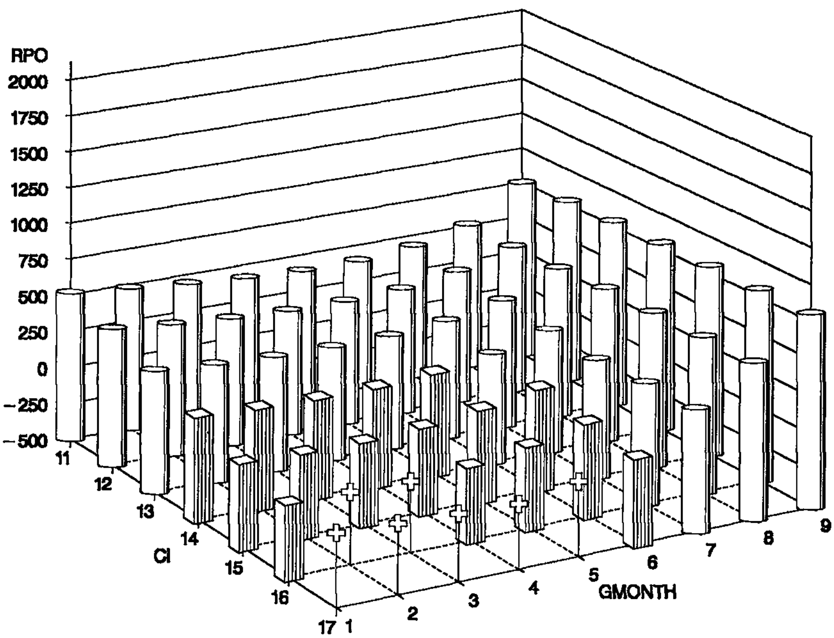

Figure 2. Effect of calving interval (CI), month of gestation (GMONTH), and mastitis state on retention pay off (RPO) for cows in first lactation. A cross means that cows should be culled anyway (i.e. retention pay off < 0), a cylinder means that cows should be kept and a square pillar means that a cow should be replaced in case of clinical mastitis.

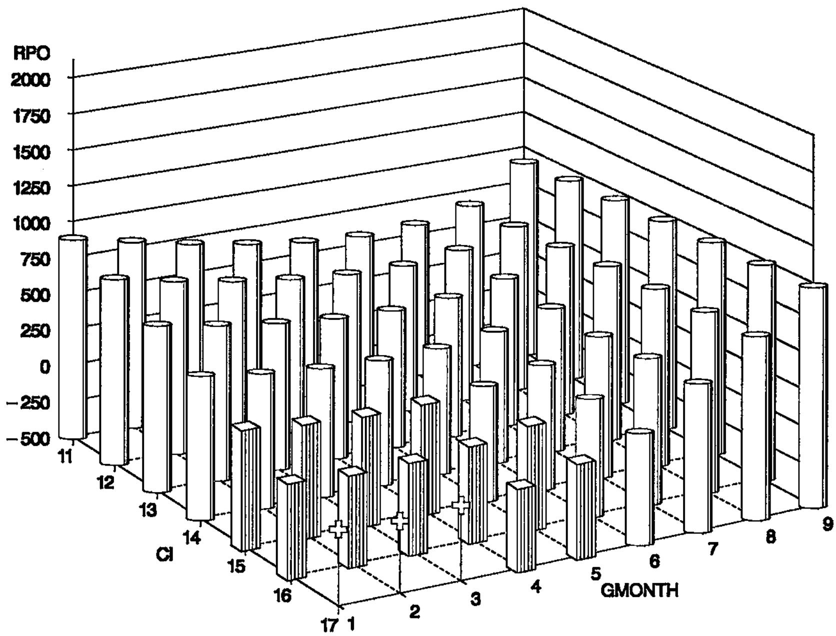

Figure 3. Effect of calving interval (CI), month of gestation (GMONTH), and mastitis state on retention pay off (RPO) for cows in second lactation. A cross means that cows should be culled anyway (i.e. retention pay off < 0), a cylinder means that cows should be kept and a square pillar means that a cow should be replaced in case of clinical mastitis.

Square pillars in those figures mean that the optimal decision changed from keeping to culling in case of clinical mastitis, thus, it could be concluded that clinical mastitis did not have an effect on the replacement decisions for average producing pregnant cows with an expected calving interval ≤ 13 and 14 months for lactations 1 and 2, respectively. Only 11.8% of the cows had calving intervals of > 13 months (Table 5), and, therefore, for most of the average or better producing pregnant cows, clinical mastitis did not have any effect on the optimal decision. It is economically optimal to replace pregnant first lactation cows immediately until the 5th mo of gestation (i.e., 14 mo in lactation) when the expected calving interval is 17 mo (Figure 2).

3.6. Relative Production

In Figures 4 and 5, the effect of relative production, month in lactation, and clinical mastitis state on retention pay off and the insemination decision are shown for open cows in first and second lactations, respectively. Those cows had not had any clinical mastitis in the past, and the production in previous lactation was 100%.

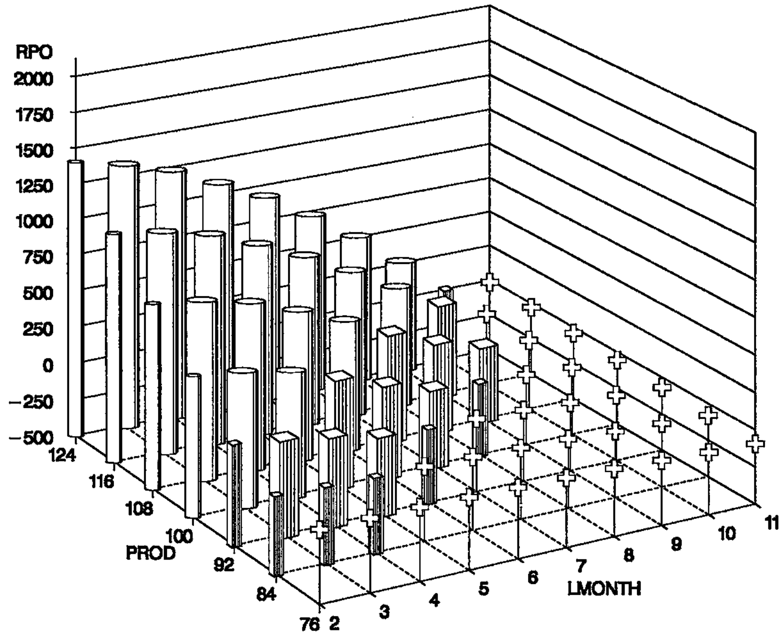

Figure 4. Effect of relative production level (PROD in %), month in lactation (LMONTH), and mastitis state on retention pay off (RPO) for open cows in first lactation. A cross means that cows should be culled anyway (i.e. retention pay of < 0), a cylinder means that cows should be kept, and a square pillar means that a cow should be replaced in case of clinical mastitis. A narrow cylinder or pillar means that it is optimal to leave the cow open at that moment (relative production level in first lactation was 100%).

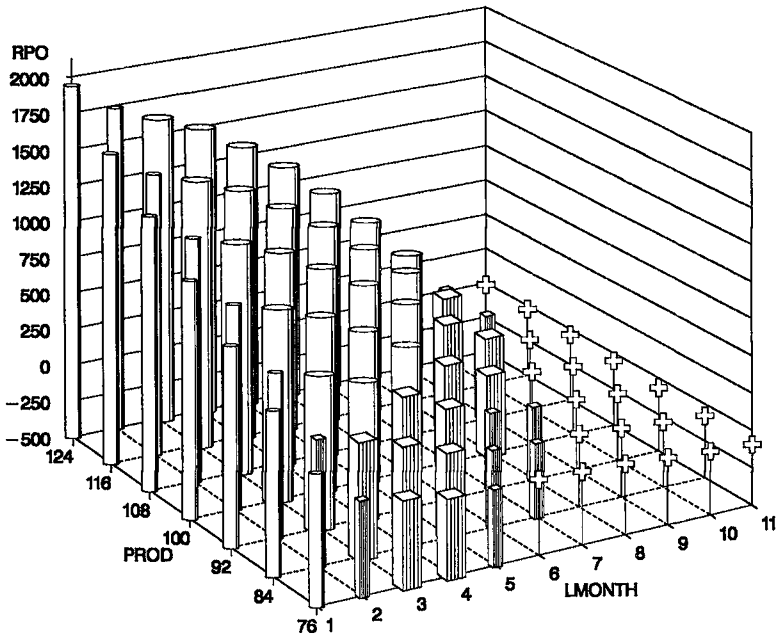

Figure 5. Effect of relative production level (PROD in %), month in lactation (LMONTH), and mastitis state on retention pay off (RPO) for open cows in second lactation. A cross means that cows should be culled anyway (i.e. retention pay of < 0), a cylinder means that cows should be kept, and a square pillar means that a cow should be replaced in case of clinical mastitis. A narrow cylinder or pillar means that it is optimal to leave the cow open at that moment (relative production level in first lactation was 100%).

It was economically optimal to replace open first lactation cows immediately in cases of clinical mastitis when production was below average (Figure 4). Open first lactation cows producing below 78% were replaced anyway and, with production of < 86%, first lactation cows were not inseminated again. Second lactation cows producing < 86% were replaced immediately in cases of clinical mastitis, but not in the 1st mo of lactation. Delaying insemination for 1 mo was optimal for only a few cows. This situation is depicted with narrow cylinders or pillars in Figures 4 and 5 (in the model, insemination in the 1st and 2nd month of lactation was not allowed). In general, the optimal economic situation was to inseminate a cow as soon as possible. Regardless of production, healthy cows were inseminated until mo 4 in second lactation. Insemination of high producing healthy cows at least until mo 9 in lactations 1 and 2 was most economical. Subsequently, cows should be replaced immediately after mo 9 or 10.

3.7. Clinical Mastitis in Previous Months

For average producing, open cows, the effect of clinical mastitis in previous months (CQ), month in lactation, and mastitis state in current month on RPO and insemination decision are shown in Figures 6 and 7.

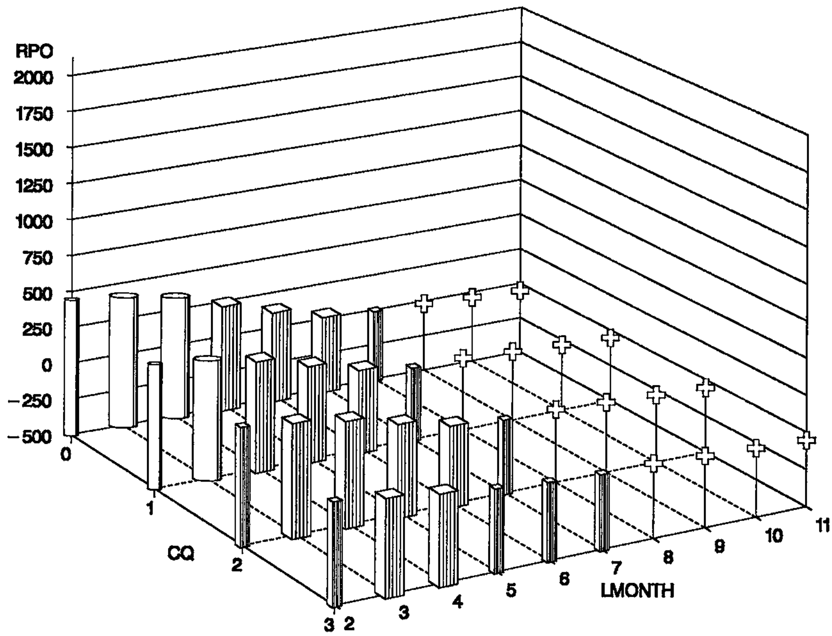

Figure 6. Effect of accumulated number of clinical quarter cases in previous months in current lactation (CQ), month in lactation (LMONTH), and mastitis state on retention pay off (RPO) for open cows in first lactation. A cross means that cows should be culled anyway (i.e. retention pay of < 0), a cylinder means that cows should be kept and a square pillar means that a cow should be replaced in case of clinical mastitis. A narrow cylinder or pillar means that it is optimal to leave the cow open at that moment.

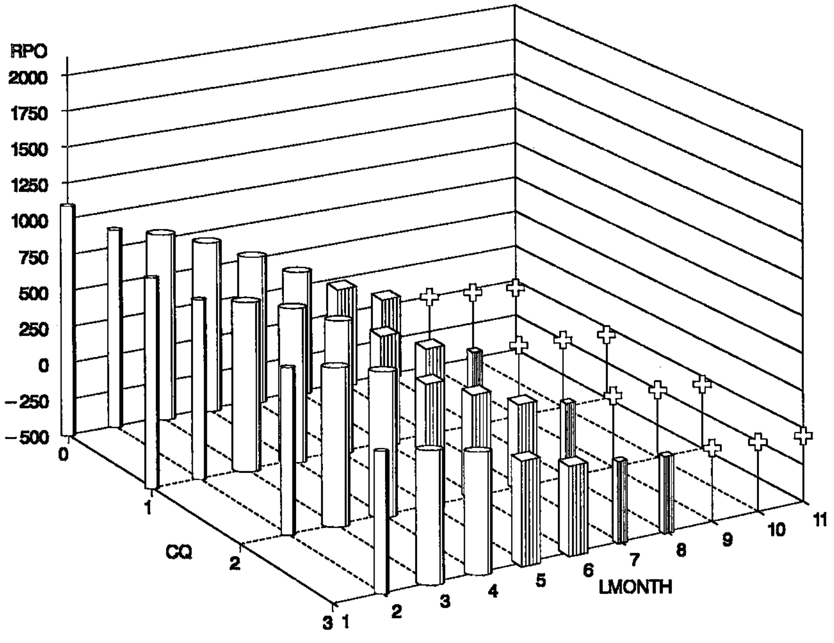

Figure 7. Effect of accumulated number of clinical quarter cases in previous months in current lactation (CQ), month in lactation (LMONTH), and mastitis state on retention pay off (RPO) for open cows in second lactation. A cross means that cows should be culled anyway (i.e. retention pay of < 0), a cylinder means that cows should be kept and a square pillar means that a cow should be replaced in case of clinical mastitis. A narrow cylinder or pillar means that it is optimal to leave the cow open at that moment.

First lactation cows with two or more clinical cases in previous months and a new quarter case in current month were replaced immediately (Figure 6). When a first lactation cow had had three or more clinical cases in previous months but no mastitis in the current month, she was not inseminated again after mo 4 of lactation. However, the first lactation cow was not replaced before mo 8. First lactation cows were culled just 1 mo earlier, and cows in second lactation not at all when clinical cases in previous months and no new quarter case had occurred.

Figure 8 shows that the effect of clinical quarter cases in previous lactation had only a very minor effect on the replacement decisions and no effect on the insemination decisons.

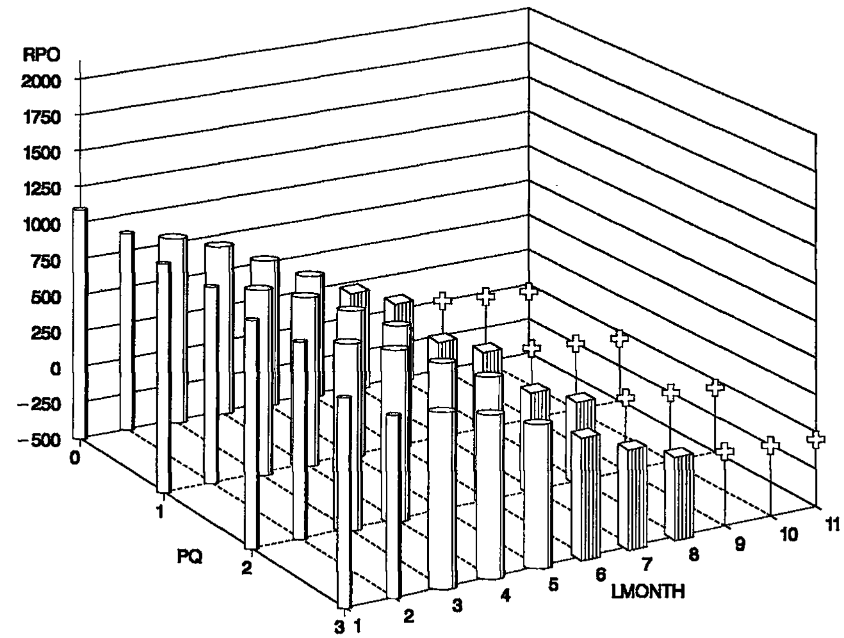

Figure 8. Effect of accumulated number of clinical quarter cases in previous lactation (PQ), month in lactation (LMONTH), and mastitis state on retention pay off (RPO) for open cows in second lactation. A cross means that cows should be culled anyway (i.e. retention pay of < 0), a cylinder means that cows should be kept and a square pillar means that a cow should be replaced in case of clinical mastitis. A narrow cylinder or square means that it is optimal to leave the cow open at that moment.

4. Discussion

The strength of the model described in this paper is the integral evaluation of age, production, fertility, and mastitis aspects to support replacement and insemination decisions. Therefore, the model was able to support 63% of all replacement decisions.

The HMP approach proved to be very useful for large replacement optimization problems. In the present study, a DP model was developed, according to the HMP approach, with 6,821,724 unique states that a cow may enter during her life. Nevertheless, because most nonfeasible transitions were eliminated in advance, during the optimization run, an optimal policy could be determined in a reasonable computation time (optimization takes approximately 6 h on a SUN SparcStation 1). This computation time, however, hardly permits for expansion of the current model. Although the HMP approach is an important step forward for replacement optimization problems, it does not solve the curse of dimensionality. This may be solved by defining a model structure in which distinction is made between main effects (state variables) and interactions (between state variables). Markov decision processes do not make this distinction, and therefore, a major part of the computations is spent on interactions between state variables that are expected to have minor influence on the optimal policy only.

In dairy cow replacement models, with exception of Kristensen's models (1987, 1989), it was assumed that transitions between different classes of milk production only occurred at the end of the lactation period. This assumption implied that the relative level of milk production performance remained the same throughout the entire lactation period. In our study, the effect of inclusion of within-lactation transitions on the farm results were examined. Results showed that more cows were replaced because of production (+2.4%) when no within-lactation transitions were included in the model. The explanation of this effect is that, if no transitions were allowed within a lactation, the cows remained at the same production during a lactation. If transitions were allowed, the expected production of cows early in the lactation were close to average (less information) and later in lactation their final production level was reached, which was exactly the same as if no transitions were allowed (because the same total lactation production correlations were used). Consequently, high producing cows were overestimated and low producing cows were underestimated at the beginning of a lactation. Low producing cows, therefore, were culled too soon. Because most of the above average producing cows were already in the herd, decisions did not change for high producing cows. For correct justification of production capacity, replacement models ought to have within-lactation production transitions.

Farm results under a policy that is optimal for production and reproduction decisions were for the basic situation mainly in agreement with Jalvingh et al. (1993), who used the same parameters in their gross margin model. The replacement rate was about 4% higher in the model of Jalvingh et al. (1993), which may be caused by exclusion of within-lactation transitions in their model and the use of higher within-lactation correlations. The course of the retention pay off was in agreement with research of Van Arendonk and Dijkhuizen (1985).

Results showed that the support of the insemination decisions in the current model is only of importance with regard to the decision not to inseminate anymore. According to the optimal policy, cows were simply inseminated as soon as possible and only for low producing cows was it sometimes optimal to leave them open one or more months and cull them afterward. The latter situation concerned only a few cows. The influence of mastitis state on replacement decisions was much bigger than on insemination decisions. The sensitivity analysis showed that parameters with regard to mastitis had hardly any effect on length of calving interval and on the percentage of cows with a calving interval 13 mo, which means that those parameters had minor influence on the optimal insemination decisions. If seasonal effects were included, support of insemination decisions was expected to become more important because shifting the moment of insemination could become optimal.

In general, clinical mastitis in the current lactation, especially clinical mastitis in the current month, has a major influence on replacement decisions. However, in contrast to the production, clinical mastitis concerns only a fraction of the total herd and, therefore, the effects of mastitis related parameters on the average gross margin were weakened.

The results showed that the number of clinical quarter cases in previous lactation had only a small effect on the optimal replacement decision in spite of the high risk associated with mastitis in previous lactation. In the model, the relative risk of contracting mastitis in current lactation in case of one, two, or more clinical cases in previous lactation was 2.0, 2.6, and 2.9, respectively. Those parameters and the ones that determine the production losses caused by clinical mastitis were taken from Houben et al. (1993). They found that production losses related to clinical mastitis in previous lactation were only significant when three or more quarters were infected in previous lactation. Morris and Marsh (1985) concluded in their study that an issue that had not been satisfactorily resolved was whether production remained decreased in the next lactation after an infection had been eliminated, or returned to normal, as both effects were found in other studies. The implemented small effect of production losses caused by clinical mastitis in previous lactation had, of course, its effect on the results, but it is still remarkable that the increased risk related to mastitis in previous lactation had only a small effect on the optimal policy. The model apparently can be reduced by a factor of 4 without affecting the optimal policy by excluding mastitis in previous lactation from the decision-making process.

The model does not focus on specific mastitis treatment decisions. Cows were assumed to have been always treated in cases of clinical mastitis when the decision was to keep or inseminate the cow. Reasons to implement this assumption in such a way were the lack of reliable data on the effect of treatment on new mastitis infections and related production losses, and moreover, because in reality 99% of the cows were treated parenterally, locally, or both (Houben et al., 1993). The bacteria that cause mastitis were not included in the decision-making process. A clinical quarter case was defined to be caused by an average bacterium. Bacteria that cause an infection with more severe production losses should in reality lead to earlier replacement than advised by the model. Because of model size limitations, it was not possible to include the bacteria directly in the replacement and insemination model.

It is hard to compare results with those from the study in which clinical mastitis was included in a DP model (Stott and Kennedy, 1990) because in their study mastitis was a binomial state variable, and replacement decisions were taken only at the beginning of a lactation. Stott and Kennedy (1990) stated in their discussion that culling of cows with mastitis is likely to reduce the risk of further infections in the herd but that the benefits of this effect were not included in their model. This statement is also valid for our model.

The results show that the value of the model for farms with a high incidence of mastitis or high production losses caused by mastitis was relatively high. When relative risk of mastitis had doubled, the number of cows per year per hundred that had mastitis at culling increased from 3.7 to 12.7. On the basis of a doubled risk, an increase to approximately 7.4 was expected.

The sensitivity analysis showed that there was a linear relationship existed between relative risk (in the range of 0 to 2) and mastitis incidence when the optimal policy was followed. Furthermore, there was also an approximate linear relation between mastitis incidence and gross margin. Additional calculations showed that from those two relations it could be concluded that the break-even point for farm-level treatments is $11 / yr per cow for each unit reduction of clinical quarter case (in the range of 0 to 20 quarter cases per 10,000 cow days). For instance, a farm-level treatment (e.g., teat dipping), which reduces the number of clinical quarter cases per 10,000 cow days from 10 to 7.5, may cost $27 / yr at maximum per cow.

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Chapter 4

The economic value of information on mastitis in making dairy cow replacement decisions

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Abstract

The economic value of taking into account the history of clinical mastitis of a cow in insemination and replacement decisions was determined by the dynamic programming technique. The technique provides a method to model a wide variety of cows, differing in age, productive performance, reproductive status, and occurrence of clinical mastitis.

Logistic regression was used to determine the between-herd variation in relative risk of contracting clinical mastitis. This variation was taken into account in the evaluation of the potential value of clinical mastitis in a replacement model. Relative risk varied widely: 12.7% of the farms had more than twice the average risk, and 3.5%, more than three times the average risk. The total losses caused by clinical mastitis were found to be $83[1] per average cow per year in a herd with average risk, and $207 in a herd with twice the average risk. On farms with twice the average risk, the losses from ignoring the history of clinical mastitis in insemination and replacement decisions were $63 per average cow present in the herd per year. This loss was 7.6 times more than on farms with average risk. Information on clinical cases in previous lactation were of no value in the decision-making process.

Advice to all farmers that was based only on farms with average health problems, may be misleading.

(**Key words:** economics, dynamic programming, mastitis, replacement)
Abbreviation key: DP = dynamic programming, RR = relative risk factor.

1. Introduction

Clinical mastitis appears to be repetitive across lactations and, therefore, may have important economic implications for insemination and replacement decisions on dairy farms (Houben et al., 1993). The inherent biological cycles of reproduction and lactation make dairy cow management decisions dynamic, recursive, and stochastic. Insemination and replacement decisions are time-dependent. In optimization problems for multiple periods, dynamic programming (DP) has the advantage of determining optimal decisions without requiring exhaustive enumeration of all sequences of production possibilities (Bellman, 1957; DeLorenzo, 1992).

In the past, DP techniques were frequently used for optimization of replacement decisions of individual cows or sows (Kristensen, 1987; Kristensen, 1989; Van Arendonk, 1985; Van Arendonk, 1985; Van Arendonk, 1986; DeLorenzo, 1992; Huirne et al. 1993; Stott and Kennedy, 1993). In most of those studies, attention was focused

[1] 1 $ = Dfl. 1.80 in this research

on reproduction, production, or both. In many countries, mastitis is the most important health problem (Schepers and Dijkhuizen, 1991). Stott and Kennedy (1993) included both production and clinical mastitis in their model. Those authors defined mastitis as a binomial variable with the time interval of decision making as one lactation. Therefore, the model could not be used to support decisions that have to be taken within a lactation. In addition, differences in reproductive performance were not included. In contrast, Houben et al. (1994) described a DP model that included clinical mastitis in a much more detailed way. A cow could be in one of 32 mutually exclusive states of clinical mastitis, and decisions were supported at a 1-mo interval. Furthermore, reproduction and the change in production within a lactation was modeled in a stochastic way. This latter aspect was not included in earlier dairy replacement decision models, except that of Kristensen (1987). Houben et al. (1994) concluded that, for an average farm, clinical mastitis had a considerable impact on expected income. Yet, in most cases, the optimal decision was to keep and treat the cow rather than to replace her. Furthermore, clinical mastitis occurring in the previous lactation showed a negligible influence on expected income.

The mastitis incidence rate varies considerably among farms (Bunch et al., 1984; Dohoo et al., 1984; Schukken et al., 1991). Therefore, the economic returns from including information on clinical mastitis in a replacement decision model appear to be greatly influenced by the relative risk (RR) of contracting clinical mastitis. The objective of this paper was to use the DP model of Houben et al. (1994) to determine how the RR of cows contracting clinical mastitis on a farm affects the economic impact of including clinical mastitis in decisions on replacement. Another objective was to determine the distribution of RR, as well as the total costs of clinical mastitis with respect to this distribution. Furthermore, suboptimal decisions were defined and analyzed to gain insight into the potential value of clinical mastitis for replacement decisions. This analysis determines whether historical data on clinical mastitis are useful in economically optimal decision making and, moreover, over what time period their usefulness is maintained.

2. Material and methods

2.1. Optimization Model

According to the properties of Markovian theory, the state reached in the next stage of action is not dependent upon the states in previous stages, but only on the state in the current stage (Howard, 1960). The increased probability of reoccurrence is one of the typical characteristics of animal health problems. To include this facet in a Markov-type DP model, the history of diseases of a cow should be an explicit component of the state vector. Consequently, the model will be very large. To be able to handle such a heavily expanded model, Houben et al. (1994) used an alternative DP algorithm, the hierarchic Markov decision process (Kristensen, 1988). The objective function was defined as maximization of expected net returns per year per cow. Time step in the model was 1 mo. The clinical mastitis state was defined in terms of the number of clinical quarter cases in the previous lactation (0, 1, 2, and ≥3), the number of clinical quarter cases in the current lactation until the previous month (0, 1, 2, and ≥3), and the occurrence (yes or no) of clinical mastitis in the previous month. The combination of those three variables yields 32 mutually exclusive mastitis states. Furthermore, the cow was described by the following state variables (number of classes in brackets): production in the current lactation [(15); <74%, 74 to 78%, . . ., 122 to 126% and ≥ 126%)], production in the previous lactation [(15); <74%, 74 to 78%, . . ., 122 to 126% and ≥ 126%)], and calving interval [(8); 11, . . ., 17 mo and open cows)]. Production was defined relative to cows of the same age and month of lactation in absence of genetic improvement and voluntary culling and adjusted for expected calving interval and mastitis status.

The model optimized three decisions that could be made for each state at each decision stage: 1) keep the cow at least until the next moment of decision (month) and do not inseminate her when in estrus; 2) keep the cow at least until the next moment of decision (month) and inseminate her when in estrus and 3) replace the cow immediately by a replacement heifer. The stages of action stages were mo 1 to 17 of lactations 1 to 12.

The basic prices and other parameters used to determine the expected net returns in each state and stage are shown in Table 1. The costs of labor, machinery, housing, and other fixed costs were included when deriving the net returns (Table 1). Other fixed costs included interest, insurance, water, and breeding costs. The labor needed per dry cow and milking cow were 3.4 and 8.2 min / d, respectively. All cows that had clinical mastitis and were not replaced were treated at a cost of $49 per clinical quarter (Houben et al., 1994).

2.2. RR

The maximum likelihood procedure of CATMOD (SAS, 1988) was used to estimate the farm-dependent RR of contracting clinical mastitis. With the exception of farm and calender month, the basic variables of the logistic model were the same as used by Houben et al. (1993): month of lactation, lactation number, production, number of clinical quarters in previous lactation, number of clinical quarters in the previous months of current lactation, and occurrence of clinical mastitis in the

Table 1. Base prices and other parameters used to determine the optimum replacement policy.

Prices	
Milk fat, $/kg	7.78
Milk protein, $/kg	4.72
Base price of milk, $/100 kg	-1.61
Female calves, $/kg	3.67
Male calves, $/kg	5.86
Roughages, $/MJ of NE[1]	.021
Concentrates, $/MJ of NE[1]	.028
Price of carcass weight (for a heifer 7 mo in lactation), $/kg	3.33
Price of replacement heifer, $	1444
Insemination, $	11
Mature equivalent (8 yr) herd level	
Milk, kg	7750
Fat content, %	4.35
Protein content, %	3.39
Other	
Age at first calving, months	24
Mature liveweight, kg	650
Labor costs, $/h	18
Labor per dry cow per day, min	3.4
Labour per milk cow per day, min	8.2
Housing, machinery, and other fixed costs, $ / mo per cow	94

[1]Net energy.

current month. Moreover, the same data were used as described in their study: 5313 lactations of 2477 cows of 22 farms in the period from June 1985 to November 1990. These Dutch farms participated in a research program of the Department of Herd Health and Reproduction of the Veterinary Faculty of the University of Utrecht. For a more detailed description of these data and the logistic model, reference is made to Houben et al. (1993).

To adjust the RR of contracting clinical mastitis, the calculation of this probability in the DP model differed slightly from Houben et al. (1994) and was calculated according to Equation [1]:

$$p(q(t+1) \mid i(t), d(t)) = \begin{cases} \dfrac{RR \times \exp\left(fh_i(t)\right)}{1 + RR \times \exp\left(fh_i(t)\right)}, & t = 1,\ldots,CI - 2 \\ RR \times pDP_{q(t)}, & t = CI - 1 \\ \dfrac{RR \times \frac{30.5}{23.5} \times \exp\left(ff_i(t)\right)}{1 + RR \times \frac{30.5}{23.5} \times \exp\left(ff_i(t)\right)}, & t = CI \end{cases} \quad [1]$$

where

$p(q(t + 1) \mid i(t), d(t))$	=	conditional probability of at least one clinical quarter in stage t + 1, given current state i(t) and decision d(t);
RR	=	RR of contracting clinical mastitis;
$fh_i(t)$	=	function of logistic regression coefficients obtained from Houben et al. (1993) for later months in lactation. Risk factors in this function are clinical mastitis in current month, in previous months, and in previous lactation, lactation number, month of lactation, and production;
$pDP_{q(t)}$	=	probability of mastitis in last month of dry period depending on occurrence of mastitis in month before last month in dry period (q(t));
$ff_i(t)$	=	function of logistic regression coefficients obtained from Houben et al. (1993) for 1st mo of lactation. Risk factors in this function are clinical mastitis in current month and in previous months; and
CI	=	expected calving interval.

As can be seen in Equation [1], a correction factor was introduced to be able to define RR. Other components of this formula were taken from Houben et al. (1994). The factor 30.5/23.5 was used to adjust the coefficients that were based on a period of 23.5 d, instead of 30.5 d.

With the RR in Equation [1], the probability of contracting clinical mastitis was adjusted. For low absolute probabilities (i.e., negative $fh_i(t)$ and $ff_i(t)$), the relationship between probability p and the RR is approximately linear.

2.3. Strategies

To obtain insight into the effect of adding clinical mastitis state to the replacement model, some suboptimal strategies were defined. In each of them, one or more aspects of the clinical mastitis state were ignored. The DP model was used to simulate the effects of those strategies on the farm results. Within each level of RR of contracting clinical mastitis, the farm results of six different strategies were compared: A) optimal strategy, B) optimal strategy when RR is zero, C) all cases of clinical mastitis are ignored, D) cases of clinical mastitis in previous months in current lactation are ignored, E) cases of clinical mastitis in previous lactation are ignored, and F) all cows with clinical mastitis are culled immediately. Strategy B is added to gain insight into the total cost of clinical mastitis on a farm. Strategy C means that the farmer assumes that there is no risk at all for cows to contract clinical mastitis, and decisions taken for cows with clinical mastitis are the same as for healthy cows. Therefore, the results of strategy C versus A show the maximum decrease in net returns resulting from ignoring the clinical mastitis state in the decision-making process. For strategies D and E, a specific part of the mastitis history of a cow is ignored. That makes it possible to evaluate the particular value of including additional mastitis history. Finally, strategy F shows the effect of using the very simplistic culling strategy (i.e., culling all cows with clinical mastitis).

3. Results

3.1. Modelling Outcome

The results of the DP model showed that, under the optimal replacement strategy, 27.2% of the cows were culled annually (Table 2). In this strategy, 16.3% were culled voluntarily and 10.9% involuntarily, thus the model supports 60% (100 x 16.3/27.2) of all decisions that lead to replacement. Furthermore, 14.3% (100 x 3.9/27.2) of the culled cows had clinical mastitis at culling (23.9% of voluntarily culled cows).

Net returns increased by $83 per cow per year when clinical mastitis did not occur at all (B vs. A; Table 2). This increase is an indication of the total loss from clinical mastitis. In that case, milk production - corrected for fat and protein - was increased by 176 kg / yr per cow (2.3%), feed costs were increased by $17 / yr per cow (1.6%), and voluntary replacement was decreased by 1.6%. Although, in the basic situation (A), 14.3% of the culled cows had clinical mastitis at replacement, only 5.5% (100 x 1.6/27.2) of them were actually culled because of clinical mastitis.

Table 2. The expected farm results when strategy A is used, and the results for strategies B to F relative to strategy A[1].

	Strategy[2]					
	A	B	C	D	E	F
Net return per cow, $ / yr	104	83	-8	-2	0	-93
Milk production per cow, kg/yr	7348	170	-21	-11	-1	-131
Milk production per cow, kg of FPCM[3]/yr	7708	176	-28	-15	0	-120
Feed costs per cow, $/yr	1055	17	-3	-2	0	-11
Labor costs per cow[4], $/yr	832	-1	-1	-1	0	3
Calves per cow, no./yr	1.14	-.01	-.01	-.01	.00	.10
Calving interval, d	371	0	0	0	0	1
Mastitis incidence per 10,000 cow days	9.75	-9.75	1.39	.82	.17	-3.93
Replacement, % / yr	27.2	-1.5	-1.5	-1.1	-.2	15.5
Voluntary replacement, % / yr	16.3	-1.6	-1.6	-1.1	-.2	15.6
Voluntary replacement with mastitis, %/yr	3.9	-3.9	-3.7	-.6	-.2	15.6

1 Relative risk for mastitis = 1.
2 Values represent increase or decrease in model parameters compared with strategy A
3 FPCM = Fat- and protein-corrected milk. FPCM = .349milk (kilogram) + 10.7fat (kilogram) + 6.7protein (kilogram).
4 Except for labor costs for mastitis treatment.

When the farmer used strategy C, which ignored the mastitis state of a cow, the expected net return was reduced by $8 / yr per cow, which was 8.0% of the net return, and the incidence of mastitis was increased by 1.36 clinical cases per 10,000 cow days at risk (13.9%). If cases of mastitis in earlier months in current lactation and in previous lactation were not taken into account (strategies D and E), then the net return was reduced by $2 or not reduced, respectively, compared with the optimal strategy. Exclusion of cases of mastitis in the previous lactation, therefore, had only a minor effect on the financial and technical parameters. Obviously, it was not a good strategy to cull all cows with clinical mastitis immediately (strategy F), as illustrated by the reduction in the net revenue of $93 in compared with the optimal strategy (A) and the increased rate of the replacement of 15.6 percentage points (96%). The suboptimal strategies, and clinical mastitis in general, had no influence on labor costs, the optimal herd calving interval, or the number of calves born per cow per year.

Table 3 shows results for the farms with a RR of half of the average risk. For those farms, the losses caused by clinical mastitis were $34 / yr per cow and the total replacement rate was 1.1 percentage points lower than for farms with an average risk. The incidence of mastitis decreased to 4.32 clinical quarter cases per 10,000 cow days at risk (44%). As expected, the returns for including mastitis in a replacement

Table 3. The expected farm results when strategy A is used, and the results for strategies B to F relative to strategy A[1].

	Strategey[2]					
	A	B	C	D	E	F
Net return per cow, $/yr	153	34	-2	-1	0	-58
Milk production per cow, kg/yr	7448	70	-5	-2	0	-86
Milk production per cow, kg of FPCM[3]/yr	7811	73	-7	-3	-1	-79
Feed costs per cow, $/yr	1064	7	-1	0	0	-7
Labour costs per cow[4], $/yr	832	0	0	0	0	2
Calves per cow, no./yr	1.13	.00	-.00	0	.00	+.06
Calving interval, d	371	0	0	0	0	0
Mastitis incidence per 10,000 cow days	4.32	-4.32	.18	.05	.01	-1.31
Replacement, %/yr	26.1	-.4	-.4	-.3	-.1	8.3
Voluntary replacement, %/yr	15.1	-.4	-.4	-.2	0	8.5
Voluntary replacement with mastitis, %/yr	1.3	-1.3	-1.2	-.1	-.1	9.0

1 Relative risks for mastitis = .5.
2 Values represent increase or decrease in model parameters in comparison with strategy A
3 FPCM = Fat- and protein-corrected milk. FPCM = .349milk (kilogram) + 10.7fat (kilogram) + 6.7protein (kilogram).
4 With exception of labor costs for mastitis treatment.

model were smaller than for farms with an average RR. In this situation, the history of mastitis of a cow was of no value in culling decisions. Ignoring the mastitis status cost a maximum of $2 / yr per cow (C). Immediate culling of all cows that had contracted clinical mastitis cost $58 / yr per cow (D).

Table 4 shows the results when the RR of contracting mastitis was doubled. The incidence of mastitis increased to 19.86 clinical cases per 10,000 cow days at risk (2.0 times the average). Clinical mastitis then cost $207 / yr per cow, which was 2.5 times more than for farms with average RR. With no clinical mastitis (B), the milk production corrected for fat and protein increased by 416 kg (5.6%). The losses caused by ignoring clinical mastitis in the decision-making process (C) were $63, or 7.6 times more than farms with average RR farms. Failure to consider the clinical cases in previous months in the current lactation (D) cost $15, which was nine times more than for average RR. Information on cases of clinical mastitis in the previous lactation again was hardly of any value ($2). When the optimal strategy (A) was used, the annual replacement rate increased to 34.0%. About 39.1% (100 x 13.3/34.0) of all replaced cows had clinical mastitis at culling. For 25.5% (100 x 8.6/34.0) of the replaced cows, clinical mastitis was the main reason for culling. In total, 68.5% (100 x 23.3/34.0) of all replacements were voluntary in this situation. If clinical mastitis

Table 4. The expected farm results when strategy A is used, and the results for strategies B to F relative to strategy A[1].

	Strategy[2]					
	A	B	C	D	E	F
Net return per cow, $/yr	-20	207	-63	-15	-2	-116
Milk production per cow, kg/yr	7110	408	-159	-67	-7	-106
Milk production per cow, kg of FPCM[3]/yr	7468	416	-189	-78	-8	-99
Feed costs per cow, $/yr	1031	41	-16	-7	-1	-11
Labour costs per cow, $/yr	834	-3	-3	-2	1	4
Calves per cow, no./yr	1.18	-.05	-.05	-.03	-.01	.14
Calving interval, d	371	0	0	0	0	1
Mastitis incidence per 10,000 cow days	19.86	-19.86	12.85	4.92	1.47	-8.77
Replacement, %/yr	34.0	-8.3	-8.3	-5.2	-.9	22.3
Voluntary replacement, %/yr	23.3	-8.6	-8.6	-5.3	0	22.3
Voluntary replacement with mastitis, %/yr	13.3	-13.3	-12.7	-2.6	-1.1	22.7

1 Relative risk for mastitis = 2.
2 Values represent increase or decrease in model parameters in comparison with strategy A
3 FPCM = Fat- and protein-corrected milk. FPCM= .349milk (kilogram) + 10.7fat (kilogram) + 6.7protein (kilogram).
4 With exception of labor costs for mastitis treatment.

state was ignored, the replacement rate decreased by 8.3 percentage points, and the optimal herd calving interval did not change. This latter finding indicated that clinical mastitis was of minor importance with regard to the insemination strategy. Culling all cows that contracted clinical mastitis reduced the net return by $116 and led to an increase of 22 percentage points in voluntary replacement.

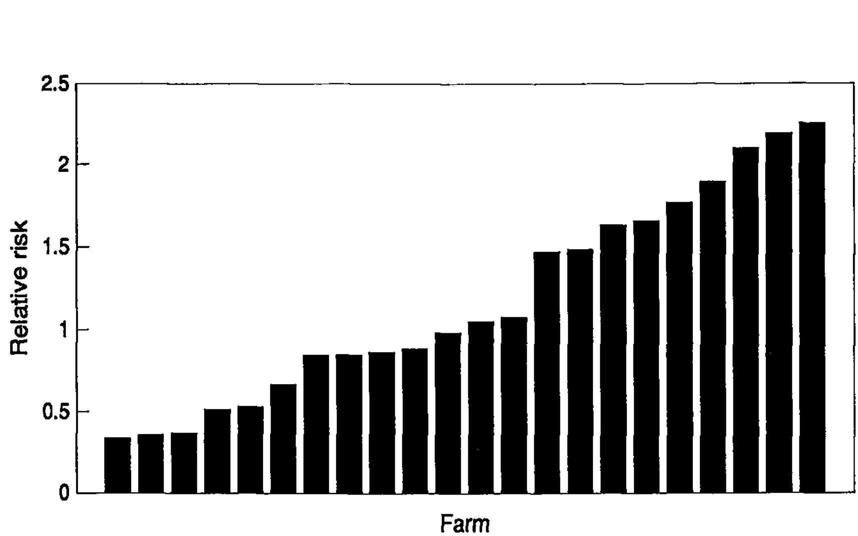

Figure 1. The risk of contracting clinical mastitis of 22 farms relative to the risk of the state average farm risk value.

3.2. Impact on Farms

The logistic regression showed a strong farm effect (P < .0001) for the RR of contracting clinical mastitis. Figure 1 shows the RR of clinical mastitis on the 22 farms used in the analysis, compared with the RR of the average farm. The RR varied from .34 to 2.25, and the logistic parameter estimates of those farms showed a standard deviation of .61. Figure 2, shows the cumulative logistic distribution of RR according to this standard deviation. In agreement with its definition, an RR (i.e., odds ratio) of 1 corresponds to a cumulative distribution of 50%. About 12.7% of the farms had an RR of < .5, and 12.7% had an RR of ≥ 2. An RR of ≥ 3 and 4 was observed for 3.5% and 1.1% of the farms, respectively. As shown in Table 3, the losses caused by ignoring clinical mastitis in a replacement model and also the general losses caused by clinical mastitis were highly sensitive to the RR of clinical mastitis. The losses caused by ignoring mastitis for different RR showed a nonlinear pattern (Figure 3). On an average farm, with an average RR, these losses were $8 / yr per cow (Table 2). For a farm with twice the average RR, the losses were $63 / yr per cow (Table 3). In other words, 12.7% of the farms (Figure 2) lost at least $63 (7.6 times the average) by ignoring clinical mastitis (Figure 3). Similarly, 1.1% of farms had losses of at least $328 (39.3 times the average). The weighted average losses caused by ignoring clinical mastitis were $31, which was 3.7 times more than the losses on a farm with average risk. The effect of seasonality was approaching significance (P = .07). There was an indication that there was a lower risk from July to September and a higher risk from November to February.

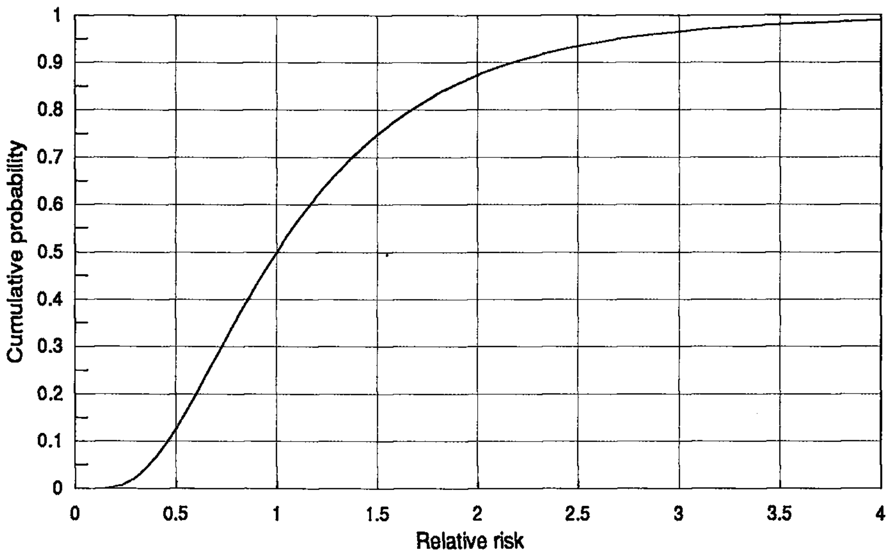

Figure 2. The cumulative logistic distribution of the relative risk of contracting clinical mastitis.

The total costs of clinical mastitis were calculated as the difference between the net return under optimal policy and the net return when clinical mastitis was absent. Figure 4 shows the costs of clinical mastitis against RR. On farms with average RR, mastitis cost $83 / yr per cow. With twice the average RR, the mastitis costs increased to $207 / yr per cow (2.5 times the average). As mentioned before, > 1.1% of all farms had a RR of 4. On these farms, mastitis cost $437 / yr per cow (5.2 times the average). The weighted average costs of clinical mastitis were $111 / yr per cow.

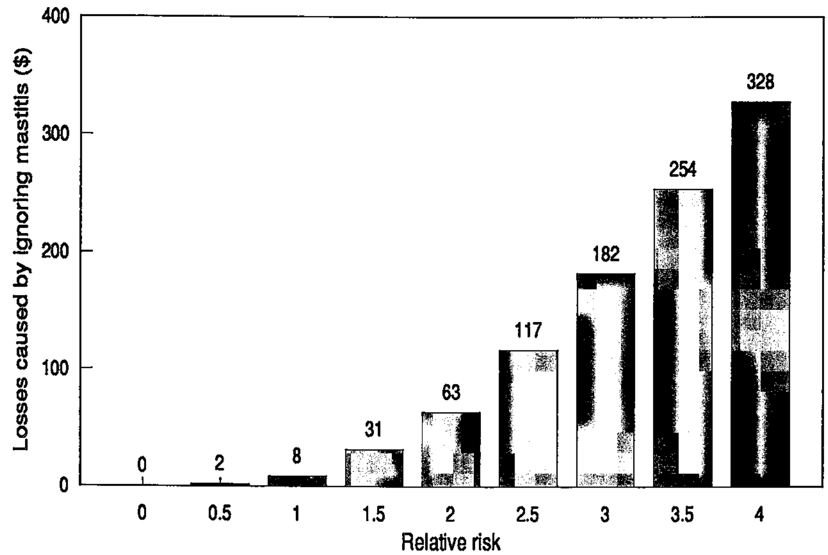

Figure 3. Effect of relative risk of contracting clinical mastitis on the maximum losses per cow per year caused by ignoring clinical mastitis in the decision-making process.

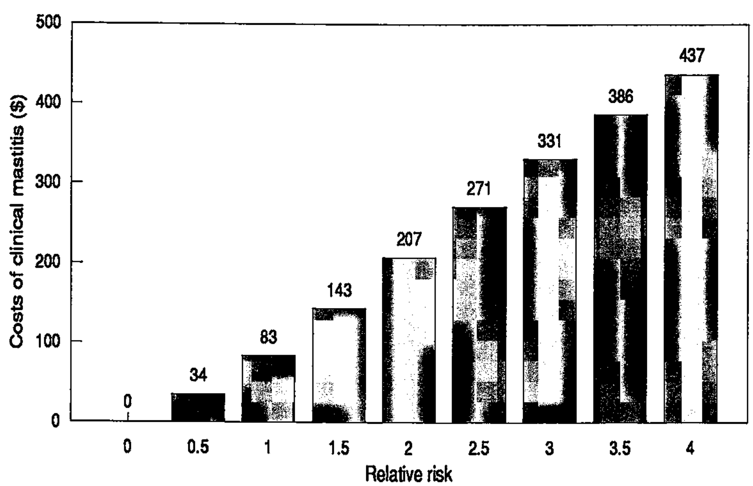

Figure 4. The effect of relative risk of contracting clinical mastitis on the total costs per cow per year caused by clinical mastitis.

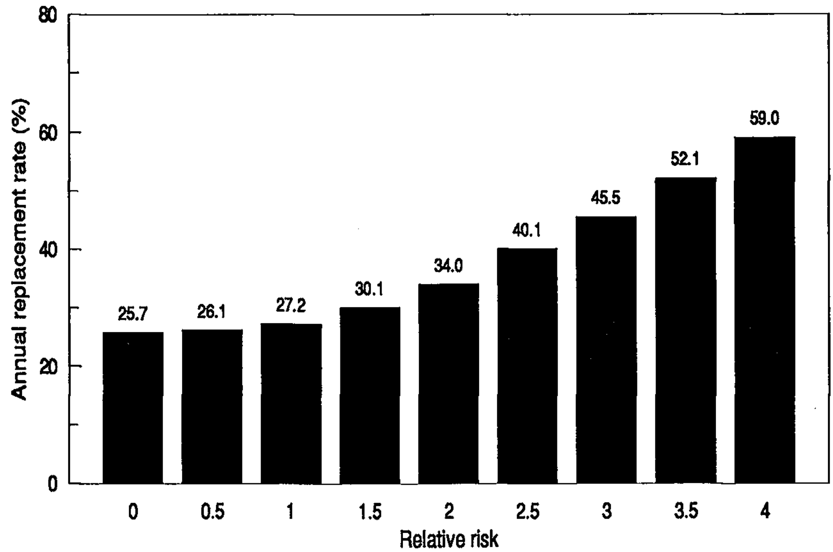

Figure 5. Effect of relative risk of contracting clinical mastitis on overall replacement rate under optimal policy.

In Figure 5, the effect of RR on overall replacement rate under optimal policy is shown. The replacement rate increased from 25.7 to 59.0% for farms with no clinical mastitis and for farms with four times the average RR respectively. The weighted replacement rate was 29.7% (2.5% more than the average). Ignoring clinical mastitis led to a replacement rate of 25.7% in all situations.

4. Discussion

A large variation was found in RR of contracting clinical mastitis. The RR for a sample of 22 farms varied from .34 to 2.25 in the RR of an average farm. The logistic distribution showed that 12.7% of the farms had a RR of more than twice the average and 1.1% of more than four times the average (Figure 2).

Total losses caused by clinical mastitis for a farm with an average RR was $83 / yr per cow, which was within the range found by Schepers and Dijkhuizen (1991). However, in their review no attention was given to the strong variation in losses between farms. In our study, the average losses (i.e. weighted for probability of occurrence) for all farms was $111 / yr per cow. On farms with twice the average RR, total losses caused by clinical mastitis were 2.5 times higher. On those farms, an insemination and replacement strategy that takes into account the mastitis states of a cow is relatively much more important than on farms with average RR. On farms with an average RR, 5.5% of all culled cows had clinical mastitis as the main reason for culling. On farms with twice the average RR, removal for clinical mastitis increased to 25.3%. Ignoring clinical mastitis state in the decision-making process on farms with double RR led to losses that were 7.6 times higher ($63 / yr per cow) than the losses caused by ignoring clinical mastitis on a farm with average RR. A farm with average RR will probably gain only a little money ($8 / yr per cow at maximum) when the clinical mastitis state is included in the decision-making process, but farms with more than twice the average RR (12.7% of all farms) benefit significantly more. Thus advice to farmers that is based only on farms with average health problems may be misleading, which may explain why the average replacement rate is in practice higher than is optimal for an average farm. Furthermore, losses are underestimated when they are based on farms with average health problems.

The inclusion of the number of clinical cases of previous lactation in the decision-making process is only of minor importance. Even farms with twice the average RR cannot expect a benefit of > $2 / yr per cow when this information is included. This means that the size of the DP model can be reduced by a factor 4, without losing important information.

For high RR, the total losses caused by clinical mastitis were slightly overestimated in this study. For instance, the costs of a veterinarian visit per quarter case would be lower because more quarter cases could be treated during one visit.

In addition to the strong significant farm effect, the logistic regression showed an approaching significant effect of calendar month on the RR of contracting clinical mastitis. The pattern of those RR indicates that RR is low from July to September and high from November to February. Van Arendonk (1986) found that the optimal policy for insemination and replacement was greatly affected by seasonal differences in production. In the absence of seasonal variation, changes in the production of the herd did not significantly affect the optimal policy of inseminating and replacing cows (Dijkhuizen et al, 1985; Van Arendonk, 1985). In our study, seasonal variation was omitted, and decisions on insemination were hardly affected by the clinical mastitis state of the cow. Optimal herd calving interval remains close to 370 d for all suboptimal strategies. The inclusion of seasonal effects in RR of contracting clinical mastitis would probably lead to analogous effects on insemination decisions, as found by Van Arendonk (1986).

A mathematical model is usually a simplification of a real world situation. DP models are no exception. Further research should focus on the value of additional information on bacterial cause and subclinical mastitis. Because subclinical mastitis is less severe (Schepers and Dijkhuizen, 1991), it might be expected to be less important than clinical mastitis. If information is available on the specific effect of bacterial cause of clinical mastitis on production losses and reoccurrence probability, then the economic value of a cow with such a specific clinical mastitis can be extrapolated from a cow with an "average" bacterial cause.

The optimization model runs on a UNIX-based workstation, which is a disadvantage for practical implementation of the system on dairy farms. However, the optimization model generates a lookup table which is stored on a hard disk. For on-line use on a dairy farm, this lookup table can easily be accessed by a personal computer. With this information, decisions on insemination and replacement can be supported for the entire range of cows. However, the lookup tables have to be generated at a centrally managed workstation. Another way of implementation could be to reduce the size of the model so that it runs on a personal computer. As mentioned before, exclusion of the information on mastitis in the previous lactation would reduce the size by a factor of four, with only a minor effect on the economic results. Reducing it by another factor of four would result in a model that can be implemented on a personal computer. This reduction can, for instance, be reached when the mastitis state is based only on clinical mastitis in the current month. Using this smaller model, the expected net returns for farms with average RR of contracting clinical mastitis would only be a little reduced ($2 / yr per cow) compared with the complete model. The information needed for running the model is already available on each modern dairy farm and, with some transformation, can be used directly. However, to make the implementation of the model practical, efforts should focus on automatic data exchange between the optimization model and the farm management computer.

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Chapter 5

The effect of milk quotas on optimal dairy cow insemination and replacement decisions

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Abstract

Dynamic programming (DP) was used to evaluate two optimization criteria for insemination and replacement decisions under a quota system: 1) maximization of expected net returns per kg of milk and 2) maximization of expected net returns per cow. Attention was particularly focused on the effect of including opportunity costs of labour, housing and other non-yield related costs on the optimal strategy. In the DP model, cows differed in age, productive performance and reproductive status.

If opportunity costs of labour, housing and other non-yield related costs were included (i.e. infinite planning horizon), then the optimal insemination and replacement decisions to maximize the expected net returns per cow were the same as those to maximize the expected net returns per kg of milk. However, when the combination of net returns to labour, housing and management was maximized, and thus no attention was paid to the number of hours that were necessary and to the housing capacity needed, then selecting the right optimization criterion was important. In this situation the optimal policy for maximizing the expected net returns per cow differed from that of maximizing the expected net returns per kg of milk (6.1% more voluntary replacements when maximizing expected net returns per cow). Total net returns were Dfl. 0.32 per 100 kg of milk higher when maximizing the expected net returns per kg of milk.

Key words: economics; dynamic programming; replacement; milk quota; dairy farming

Abbreviation key: **DP** = dynamic programming; **NRC** = maximum expected net returns per cow per year; **NRM** = maximum expected net returns per cow per kg milk produced.

1. Introduction

In the Netherlands about 30 to 35% of the cows are replaced annually, mostly for reasons of insufficient production capacity, reproductive failure and mastitis (Sol et al., 1984). Usually these cows are culled not because they are no longer able to produce in a biological sense, but because replacement animals are expected to yield a higher profit. The income potential of the replacement animal cannot be realized as long as the other animal is still present in the herd. Not realizing the income potential can be considered as the opportunity costs of postponed replacement. So, in optimizing replacement decisions net returns of not only the animals present in the herd but also the net returns of all subsequent replacement animals have to be maximized (Dijkhuizen et al., 1985).

A common criterion in various dairy cow replacement models is to maximize the expected net returns per cow per year (NRC) (Van Arendonk, 1985b; DeLorenzo et al., 1992; Stott and Kennedy, 1993). Under a milk quota system, however, such a criterion may no longer be appropriate because economic efficiency should be expressed in terms of the most limiting restriction. The appropriate criterion to apply in this situation is maximization of net returns per kg of milk produced (NRM) (Kristensen, 1989; Kristensen and Thysen, 1991). The authors proved that culling should be less intensive under a quota system because of a smaller variation in future profitability between cows. Considerable differences between those two criteria were found in future profitability and ranking of cows.

In the short term fixed costs do not change with the level of output. As the length of the planning period increases, more costs are considered as variable costs. In the long term, virtually all inputs can change and hence become variable costs. Variable costs should be taken into account in making production decisions (Boehlje and Eidman, 1984). Kristensen (1989) and Kristensen and Thysen (1991) did not include costs of labour, housing and other non-yield related costs in their optimization models. So, they assumed that farmers maximize the net returns per kg of milk produced, not taking into account the amount of labour and number of cow places needed. In other words, they, in fact, maximized for a short planning horizon. Kristensen (1989) and Kristensen and Thysen (1991) assumed farmers to have a surplus of labour and building capacity, because they had had to reduce their herd size due to the quota system. Therefore the opportunity costs of those factors were assumed to be zero. This may be a good assumption for some farmers on the short term, but is certainly not true for modern well-equipped farms on the long term.

The objectives of this paper were to use the DP model of Houben et al. (1994) 1) to determine the optimal insemination and replacement strategy under a milk quota system and with an infinite planning horizon, and 2) to determine the effect of including opportunity costs of labour and buildings on the optimal insemination and replacement strategy in a situation with and without milk quota.

2. Material and methods

2.1. Optimization Model

Insemination and replacement decisions concerning individual animals can be defined as a multistage decision problem, which is a sequence of similar decisions over time. The inherent biological cycles of reproduction and lactation make dairy cow management decisions dynamic, recursive and stochastic. Insemination and replacement decisions are time-dependent. In multistage optimization problems, dynamic programming (DP) has the advantage of determining optimal decisions without requiring exhaustive enumeration of all sequences of production possibilities (Bellman, 1957; DeLorenzo et al., 1992). Major advantages of DP include the possibility of accounting for variation in, and repeatability of traits (Van Arendonk, 1984). The risk that a high-producing animal may have a low future production and the risk that an animal may be replaced by a low-producing animal can both be taken into account. However, a DP model may easily become very large, which would result in high memory requirements and high computation costs. Kristensen (1988) developed an efficient DP algorithm, i.e., the hierarchic Markov Process (HMP), which can be used to optimize relatively large problems. The HMP approach was used by Houben et al. (1994) in the cow insemination and replacement problem in maximizing the objective function of expected net returns per cow per year. The HMP technique allows the replacement problem to be solved by other objective functions, as long as these functions can be formulated as ratios.

In the DP model of Houben et al. (1994), one month was taken as the time step. One of the specific characteristics of the model was that a cow could be in one of 32 mutually exclusive clinical mastitis states. Consequently, the model was very large (a cow might enter 6,821,724 different states during her life), and it had to run on a workstation because of memory requirements. Because the only purpose of the current paper was to evaluate the effect of opportunity costs of labour and housing under a quota system, the mastitis state variable was excluded from the optimization model. This simplified the interpretation of the results. After excluding the mastitis states the model comprised 214,344 states and (thanks to the HMP approach) could run on a PC. The cow was described by the following state variables: 15 production levels in current lactation (<74%, 74 to 78%, . . ., 122 to 126%, and ≥ 126%), 15 production levels in previous lactation (<74%, 74 to 78%, . . ., 122 to 126%, and ≥ 126%), and 8 calving intervals (11, . . ., 17 months and open cows). Production level was defined relative to cows of the same age and month of lactation, in absence of genetic improvement and voluntary culling and adjusted for expected calving interval.

The model optimizes the decision variable that includes three decisions for each state at each decision stage: 1) keep the cow at least until the next decision moment (month) and do not inseminate her when in oestrus, 2) keep the cow at least until the next decision moment (month) and inseminate her when in oestrus, and 3) replace the cow immediately by a replacement heifer. The action stages were months 1 to 17 of lactations 1 to 12.

2.2. Net returns

The performance model that calculates net returns from milk production, calf sales, feed costs and sundry costs was described by Van Arendonk (1985a). The basic prices and other parameters used to determine the expected net returns in each state and stage were updated and are shown in Table 1. These parameters represent a typical Dutch situation for Black-and-White cows. The milk production of a mature cow was set at 7750 kg containing 4.35% of fat and 3.39% of protein (Table 1). For each month in lactation (stage of action) the net returns from milk production were determined and based on fat and protein contents. Feed costs were calculated from consumption of roughage and concentrates, estimated from the energy requirements. Furthermore, the calf revenues were included. Because in general the milk quota system leads to a reduction in herd size, there may be a surplus of labour and housing. In order to determine the effect of the inclusion of the opportunity costs of labour and housing on the optimal insemination and replacement strategy, two extreme situations were defined: 1) there is no alternative use of labour and housing and, hence, the opportunity costs are zero, and 2) all surplus of labour and housing capacity can be used for other purposes and is therefore valued correspondingly. In the situation with alternative use of housing, the opportunity costs were assumed to be Dfl. 960 per cow per year (Table 1). In that case total costs of labour per cow depended on the herd structure and calving interval because it was calculated from the time needed per cow per day. The labour needed per dry cow and milking cow was 3.4 and 8.2 minutes per day respectively. The opportunity costs of labour were set at Dfl. 33 per hour, which is equal to the normal wage rate in the dairy farm production process. In both situations the same non-yield related costs were included, such as costs of machinery, interest, use of water and electricity, insurance, membership fees, breeding costs, etc. The total costs of these factors were Dfl. 1080 per cow per year (Table 1).

In most optimization models these none-yield related costs (i.e., other than labour and housing costs) are only partly included (Van Arendonk, 1985b; Kristensen and Thysen, 1991; DeLorenzo et al., 1992; Stott and Kennedy, 1993). Therefore, the effect of excluding them was evaluated as well.

An adjustment was made to the model of Houben et al. (1994) by including the culling of cows due to clinical mastitis in the involuntary instead of the voluntary replacement category. The marginal probabilities of involuntary disposal were taken from Dijkhuizen (1983): 12, 13, 14, 15, 17, 17, 18, 19, 21, 23, 25, and 28% for lactations 1 to 12 respectively. These probabilities include all reasons for culling except those determined by the model (i.e. low production, poor reproduction and old age). The proportions of disposal during each month of lactation were: 20, 8, 7, 7, 8, 9, 9, 9, 8,

Table 1. Base prices and other parameters used to determine the optimum replacement policy.

Prices	
milk fat (Dfl / kg)	8.45
milk protein (Dfl / kg)	12.90
base price of milk (Dfl / 100 kg)	-5.60
female calves (Dfl / kg)	6.60
male calves (Dfl / kg)	10.55
roughage (Dfl / MJ NE[1])	0.057
concentrates (Dfl / MJ NE[1])	0.058
carcass weight (Dfl / kg (for a heifer 7 months in lac)	6.00
price of replacement heifer (Dfl)	2600
insemination (Dfl)	20
Mature equivalent (8 year) herd level:	
milk (kg)	7750
fat content (%)	4.35
protein content (%)	3.39
Other:	
age at first calving (months)	24
mature liveweight (kg)	650
labour costs (Dfl / hour)	33
labour / dry cow / day (minutes)	3.4
labour / milk cow / day (minutes)	8.2
housing (Dfl / cow / year)	960
machinery and other non-yield related costs (Dfl / cow / year)	1080

[1]Megajoules of net energy

7, 6, and 5% for months 1 to 12 respectively, and 4% for higher months (Van Arendonk, 1985a).

3. Results

3.1. Basic situation

The two objective functions, maximization of expected net returns per cow per year (NRC) and maximization of expected net returns per kg of milk (NRM) were first compared for a situation with opportunity costs of labour and housing and then without those costs. In the situation with opportunity costs (Table 2) there was only a slight difference in the technical and economic results. For both optimization criteria the net returns per cow per year were Dfl. -249. When maximizing NRM the milk production was slightly higher (16 kg per cow per year) and, hence, the negative net returns per cow were distributed over more kilograms of milk, which resulted in a slightly higher net return per 100 kg of milk (Dfl. 0.004 per 100 kg of milk). Also, the voluntary replacements increased by 1.0% per year (Table 2). The technical results showed that the optimal insemination and replacement policy was approximately the same for both objective functions.

Table 2. The expected farm results when objective function is to maximize expected net returns per cow (NRC), and to maximize expected net returns per kg of milk (NRM), and the differences. Opportunity costs of labour, housing, and other non-yield related costs are included.

	NRC	NRM	NRM-NRC
net returns[1] (Dfl / yr per cow)	-249	-249	0
net returns[2] (Dfl / 100 kg milk)	-3.345	-3.341	0.004
milk production (kg / yr per cow)	7431	7447	16
fat production (kg / yr per cow)	327	328	1
protein production (kg / yr per cow)	255	255	0
feed costs (Dfl / yr per cow)	2283	2286	3
labour costs (Dfl / yr per cow)	1498	1498	5
number of calves (per yr per cow)	1.14	1.14	0
calving interval (days)	371	371	0
replacement (% / yr)	27.6	28.6	1.0
voluntary replacement (% / yr)	11.7	12.7	1.0

[1]net returns to housing, labour and management are Dfl 2209 per year per cow for both optimization criteria.
[2]net returns to housing, labour and management are Dfl 29.72 and 29.66 per 100 kg of milk for maximization of NRC and NRM respectively.

In Figure 1 the pattern of optimal decisions for lactations 1 to 3 is shown for the NRC criterion with respect to the relative production of an open cow. In the first month of lactations 1 to 3 an open cow was never culled, but was culled after month 10. In the period that insemination was allowed in the model (months 3 through 9), cows were replaced, if production was below 74% relative to cows of the same age and month of lactation with exception of lactation 3. This percentage increased to 100% (average production level) in month 9. In the first lactation virtually all cows in oestrus were either replaced or inseminated; none of them were kept without insemination.

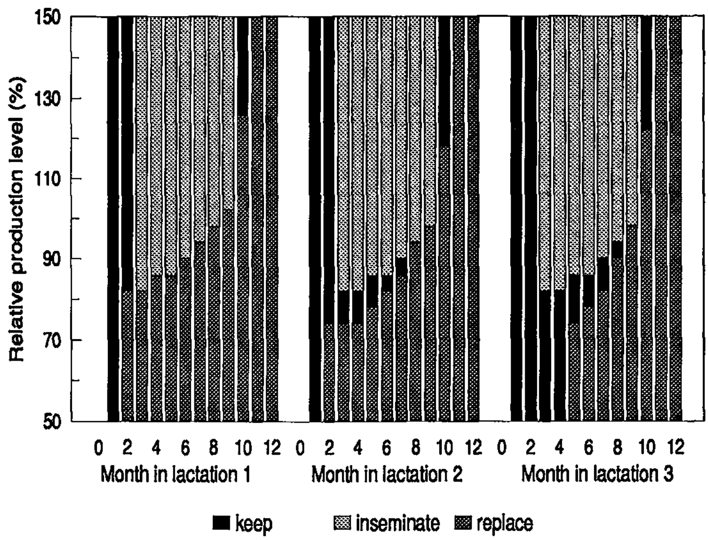

Figure 1. Optimal decision pattern for an open cow with respect to relative production level with NRC and inclusion of opportunity costs of labour and housing.

3.2. Excluding opportunity costs of labour and housing

Table 3 shows the results for both optimization criteria when the opportunity costs of labour and housing were set at zero. When maximizing NRC, the net returns per cow per year (which in this case equal the net returns to labour, housing and management) were Dfl. 34 higher and the net returns per 100 kg of milk were Dfl. 0.320 lower than when maximizing NRM. It should be obvious that another insemination and replacement policy was chosen to achieve the optimal results. When maximizing NRM, costs were kept low, even if that meant that the production would decrease (here 193 kg per cow per year). The length of calving interval increased by 13 days and voluntary replacements decreased by 6.1 cows per hundred annually.

The effect of the optimization criteria NRC and NRM on the optimal insemination and replacement decisions for individual cows when excluding opportunity costs of labour and housing is shown in Figures 2 and 3. When maximizing NRM criterion, cows in heat and producing more than average were not inseminated in the third month of lactation (i.e. the first month that insemination was allowed in the model); insemination was delayed for those cows. Moreover, open cows were not replaced before months 7 and 8 in lactations 2 and 3 respectively, irrespective of their

Table 3. The expected farm results when objective function is to maximize expected net returns per cow (NRC), and to maximize expected net returns per kg of milk (NRM), and the differences. Opportunity costs of housing and labour are not included. Costs of machinery and other non-yield related costs are included.

	NRC	NRM	NRM-NRC
net returns[1] (Dfl / yr per cow)	2210	2176	-34
net returns[1] (Dfl / 100 kg milk)	29.642	29.962	0.320
milk production (kg / yr per cow)	7457	7264	-193
fat production (kg / yr per cow)	328	321	-7
protein production (kg / yr per cow)	255	249	-6
feed costs (Dfl / yr per cow)	2287	2251	-36
labour costs (Dfl / yr per cow)	0	0	0
number of calves (per yr per cow)	1.15	1.07	-0.08
calving interval (days)	371	384	13
replacement (% / yr)	29.6	23.4	-6.2
voluntary replacement (% / yr)	13.8	7.7	-6.1

[1]equals net returns to housing, labour and management

production level. In the first 7 months of lactation 1 the open cows were only replaced if their production was below 74%. High-producing open cows were even kept until month 12 of lactations 1 and 2.

Table 4. The expected farm results when objective function is to maximize expected net returns per cow (NRC), and to maximize expected net returns per kg of milk (NRM), and the differences. Opportunity costs for labour and housing, and machinery and other non-yield related costs are not included.

	NRC	NRM	NRM-NRC
net returns[1] (Dfl / yr per cow)	3290	3164	-126
net returns[2] (Dfl / 100 kg milk)	44.125	45.011	0.886
milk production (kg / yr per cow)	7457	7030	-427
fat production (kg / yr per cow)	328	312	-16
protein production (kg / yr per cow)	255	242	-13
feed costs (Dfl / yr per cow)	2287	2205	-82
labour costs (Dfl / yr per cow)	0	0	0
number of calves (per yr per cow)	1.15	1.00	-0.15
calving interval (days)	371	407	36
replacement (% / yr)	29.6	22.0	-7.6
voluntary replacement (% / yr)	13.8	6.6	-7.2

[1]net returns to housing, labour and management are Dfl 2210 and 2084 per year per cow for maximization of NRC and NRM respectively.
[2]net returns to housing, labour and management are Dfl 29.64 and 29.64 per 100 kg of milk for maximization of NRC and NRM respectively.

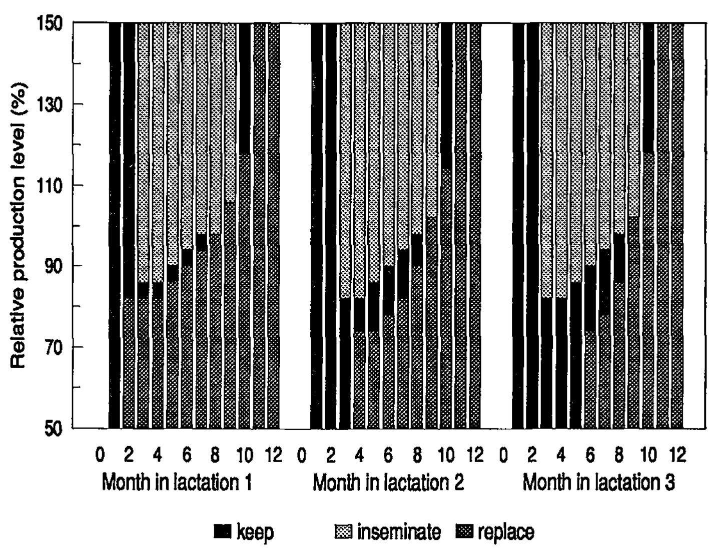

Figure 2. Optimal decision pattern for an open cow with respect to relative production level with NRC and exclusion of opportunity costs of labour and housing.

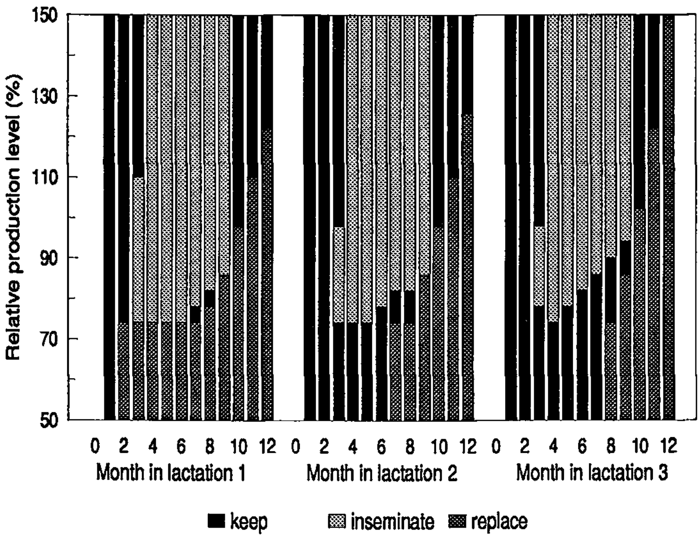

Figure 3. Optimal decision pattern for an open cow with respect to relative production level with NRM and exclusion of opportunity costs of labour and housing.

The exclusion of opportunity costs of labour and housing seems to have only a slight effect with respect to the NRC criterion. In lactations 2 and 3, cows in heat with average production were treated more tolerantly (Figures 1 and 2). Instead of culling immediately they were kept for one month without inseminating them. Nevertheless, when excluding opportunity costs of labour and housing, the voluntary replacement rate was 2.1% higher for the NRC criterion (Tables 2 and 3) than when those costs were included. This was caused by more culling of cows with a longer expected calving interval, which resulted in a slightly shorter calving interval (Tables 2 and 3). The reason for this can be found in the expected costs of labour which were lower for cows with a longer calving interval, since the next dry period was longer.

3.3. Excluding other non-yield related costs additionally

Also the alternative that excluded opportunity costs of labour and housing together with other non-yield related costs was evaluated. Table 4 shows the farm results for both optimization criteria. The technical and economic results when applying the NRC criterion were exactly the same as the results when only labour and housing costs were excluded (Tables 3 and 4). However, maximizing the net returns per kg of milk (NRM) resulted in a completely different optimal insemination and replacement policy from the one when maximizing per cow (NRC). With the latter criterion, the voluntary replacement rate was 7.2% lower (Table 4) and the milk production decreased by 427 kg. When maximizing NRM, the calving interval increased by 36 days and the number of calvings per year was 1.00 instead of 1.15. Figure 4 shows the optimal insemination and replacement policy for an open cow in lactations 1, 2, and 3 when maximizing NRM. The first insemination of high-producing cows was shifted to the fifth month in lactation and open cows were not culled until month 10 in lactations 1, 2, and 3. With the exception of months 8 and 9 in lactation 3, all cows were inseminated irrespective of time and production level. High-producing open cows were even kept until month 12 in each of the lactations.

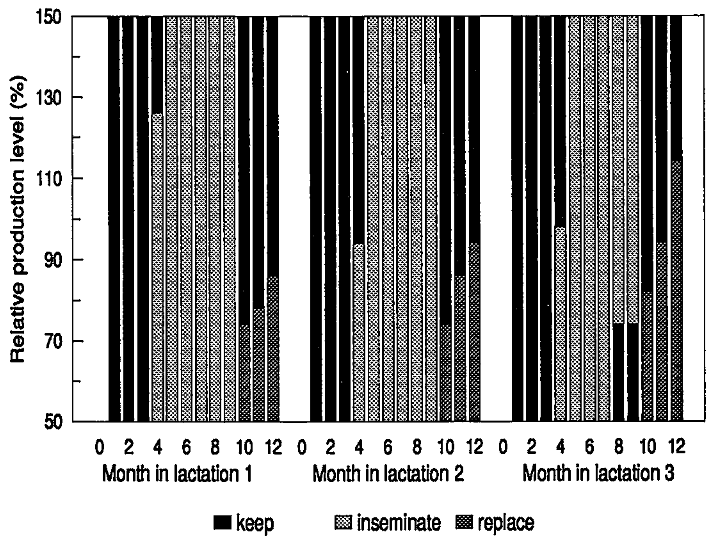

Figure 4. Optimal decision pattern for an open cow with respect to relative production level with NRM and exclusion of opportunity costs of labour, housing and other non-yield related costs.

4. Discussion

The results showed that the level of opportunity costs of housing and labour had a considerable effect on the optimal replacement policy in case of maximization of net returns per kg of milk. When maximizing net returns per cow, the level of those costs showed hardly any effect. The situation a farmer is in determines the choice for the appropriate optimization criterion. If a farmer hires labour or wants to expand his business, full costs of labour and housing must be included, in case of a infinite planning horizon. Then both optimization criteria will yield approximately the same results. Additional calculations showed that as soon as a positive net return was obtained (which was - according to reality - not the case in Table 2), both optimization criteria even led to exactly the same policy. Consequently, the statement by Kristensen and Thysen (1991) that a decision support system based on maximization of net returns per cow will directly misinform the dairy farmer if used under a quota system, does not hold for those farmers, at least not for Dutch conditions. If a farmer wants to maximize net returns to labour, housing and management (which was the case in the research of Kristensen and Thysen (1991), also shown in Table 3), and does not care how much time he has to spend or how much housing he needs (so, a situation without any opportunity costs), then choosing the correct optimization criterion is important. In the latter case the optimal policy to maximize the net returns per cow differed considerably from that one to maximize the net returns per kg of milk (6.1% more voluntary replacements in case of maximization per cow) and the total net returns per 100 kg of quota were Dfl. 0.35 higher when the correct optimization criterion was used. This is approximately 1% of the net returns to labour, housing and management. Although Kristensen and Thysen (1991) noted in their thorough description of theoretical aspects of a milk quota that costs of keeping a cow should be considered, they did not include the opportunity costs of labour and housing, nor other non-yield related production costs. Under these assumptions, they came to the conclusion that the culling rate should be reduced drastically under a quota system. These results were not in agreement with our findings. This difference in results can be explained by the course of net returns per cow and net returns per kg of milk, which is illustrated in Figure 5 for an open cow averaging in production in lactation 3. The lines, which show the course of net returns per cow per month, are in both situations parallel (with and without opportunity costs of labour and housing). The constant difference between those two alternatives makes that there is no preference for one particular situation. Moreover, the net returns per cow per month decrease continually over time and, therefore, an optimal insemination and replacement policy will aim at many cows early in the lactation, i.e. a short calving interval. The lines showing the net returns per kg of milk follow a completely different course. Only if those lines are parallel can one assume that cost of labour, housing and other non-yield related costs do not affect the optimal strategy. Until month 10 in lactation, the course of the net returns per kg of milk was very flat for the situation without opportunity costs of labour and housing (i.e. the situation Kristensen and Thysen (1991) assumed), in contrast to the situation in which opportunity costs of labour and housing were included. Because the fixed amount of costs of labour and housing per month had to be distributed over a non-fixed amount of milk production, this resulted in another pattern for both situations. Moreover, this flat pattern makes longer calving intervals acceptable, if opportunity costs of labour, housing and other non-yield related costs are not included (which is also shown in Table 4 and Figure 4). According to Boehlje and Eidman (1984) all costs should be considered variable in the long term, and, consequently, these costs should be taken into account when making production decisions on the long term.

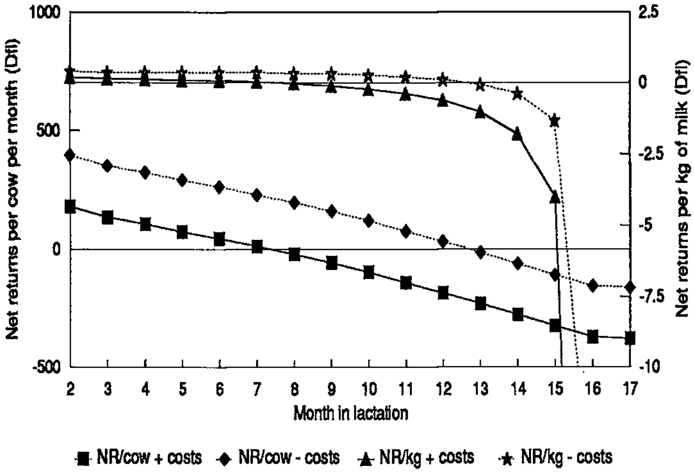

Figure 5. Course of net returns per cow per month (NR/cow) and net returns per kg of milk (NR/kg) with (+) or without (-) the inclusion of costs of labour and housing for a open cow with average production in lactation 3.

If labour really has no opportunity value, then home-bred replacement heifers will be cheaper and, hence, the replacement costs will be lower. This affects the optimal insemination and replacement strategy. This may be the reason that the replacement rate has increased since the milk quota system started (Van de Venne, 1987). Dijkhuizen (1983) and Van Arendonk (1985b) showed that the proportion of voluntarily replaced cows increased by 23.4%, if the price of a replacement heifer was decreased by 20%. When the number of voluntary replacements increases, the potential value of a decision support system will be higher, and, consequently, the differences between the two optimization criteria are expected to be larger in the case of high voluntary replacement rates.

Harris and Freeman (1993) concluded that imposing production quotas on the producer may change both the magnitude and direction of economic weights for traits under quota systems. In our research, the economic weights for the traits milk, fat, and quota were assumed to be the same for both optimization criteria. Although

Van Arendonk (1985b) found that changes in the price of milk and feed did not greatly affect the optimum insemination and replacement policy, it is not clear whether a combined change of economic weights for milk, fat, and protein would change the optimal policy. Since the economic weights hold for all farmers, the differences between both optimization strategies are not expected to change much for other weights.

In this study, the optimal insemination and replacement strategy was defined with respect to the long term. However, under a quota system a farmer has also to decide on what to do if the total milk production for a specific year threatens to exceed the milk quota. Reducing herd size by culling cows that otherwise would have been kept is suboptimal in the long term but can be optimal in the short term. In theory, dynamic programming could be a good tool in optimizing this kind of decisions. Such a model should include all individual cows and will then optimize the decisions for all cows in the herd simultaneously. In practice, such a model cannot (yet) be built because of limitations of model size. Future research should focus on the development of other optimization techniques to solve these short-term decisions satisfactorily.

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Chapter 6

Genetic algorithm to link decisions at animal and herd level on dairy farms

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Abstract

A hybrid decision support system for culling decisions was described consisting of a dynamic programming model integrated with a genetic algorithm. In the decision support system a genetic algorithm was used to adjust the culling advice calculated by a dynamic programming model. The approach was used to include herd level effects, such as shortage of replacement heifers and milk quota. Results showed that the genetic algorithm was very capable of finding the decision set which minimized the levy to be paid for exceeding the milk quota and maximized total future herd income. The model most often advised to reduce the herd size to meet quota restrictions by culling those cows with the lowest future value. But in more extreme situations, however, also cows with a high future value were culled instead of those with a low future value. Results of this decision support system were robust and it was shown that the system can also be used for larger farms without running into the problems of combinatorial explosion.

1. Introduction

Decision support systems (DSS) that help farmers and advisors make optimal veterinary treatment and culling decisions most often focus on individual animals only (Houben et al., 1994). However, veterinary treatment and culling decisions of individual animals also affect the rest of the herd. For instance, culling cows with mastitis is likely to reduce further spread of infections in the herd, and if so, benefits from this should be included in the model. Another example is the quota restriction on milk production, as is currently effective in countries of the European Union. Sub-optimal decisions for individual cows may become optimal from a herd level point of view (and vice versa), especially at the end of a quota year. A final example concerns the shortage of replacement heifers, which may also have an effect on single-cow decisions.

Dynamic programming has shown to be a powerful tool in determining the expected future value of an individual cow (Houben et al., 1994). It is used in multi-period optimization problems and has the advantage of determining optimal decisions without requiring exhaustive enumeration of all sequences of production possibilities (Bellman, 1957). However, it cannot include herd level effects and constraints because of the limited number of states such a model can handle. Ben-Ari and Gal (1986) and Kristensen (1992) used an approximation technique, called parameter iteration, to include the possibility of having a shortage of replacement heifers in a replacement model. Because of the complicated short-term characteristics of milk quota, herd level quota effects have not yet been included in a dairy cow optimization model.

Genetic algorithms are search algorithms based on the mechanics of natural selection and natural genetics. They combine the survival of the fittest principle among string structures with a structured, yet randomized information exchange to form a search algorithm, with some of the innovative capacity of human search. In every generation, a new set of artificial creatures (chromosomes) is created using bits and pieces of the fittest of the old one (reproduction and crossover); an occasional new part is tried for good measure (mutation). Although randomized, genetic algorithms are no simple random walk. They efficiently exploit historical information to speculate on new search points with expected improved performance (Goldberg, 1989). Genetic algorithms were theoretically and empirically proven to provide robust search in complex spaces (Holland, 1975). These algorithms are computationally simple yet powerful in their search for improvement. Furthermore, they are not fundamentally limited by restrictive assumptions on the search space (Goldberg, 1989).

The aim of this study was to develop and explore a hybrid DSS by extending the dynamic programming model by a genetic algorithm to include herd level effects on culling decisions. Culling decisions in this context were generally defined as: 1) replacing individual cows by replacement heifers, 2) expanding the herd with replacement heifers, and 3) culling cows without replacement (i.e. reducing herd size). The DSS should be able to optimize short- and long-term culling decisions with regard to maximization of the returns per kg of milk quota. Those decisions are affected by the expected excess of the limited milk quota on the farm.

This paper deals especially with the description of the genetic algorithm and the experiments which show how the DSS performs for large farms with quota restrictions.

2. Material and methods

2.1. Problem definition of quota example

After the introduction of the quota system in the European Union, the number of cows have been reduced considerably and, because of genetic improvement of milk production, is still reducing. Farmers want information to economically optimize culling decisions. Especially towards the end of the quota year they have to decide which cows to cull because of an imminent excess of milk quota. For instance, culling high-producing cows will be very effective in the short term, but will reduce the net returns in the long term. Culling the lowest-producing cow(s) (being optimal in the long run) on the other hand, may not solve the quota problem, especially not when they are already dry for the remaining part of the quota year. In this study, the optimal set of immediate culling decisions was defined as: an immediate keep/replace decision for each cow, and furthermore, an immediate decision on expansion or reduction of the herd size. The optimal set of decisions maximizes the herd value (HV). The HV was corrected for predicted levies to be paid in the current year as a result of exceeding the milk quota. The HV was defined as the sum of expected future economic profitability of all cows, determined by using the dynamic programming model of Houben et al. (1994), corrected for predicted milk quota levies to be paid in the current year and a recompense for use of labour and building resources. Furthermore a correction was made if more replacement heifers were needed than available at that moment. The herd milk (HM) and herd fat (HF) production was calculated from the sum of predicted milk and fat productions of all cows and replacement heifers up to the end of the current quota year. Each possible culling decision had its specific effect on the HV, HM and the HF. A recompense for use of labour and building resources (LBR) encourages expansion of the herd. Table 1 shows the contribution of each possible culling decision (mutually exclusive) to the HM and HV at a cow place in terms of LBR, predicted production of a cow up to the end of the quota year (M), and replacement heifer (M_h), and future value of a cow (V), and replacement heifer (V_h). Herd fat (HF) was determined analogous to HM. Table 1 shows, for instance, that when a cow was replaced by a heifer, the milk production for that cow place was assumed to be the expected milk production of a replacement heifer (M_h) and the compensation for use of labour and building resources was LBR for that specific cow place. When a cow was culled (without replacement), then both expected values at that specific cow place were zero. The sum of expected milk production corrected for fat production determined whether or not a levy was to be expected. The levy was set at 115% of the gross milk price (Anonymous, 1993) per kg of fat corrected milk surplus.

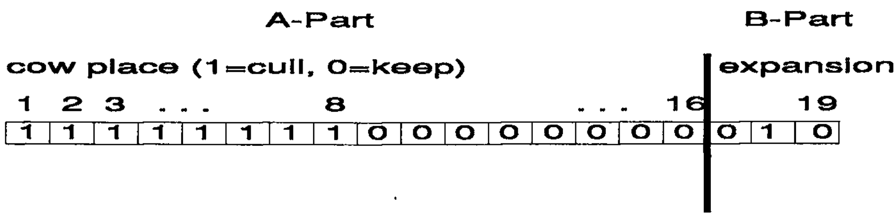
At herd level many combinations of the four culling decisions were possible and, therefore, exhaustive enumeration and evaluation of all combinations could not be done. As an example: on a farm with 5 cow places 1024 different combinations of culling decisions are possible (4^5 = 1024), on a farm with 10 cow places already 1,048,576 combinations can be made and on a farm with 50 cow places even $1.27*10^{30}$. A genetic algorithm can help to determine a good (although not necessarily optimal) combination of decisions. With this approach culling decisions for individual animals are converted into genes on chromosomes, where the latter represent the combination of decisions for the herd as a whole. Then genetic principles (such as crossover and mutation) are used to maximize the fitness of a chromosome, i.e. to find the set of decisions at the herd level that maximizes expected farm income.

Table 1. The contribution to the expected milk production (HM) and future value (HV) as a result of a decision at a cow place in terms of future value of that specific cow (V), future value of a replacement heifer (V_h) (i.e. by definition zero), compensation for use of building and resources (LBR), expected production until the end of the quota year of that specific cow (M) and the expected production of a replacement heifer (M_h)

Decision	HM (kg)	HV (Dfl.)
keep the cow	M	V+RS
replace cow with heifer	M_h	RS
cull cow without replacement	0	0
add a replacement heifer to the herd	M_h	RS

2.2. Decision representation

The issue in defining a genetic algorithm that causes most problems is the translation of the real-world decision process into a chromosome. To make the algorithm efficient, the number of possible values of a gene (i.e. the gene-alphabet or allele) must be small (preferably binary). In this study the chromosome was split up into two parts: A and B. The A-genes show whether a cow at a certain place in the herd is kept or culled. The B-genes build up a marked integer: a negative value means a decrease in herd size, and a positive one an increase. In Figure 1, both parts of the chromosome are shown. The right-most gene of the B-genes is the marked gene. The remaining B-genes determine the magnitude of change in herd size (delta herd size DHS) according to a binary coding schedule. The length of the B-part of the chromosomes depends on the maximum number of cows by which the herd may be expanded or shrunk in one go. The A-genes show whether a cow at a certain place is culled or kept. It does not include information on replacement, because that information is stored in the B-part of the chromosome. In Figure 1 some examples of a herd with 16 cows are shown with their translation of the decision problem. The first part of Figure 1 indicates that 8 cows have to be removed from the herd (A-Part; genes 1-8) and that the herd has to be reduced by one cow (B-Part), which means that 8 cows are culled, 7 of which will be replaced by a heifer.



Allele sequences in case the length of the B-Part is 3 genes:

B-Part	Translation in terms of delta herd size
0 0 0	DHS = 0
0 1 0	DHS = -1
1 0 0	DHS = -2
1 1 0	DHS = -3
0 1 1	DHS = 1
1 0 1	DHS = 2
1 1 1	DHS = 3

Figure 1. Graphical representation of reproduction, crossover and mutation operators. Reproduction is the selection of chromosome to produce a new generation.

2.3. Genetic Algorithm

2.3.1. Genetic operators

The chromosome, decode function and value (or fitness) function are the basic components of a genetic algorithm. The decision problem described above had to be translated into terms of a chromosome first, and then the decode function was used to translate the information on the chromosome back to the real-world situation. Furthermore, the value function was used to determine the value of the decision set (i.e. the fitness). Genetic algorithms require the underlying parameter set of optimization problems to be coded as a finite-length string over some finite gene alphabet. The task of the genetic algorithm is to first generate a set of strings (chromosomes), each chromosome of which resembles the decision problem. The first set of chromosomes is generated completely at random. The decode and value functions are used to determine the fitness of each chromosome and, subsequently, a new generation of chromosomes is made by using reproduction (the chromosomes with the highest fitness have the highest probability of passing on genetic information), crossover (i.e. exchange of information between chromosomes), and mutation (one or more genes on the chromosome are changed on a random basis). This process of reproduction, crossover, and mutation is shown in Figure 2. According to Goldberg (1989), those characteristics of genetic algorithms (GAs) make that:

1. GAs directly manipulate the coding instead of dealing with underlying functions and their control variables;
2. GAs search from a population of points, not a single point;
3. GAs search via sampling, a blind search; and
4. GAs use stochastic operators, not deterministic rules.

This makes a GA a very efficient and powerful search algorithm.

A genetic algorithm that gives good results in many practical problems is composed of three operators: 1) reproduction, 2) crossover, and 3) mutation. Goldberg (1989) described those elements and his description of the simple genetic algorithm was used here as a basis. In the next sections each of these operators is defined for our culling-decision problem.

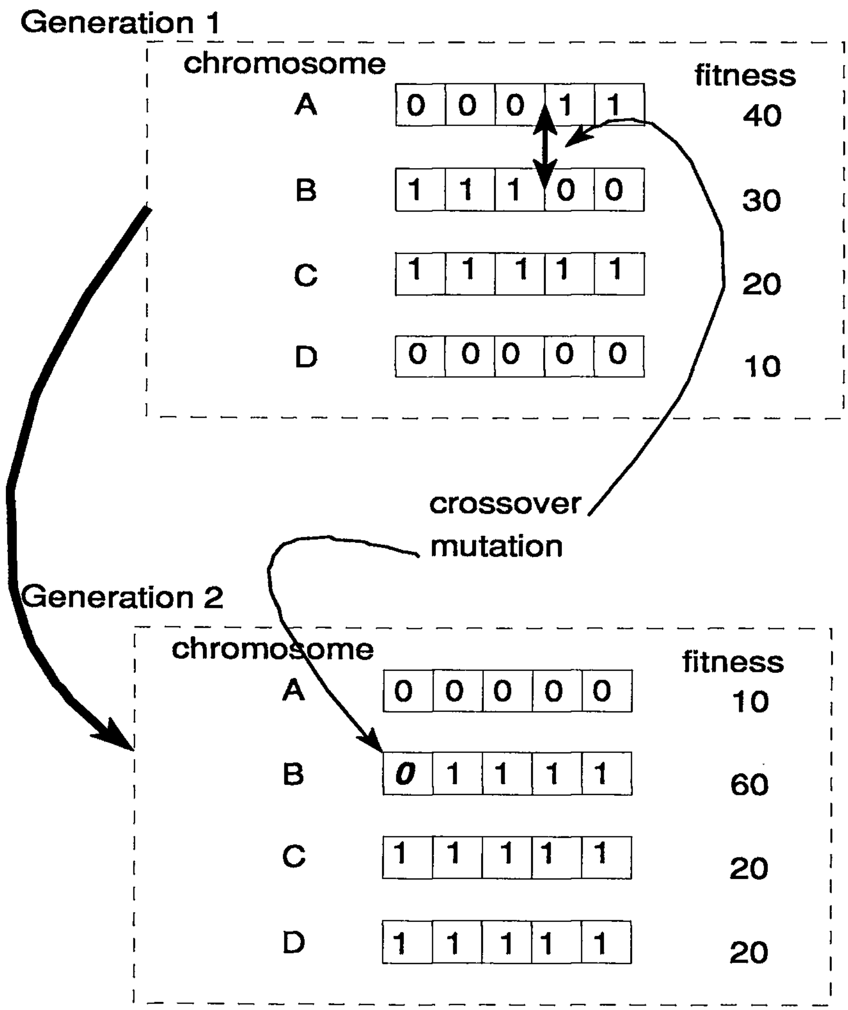


Figure 2. Representation of a chromosome if the initial herd size is 16 cows. I.e. an A-Part (16 genes, one for each cow place) and a B-Part (3 genes for expansion or reduction of the herd) The second part of the figures shows the several allele sequences of the B-Part and their translations in terms of delta herd size (DHS).

Reproduction

Reproduction is a process in which individual chromosomes are copied according to their objective function values (i.e. their fitness). Copying chromosomes according to their fitness values means that chromosomes with a higher value have a higher probability of contributing to one or more offspring in the next generation. This is the so-called weighted roulette wheel selection. For instance, if a chromosome has a fitness which is 10% of the sum of fitnesses of all chromosomes, then each chromosome in the next generation has a 10% probability of being a copy of this specific chromosome. Furthermore, the chromosome with the lowest fitness value in the new population is replaced by a chromosome with the current highest fitness in each generation. In this way the fitness of the best chromosome cannot decrease or disappear during evolution.

To determine the fitness of a chromosome, it first has to be decoded in terms of herd value (HV). The HV was calculated according to Formula 1, and, moreover, used to calculate the fitness (Formula 2):

$$HV = (DHS \times LBR) - LV - (EH \times EHC) + \sum_{a=1}^{A} (V(a, d) + LBR) \qquad [1]$$

where

HV = herd value

A = number of genes in A-part of chromosome (i.e. herd size)

V(a, d) = expected future profitability of cow place a under decision d (d= keep or replace), determined by using the dynamic programming model of Houben et al. (1994)

DHS = delta herd size

LBR = compensation per cow for use of labour and building resources for the remaining period in the current quota year

LV = levy to be paid because of exceeding the for fat corrected milk quota

EH = number of additional heifers (i.e. more than available)

EHC = extra costs for additional heifers (i.e. more than available)

Note that in Formula 1, A is the herd size at the moment of decision making. At the next moment of decision making, herd size has changed according to DHS so A = A + DHS.

Of course, only extra costs of additional heifers have to be added if more heifers are needed than are available at that moment:

EH = number of additional heifers (i.e. more than available)

$$= \begin{cases} 0, & HN \leq HA \\ HN - HA, & HN > HA \end{cases}$$

HA = number of heifers available

HN = number of heifers needed

= repl + DHS

repl = number of cows replaced

Levy is only paid if the milk production exceeds the for fat corrected milk quota. No money is paid back if production is below quota:

LV = levy to be paid because of exceeding the for fat corrected milk quota

$$= \begin{cases} 0, & levy(HM, HF) \leq 0 \\ levy(HM, HF), & levy(HM, HF) > 0 \end{cases}$$

HM = total expected milk production for the herd as a whole until the end of the current quota year

$$= (DHS \times M_h) + \sum_{a=1}^{A} M(a, d)$$

HF = total expected fat production for the herd as a whole until the end of the current quota year

$$= (DHS \times F_h) + \sum_{a=1}^{A} F(a, d)$$

M_h = expected milk production of a replacement heifer until the end of the current quota year

M(a, d) = expected milk production in the remaining part of the current quota year at cow place a under decision d (d= keep or replace).

F_h = expected fat production of a replacement heifer until the end of the current quota year

F(a, d) = expected fat production in the remaining part of the current quota year at cow place a under decision d (d= keep or replace).

The expected levy to be paid at the end of a quota year (Anonymous, 1993) depends on the milk and fat production, milk price and level of penalty when exceeding quota (115%). The farm quota is corrected for the farm fat reference:

levy(HM, HF)= expected levy to be paid at the end of the quota year (Anonymous, 1993)

$$(HM \times (1 \times (1 + \left(\left(100 * \frac{HF}{HM}\right) - Fref\right) \times 0.18 - quota) \times \left(\frac{mprice \times 115}{100}\right)$$

Fref = fat reference (%)

quota = the amount of levy-free milk which can be produced until the end of the quota year (kg per year)

mprice = average milk price (Dfl. per kg of milk)

With this HV the fitness of a chromosome is determined by taking the power of 4 of the value fit (the value 4 is arbitrarily chosen):

$$fitness = \begin{cases} 0, & fit \leq 0 \\ (fit)^4, & fit > 0 \end{cases} \qquad [2]$$

where

$$fit = 4 \times \frac{HV - HV_{min}}{HV_{max} - HV_{min}}$$

HV_{min} = the herd value of the chromosome with the lowest HV

HV_{max} = the herd value of the chromosome with the highest HV

By using Formula 2, the fitness is rescaled according to the maximum variation in HV between chromosomes. In this way, still enough power is available to discriminate between chromosomes in later generations, in early generations on the other hand also the poor chromosomes have still a probability of staying in the population. The latter is important because the chromosomes may carry important gene sequences (i.e. building blocks) which, combined with other pieces, can result in a relatively high fitness.

Crossover

After reproduction, crossover may proceed in two steps (Figure 2). First, members of the new generation of chromosomes in the mating pool are mated at random. Second, each pair of chromosomes undergoes (with a certain probability p_{cross}) crossover as follows: position l along the chromosome (i.e. a locus) is selected uniformly at random between 1 and the chromosome length L minus one ($L = A + B$). Two new chromosomes are created by swapping all characters between position $l + 1$ and L. With crossover, high-performance building blocks (i.e. a sequence of genes) are combined with other building blocks, so some of the new chromosomes may have a higher fitness than the original ones.

Mutation

Mutation is needed because, even though reproduction and crossover effectively search and recombine high-performance building blocks, occasionally they may become over- enthusiastic and lose some potentially useful genetic material (1s or 0s at particular locations). In artificial genetic systems, the mutation operator protects against such an irrecoverable loss. Mutation is the occasional (with small probability p_{mut}) random alteration of the value of a string position. In the binary coding of our decision problem, this simply means changing 1 to 0 and vice versa. In itself, mutation is a random walk through the chromosome space. When used sparingly with reproduction and crossover, it is an insurance policy against premature loss of important notions.

In our application of the genetic algorithm the marked gene, which determines whether the herd size is increased or decreased, was assumed not to mutate. The genes which determine the level of increase or decrease of the herd size (i.e. all genes of the B-part except of the last one) could mutate in a normal way. The reason for this modification was that the mutation of the size gene influences the fitness of the chromosome in an extreme way, which results in a large variation between chromosomes. As is shown by Formula 2, a large variation means that the power to discriminate between chromosomes is small, and therefore the evolution path much longer. Intuitively this modification fits well in the culling decision problem. It was therefore decided to carry out a sensitivity analysis to determine the effects of changing herd sizes.

As a result of crossover or mutation, a chromosome could reflect a situation in which the advised reduction of herd size was larger than the number of cows to be culled immediately. To avoid this conflict between the A- and B-parts of the chromosome a check was included and when this conflict was observed, the reduction in herd size was set at the number of culled cows.

2.3.2. Parameterizing the genetic algorithm

To run the genetic algorithm a decision has to be made first on the value of the following key parameters: maximum number of generations, number of chromosomes in the population, crossover probability, and mutation probability. Determining the level of those parameters is quite troublesome because there are no straightforward rules. It is rather the researcher who defines the range of parameters.

According to Davis (1991), researchers used four techniques to find good parameter settings for genetic algorithms: 1) carrying out an optimization by hand, 2) using a genetic algorithm as a meta-model, 3) carrying out brute force search, and 4) adapting parameter settings. Since the first three techniques may take a good deal of time and resources, the fourth method was advised by Davis (1991). Adapting parameter settings means that the performance of any operator is measured over a recent interval. In our study the operator performance was measured by calculating the fitness correlation coefficients of the operator r_{op} as described by De Weger et al. (1991). For the reproduction and crossover operator *op*, the values F_p and F_c represent the fitness of the parent and the child. For the mutation operator *op*, the values F_p and F_c represent the average fitness of the parents and childs. Then the correlation coefficient was calculated as

$$r_{op}(F_p, F_c) = \frac{cov(F_p, F_c)}{\sigma(F_p)\ \sigma(F_c)}$$

where

$cov(F_p, F_c)$ = covariance between F_p and F_c
$\sigma(F_p)$ = standard deviation of F_p
$\sigma(F_c)$ = standard deviation of F_c

Moreover, to obtain insight into the overall performance of the genetic algorithm the heritability (in terms of h^2) was calculated according to Formula 3:

$$h^2 = \frac{\sum_{g=1}^{G-1} (HV_{sel}(g) - HV_{avg}(g))}{\sum_{g=1}^{G-1} (HV_{avg}(g+1) - HV_{avg}(g))} \qquad [3]$$

where

G = maximum number of generations g
$HV_{avg}(g)$ = average fitness of the population of chromosomes in generation g
$HVt_{sel}(g)$ = average fitness of the population of chromosomes selected for reproduction in generation g

When searching for a good crossover probability and mutation probability the population size (i.e. number of chromosomes) was fixed at 100, a number also chosen by many other researchers (Davis, 1991). Furthermore, the maximum number of generations (g) was set at 200, but evolution stopped as soon as the variation in fitness was zero.

2.4. Experiments with the genetic algorithm

2.4.1. Herd size experiment

For small herd sizes, exhaustive enumeration of all decision combinations is possible and there is therefore actually no need to use a genetic algorithm. However, if the herd size is larger than about 30 cows, exhaustive enumeration means an extreme amount of function evaluations ($1.15*10^{18}$). To evaluate the power of the genetic algorithm the following experiment was defined: first, 16 cows were taken from the dynamic programming database. The future value of those cows on individual basis was known (determined by the dynamic programming model) and also the expected milk and fat productions until the end of the lactation (Table 2) were known. Eight of those cows had a negative future value and should from an individual-cow point of view be replaced immediately by replacement heifers. Furthermore, the remaining quota was set exactly at the amount of milk which the 16 cows and replacement heifers would produce during the remaining part of the current quota year. Under the assumption that enough replacement heifers were available, and also that the fat production of those cows was exactly according to the fat reference of the milk quota, the genetic algorithm should give the same replacement advice as the dynamic programming model. Moreover, if a herd is assumed to consist of multiple groups of those 16 cows, the herd value is known beforehand. To determine the robustness of the results, ten optimization runs were performed for herd sizes of 16, 32, 64, 128, and 256 cows. In those runs the compensation for labour and housing was set at Dfl. 100 per cow per month, and further it was assumed that the actual moment of optimization was assumed to be one month before the end of the quota year (in practice this optimization model should be run each time when information on expected production and future value has changed).

2.4.2. Quota experiment

To obtain easily interpretable results, the herd size at the beginning of the optimization run in the quota experiment was set at 16. Production figures and future values of those cows are presented in Table 2. In this experiment optimization was assumed to take place one month before the end of the quota year, and eight heifers were assumed to be available for immediate replacement. Extra replacement heifers could be bought on the market for an additional cost of Dfl. 200 compared with home-raised heifers. Those replacement heifers were expected to produce 669 kg of milk and 30.1 kg of fat in the remaining month. The milk price was set at Dfl.

Table 2. Expected milk and fat production of 16 cows for the remaining part of the current quota year and their future value as determined by the dynamic programming model.

Cow	Exp. milk prod. (kg)	Exp. fat prod. (kg)	future value (Dfl.)
1	10	0.50	-390
2	81	4.06	-335
3	155	7.75	-279
4	227	11.28	-224
5	300	14.84	-169
6	372	18.22	-117
7	445	21.82	-67
8	517	25.30	-21
9	591	26.92	21
10	662	30.00	60
11	736	32.69	101
12	807	35.06	135
13	881	37.83	171
14	952	40.32	204
15	1023	43.40	250
16	996	44.18	622

0.70 and the levy to be paid for exceeding the milk quota was 115% of this milk price. The remaining for fat corrected milk quota (fat reference was 4.45%), needed to meet the expected milk and fat production, was 12000 kg. The genetic algorithm was run for the following remaining fat corrected milk quotas: 6000, 8000, 10000, 12000, and 14000 kg. Furthermore, the size of the B-part of the chromosome was set at 3 genes, which allowed the herd to increase or decrease by 3 cows at maximum for the remaining period. For each level of remaining quota ten runs were carried out to gain insight into the robustness of the results.

3. Results

3.1. Parameterizing

Using the dataset of the 16 cows, experiments showed that good results for the operator correlations and heritability were obtained when the crossover probability was about 0.6 and the mutation probability was below 0.02. In these circumstances all operator correlations were higher than 0.90, which means that the operators do gradually change the fitness of a chromosome. This is important because otherwise the algorithm would become a random search. The estimated heritability was about 0.35, which means that in each generation about 35% of the selection difference was passed on to the next generation. For larger herd sizes the mutation probability had to be even smaller than 0.02 and the heritability decreased to 0.20. If the mutation probability was above 0.20, then the operator correlation and heritability was zero. This showed that random search would not give the results desired. It was concluded that for our type of model a crossover probability of 0.60 and a mutation probability of 0.01 gave, on average, the best performance.

3.2. Herd size experiment

In Table 3, the results of the herd size experiment are shown. Ideally the herd value divided by the number of cow places should be the same for all herd sizes in this experiment. However, because of the combinatorial explosion, the genetic algorithm was expected to have more problems in finding the optimal decision set for larger herd sizes. As is shown in Table 3 this effect was only very small. The best chromosome found during ten runs of the genetic algorithm was even exactly the same up to a herd size of 64 cows. The standard deviation for the highest herd value found after 200 generations increased a little. For a herd size of 16 cows already after 11 generations the optimal chromosome was found and subsequently many other chromosomes became a copy of this one, so there was hardly any room for improvement in the remaining generations. For this reason the average herd value of the new generation was in most of the generations higher than the herd value of the selected population (i.e. the selected chromosomes to produce the new generation). Subsequently, the overall heritability (h^2 in Table 3) was even slightly negative. However, if the heritability was measured up to the generation with the best chromosome (i.e. generation 11), then a high heritability was found (h^2_G in Table 3 is 0.75). The h^2_G in case of herd size of 32 cows dropped to 0.26, but reduced only very gradually for larger herd sizes. The optimal chromosome was not found in each of the 10 runs with 200 generations for a herd size of 256 cows, but nevertheless the herd value per cow place of the best chromosome was only Dfl. 1.90 lower than the optimal one. Also in this case the standard deviation of the results was low (Dfl. 0.41). For this largest herd size the best chromosome was, on average, found in generation 187 and the heritability until that moment was 0.17. For all runs and herd sizes the operator correlations were above 0.90. In Figure 3 the typical course of the maximum, average, and minimum total herd value is shown for one run of this 256-cow herd. Both increased rapidly up to generation 100, and thereafter there was only a minor increase in herd value.

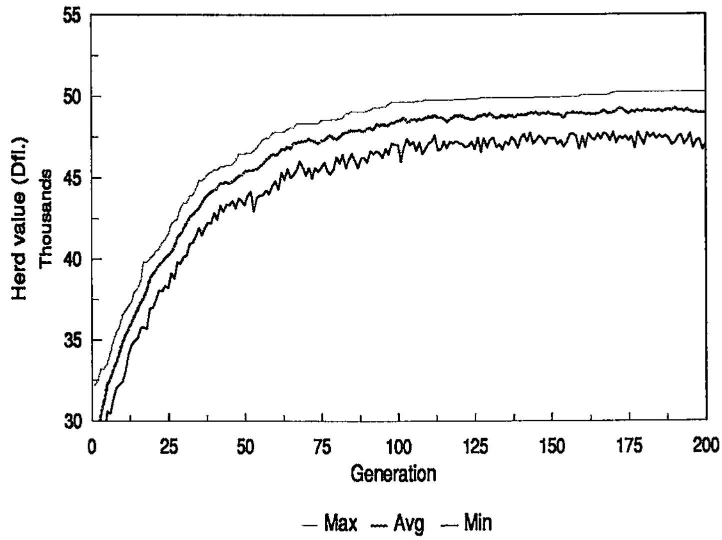


Figure 3. The course of the maximum (Max), average (Avg), and minimum (Min) herd value of the chromosomes of a 256-cow herd size decision problem over 200 generations.

Table 3. The effect of the herd size on the performance of the genetic algorithm in terms of the herd value divided by herd size (IHV). Max, Avg, Min, and Std are the largest IHV, average IHV, minimum IHV and standard deviation of IHV, respectively, found after 10 runs of a genetic algorithm with 100 chromosomes in the population and 200 generations per run. G is the average generation in which the chromosome with value Max was found, and h^2 is the heritability until generation 200 and h^2_G is heritability until generation G. CPU is the average PC-time* in seconds to finish a run.

Herd size (cow places)	Max (Dfl.)	Avg (Dfl.)	Min (Dfl.)	Std (Dfl.)	G	h^2	h^2_G	CPU (s)
16	197.75	197.75	197.75	0.00	11	-0.06	0.75	15
32	197.75	197.45	195.38	0.76	92	0.00	0.26	22
64	197.75	194.34	190.38	2.98	85	0.08	0.18	37
128	197.48	195.79	194.76	0.69	156	0.16	0.22	67
256	195.85	194.93	194.39	0.41	187	0.17	0.19	126

* On a 486-PC with a DX2/66 MHz processor.

Although there was a combinatorial explosion of decision combinations, the computer time needed did only increase proportionally with herd size. For a herd size of 16 cows the average computer time was 15 seconds for a complete run (Table 3), and this increased to 126 seconds for a 256-cow herd, which can still be regarded as very acceptable for practical use.

3.3. Quota experiment

The A-part of the chromosome in Table 4 shows whether cows were kept (0) or culled (1) at several levels of remaining quota. Cows were put on this chromosome in the same order as they appeared in Table 2 (i.e. the first gene is a cow with the lowest future value and so on).

As could be expected, the best set of decisions in a situation with a remaining quota of 12000 kg was equal to the individually based decisions. No variation in herd value was found between the best chromosome of those 10 runs. If the remaining for fat corrected milk quota was 14000 kg, then the advice of the genetic algorithm was to cull 6 cows instead of 8, and, moreover, to bring all the available heifers in production, so that the actual herd size was increased by 2. The advantage of this decision (i.e. Dfl. 112; Table 4) in comparison with keeping the herd size stable is that more revenues for labour and building resources were acquired. However, in these circumstances still 1050 kg of the milk quota was not used.

Table 4. Herd value of best set of decisions (A-part of chromosome (0=keep, 1=cull)) of the best (HV max) and worst (HV min) of 10 runs for several levels of remaining quota. Of the best chromosome the A-part is shown, as also the change in herd size (as a result of the B-part of the chromosome), the total expected milk and fat production for the best set of decisions, and the improvement in herd value (IHV) compared with the decision set of replacing the first eight cows under quota conditions.

remaining quota (kg)	HV max (Dfl.)	HV min (Dfl.)	best chromosome A-part + B-part	DHS	milk (kg)	fat (%)	levy (Dfl.)	IHV (Dfl.)
6000	574	574	0000000000001110 110	-3	5887	4.63	63	2193
8000	1883	1870	1100000000100000 110	-3	7916	4.51	0	1895
10000	2864	2864	1111111100000000 110	-3	9981	4.42	0	1263
12000	3164	3164	1111111100000000 000	0	11988	4.43	0	0
14000	3276	3243	1111110000000000 101	2	12950	4.46	0	112

If a shortage of milk quota was expected, the genetic algorithm advised first of all to reduce the herd size until the established maximum of 3 cows (up to a remaining quota of 10000 kg) and if with those measures the milk quota was not met, the advice was to cull some cows with a relatively high future value and to keep the low-producing cows for at least one more month (see Table 4). The advantage of following this advice instead of the individually based advice of the dynamic programming model was, in the most extreme situation of a remaining quota of 6000 kg, Dfl. 2193 for those 16 cows. Only in these circumstances a small levy had to be paid (Dfl. 63), so in most situations the milk quota was not exceeded.

4. Discussion

4.1. Search methods

According to Goldberg (1989) literature identifies three main types of search methods: calculus-based, enumerative, and random. Calculus-based methods depend upon the restrictive requirements of continuity and derivative existence and, therefore, are only suitable for a very limited problem domain. Certainly not for the domain of for fat corrected milk quotas which is discontinued and non-linear. Especially if aspects on availability of heifers are considered. The idea behind the second type of search methods (enumerative schemes) is fairly straightforward: within a finite search space, or a discretized infinite search space, the search algorithm starts looking for objective function values at every point in the space, one at a time. Although the simplicity of this type of algorithm is attractive, they lack efficiency for most practical problems. Even dynamic programming, which uses a very efficient enumerative scheme, breaks down on problems of moderate size and complexity. The last-mentioned type of search methods (i.e. random search algorithms) is expected to do no better than enumerative schemes in the long run. However, randomized techniques (such as genetic algorithms and simulated annealing) differ from random search techniques in the way that randomized techniques use random choice as a tool to guide a highly explorative search through a coding of a parameter space.

4.2. Genetic Algorithm

Tables 3 and 4 show that the genetic algorithm was very capable of finding the decision set which minimized the levy and maximized total herd income. The difference between the highest herd value in the best and the worst run was mostly zero, or low in other cases (Tables 3 and 4). This showed that the results were very robust, which is, according to Goldberg (1989), one of the main characteristics of this type of randomized search algorithm. This is caused by the central theme of research on genetic algorithms being the balance between efficiency and efficacy necessary for survival in many different environments. It can be expected that the herd size as such will not be a major problem when using the genetic algorithm approach for quota decision problems.

Genetic algorithms generally benefit from an operator that makes small rather than big changes in policy, in order to refine solutions (Davis, 1991). Instead of using marked binary strings to define the change in herd size, the gray scale coding (Davis, 1991) could be used, so only small changes would occur. Gray scale coding basically means that subsequent integer values do differ in their bit-representation at only one place. Also in our application the algorithm is likely to benefit from gray scale coding, but on the other hand our binary representation of a value is only a very small part of the chromosome (the B-part) and the advantages is therefore to be expected only very small. Generally: in the literature (Goldberg, 1989; Davis, 1991) all kinds of more complicated reproduction, crossover, and mutation operators were described which are likely to be helpful in improving the performance of the genetic algorithm. Because it was not the scope of this research to compare all types of operators and all types of optimization techniques it is certainly possible that one may find an even more efficient method to solve the decision problem above. However, the method described in this paper already produced very satisfactory results, and therefore this research can at least be regarded as a first and promising step in solving the very complicated milk quota optimization problem.

4.3 Further research

Future research should pay attention to: 1) whether it is enough to include only the current quota year in the penalty function (see Formula 1), 2) determining the best way of decision support early in the quota year; should the time left to the end of the quota year have an effect on the optimal decisions (i.e. discounting the moment that information comes available), 3) whether one can deduct more simple rules (heuristics) from the results of genetic algorithm, 4) whether the parameterizing of the genetic model can be improved (such as the arbitrarily chosen rescale factor in the fitness function (Formula 2)), and 5) whether the method can be used for other optimization problems where herd level effects interact with decisions for individual animals, such as treatment decisions of diseases that may spread within the herd.

Moreover, further research should show what the best way is to implement such a Decision Support System in practice. Potentially it is very easy to implement, because it has few resource requirements, but on the other hand, the computer time consuming dynamic programming model is part of this DSS. Moreover, it should become clear whether it is worthwhile to run the DSS in practical circumstances with large biological variation. This would also give insight into whether other measures to reduce milk production, such as reducing feed intake, should be considered an optional decision. Also, further research should show how often the DSS has to be run to give the farmer an up-to-date advice about replacement decisions.

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Chapter 7

General Discussion

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1. Introduction

The research described in this thesis was directed towards decision support in dairy cow health management. Attention was focused on clinical mastitis, in many countries considered to be the most important dairy health problem (Schepers and Dijkhuizen, 1991; DeGraves and Fetrow, 1993). First a statistical analysis was carried out to obtain biological and economic parameters with respect to clinical mastitis which fitted in the state space definition of the stochastic dynamic programming model (Chapter 2). This optimization model was based on the hierarchic Markov process structure and was fully described in Chapter 3, including the results of an extensive sensitivity analysis of the key parameters. In Chapter 4 the economic value of information on clinical mastitis in making insemination and replacement decisions was determined for a broad range of mastitis incidences. The effect of maximization per unit of physical output (i.e. milk) instead of maximization per cow in the context of inclusion of opportunity costs of labour and housing was described in Chapter 5. Lastly, a method was developed to include the effects of decisions for individual animals within herd level restrictions, such as exceeding of milk quota, shortage of replacement heifers, and disease transmission between animals (Chapter 6). The methods described are general of nature and can also be used for other diseases and species.

In this general discussion the experiences obtained concerning clinical mastitis are reviewed and discussed against decision support in dairy cow health management in general.

2. Data quality

For decision support in dairy cow health management it is crucial that the health status of the cow can be determined and that the relationship between the health status and the future production is known. These two issues make health related decision support complicated. The health status is, in practice, most often not uniquely defined, in contrast to the production characteristics. In this study clinical mastitis state was defined in a specific way: 1) number of clinical cases in previous lactation, 2) number of clinical cases in current lactation until current month, and 3) clinical mastitis in current month. According to this definition it was assumed that the actual moment of mastitis occurrence was less important than the number of mastitis cases. The major reason to choose for this definition was the availability of data. The milk production data were collected at monthly intervals and therefore it was not possible to estimate time effects very precisely with respect to the relation between health status and future production. Within a 1-month period, a cow may contract mastitis, suffer substantial milk losses, recover completely, and reach her previous production level (Bartlett et al., 1991). Therefore, the short-term effect of mastitis on production can be expected to be underestimated, and hence in this study this effect was based on the literature. In practice, the interval between official measurements of milk production is usually three weeks and six weeks will become even more common. As was shown in a small scale data analysis (De Haan, 1994), this interval should preferably be shorter than 10 days in order to be able to determine the precise effects of disease on production. In practice this means that automated recording of milking parlour data is necessary to obtain insight into the way diseases affect production.

According to Lucey and Rowlands (1984), the severity of clinical mastitis substantially varies with the pathogens involved, and therefore estimates for each type of mastitis would have been preferable. However, the size of the data set did not allow the division of mastitis into more classes, and, moreover, it would not have been possible to include more mastitis classes in the optimization model. Further research is required to see whether the information available on the 'average pathogen' can be used to adjust the future value of a cow for a specific pathogen.

The data analysis showed a slightly positive effect of single or double infection in previous lactation on production in current lactation. Dohoo and Martin (1984) reported also such a minor beneficial effect of clinical mastitis on milk production. They suggested that this positive effect might be the result of the mastitis therapy, which probably eliminated subclinical infection successfully. Almost all clinically infected cows of our dataset were treated parenterally, locally, or both. Therefore, an effect similar to that suggested by Dohoo and Martin (1984) could be the reason for the slight increase in production.

3. Economic replacement

Bio-economic model

The model that calculates gross margins from milk production, calf sales, feed costs, and sundry costs apart from any disease was mainly based on work of Van Arendonk (1985) and the updates by Groen (1988) and Jalvingh et al. (1993). Major adjustments made in our research were not only the inclusion of the effect of clinical mastitis on production, but also the allowance of within-lactation transitions of production classes. In the previous versions of the bio-economic model, the transitions between different classes of milk production were assumed to occur only once per lactation, which implied that the relative level of milk production performance remained the same throughout the entire lactation period. More cows were replaced because of low production when no transitions within a lactation were included in the model. This is because the economic value of low-producing cows was underestimated (and that of high producing cows overestimated) at the beginning of the lactation. For a correct inclusion of the production capacity, therefore, replacement models should have production transitions for each time step considered.

The bio-economic model and the optimization model developed in this study are very well suited for all kinds of other diseases, as long as a disease can be defined in terms of 1) number of cases in current month, 2) number of cases in previous months in current lactation, 3) number of cases in previous lactation, 4) probability of contracting the disease in relation to the disease history, and 5) expected production losses in terms of reduced milk, fat and protein production. In those cases only the disease specific parameters have to be adjusted to run the current model. These requirements seem to be applicable to many diseases.

Hierarchic Markov process

The strength of the HMP optimization model described in Chapter 3 is the simultaneous evaluation of age, production, fertility, and clinical mastitis in supporting insemination and replacement decisions. The HMP approach (Kristensen, 1988) proved to be very useful for large optimization problems, although it does not solve the problems caused by combinatorial explosion of what is commonly called the curse of dimensionality (Bellman, 1961).

A major problem of using such a large dynamic programming model is the presentation and interpretation of the outcome. In our model a cow can be in one of 6,821,724 states and consequently for all those states an optimal decision is derived. Already at an early stage of the research it was tried to use the machine learning technique ID3 (Quinlan, 1986) to derive decision trees from the outcomes of the dynamic programming model. ID3 was used to induce general rules from all optimal decisions of the full-state space version. These rules were a set of practical decision rules to be used instead of the large decision database. Although a compact decision tree could be derived from a model without clinical mastitis, it was not possible to obtain one from the outcome of the complete model. The reason for this was that all information from the decision database was stored in the decision tree, even if states had only a very small probability of occurrence. The latter is often the case when disease aspects are included in a decision model. If those states are all included in a decision tree, it will explode in terms of size. Further research should show whether this problem can be solved by adding threshold values for the probability of occurrence and the machine learning algorithm can be modified so that this information on probabilities can be used to generalize decisions for groups of states. More in general it can be stated that in decision problems where many states have a small probability of occurrence it is hard to derive general decision rules (i.e. rules of thumb). Thus, it is more important to use an automated system which can extract the optimal decision directly from a decision database and is also able to update those decisions automatically. Recently, Tronsted and Gum (1994) described that they were able to capture 99% of the optimal dynamic programming results by using automatically generated decisions trees from a relative small beef cow replacement model (approximately 5000 state combinations). Their research showed that generating decision trees can provide, in certain circumstances, good rules of thumb.

The HMP-type of optimization model is very well suited to determining the break-even costs for measures which decrease the average mastitis incidence on a farm. To determine these costs, usually partial budgeting is used. Partial budgeting considers only those items of income and expense that change (Boehlje and Eidman, 1984), but usually does not - automatically - include any differences in optimal management decisions between the two situations. Many assumptions on additional and reduced income and expenses have to be made for this procedure. In contrast, using the dynamic programming model only one assumption has to be made: the extent to which the measure affects the relative risk of contracting clinical mastitis. The measure usually affects the optimal insemination and replacement policy, but this is, in contrast to partial budgeting, already included in the evaluation. The same is true for all changes in costs and returns. Moreover, it is fairly easy to define a certain suboptimal policy and use the HMP model to determine the effects on net returns. This 'simulation' aspect of HMP models is very powerful as was shown in Chapters 3, 4 and 5. Notice that the word simulation is quoted because economic and technical consequences of a suboptimal policy were calculated directly by solution of the equations. This should actually be considered an advantage of using the policy iteration method (Kristensen, 1993).

As shown in Chapter 4, a large variation in expected profitability of the HMP-model was found. The average mastitis incidence had a major effect on the losses caused by clinical mastitis. Farms with average risk appear to gain only slightly (Dfl. 15 per cow per year) when including the clinical mastitis state in the decision-making process, but farms with more than twice the average risk (12.7% of all farms) will benefit at least 7 times as much. Consequently, the break-even point of costs of a general treatment differs substantially between farms and, therefore it may be misleading to give farmers advice that is based only on farms with average health problems. Herd health advice, therefore, should be based on farm-specific information.

In practice, Dutch farmers did not really change their culling strategy after the milk quota system was introduced. Results of Chapter 5 showed that, in case labour and housing did have opportunity costs, this was the right policy. Both maximization criteria (i.e. maximization of net returns per cow, and maximization of net returns per kg milk) led to the same optimal insemination and replacement policy. These results were not in agreement with those of Kristensen and Thysen (1991): they advise a considerably less intensive culling strategy in case of maximization per kg of milk (i.e. under a milk quota system). The results in Chapter 5 showed however, that if opportunity costs of labour and housing were not included in the decision-making process, the optimal calving interval was also longer and culling less intensive in Dutch circumstances, but never reached the level as described by Kristensen and Thysen (1991). Only farmers who are not able to use their excess labour and other resources for other tasks (i.e. opportunity costs are zero) in case of a milk quota restriction should change their insemination and replacement policy into this direction.

4. Interaction between cow and herd: Genetic Algorithm

In this study a genetic algorithm was used to include the effect that, in case of milk quota, the optimal replacement decision for each cow depends not only on its own state, but also on those of the other cows in the herd (i.e. a multi-component system). Ben-Ari and Gal (1986) and Kristensen (1992) developed a multi-component system, but those systems only focused on a shortage of replacement heifers. In their approach, they used an iterative method which combined simulation and dynamic programming to calculate successive approximations of the value functions. In our hybrid model two optimization techniques (i.e. genetic algorithm and dynamic programming) were combined to overcome the extremely large dimensionality of the decision variable in case of a milk quota. Attention was paid only to the imminent exceeding of the milk quota in current quota year, and the assumption was made that in future quota years there will neither be oversupply nor shortage of milk. In our model also the herd size was optimized taking into account a possible shortage of replacement heifers. The latter aspect was implemented in more detail in the models of Ben-Ari and Gal (1986) and Kristensen (1992) since they included also the time lag between birth and first calving.

The hybrid model (genetic algorithm and dynamic programming) can also be used, in more general terms, for modelling of interactions between sick and healthy cows. In the databases, the future economic values of cows are stored which are related to optimal decision making for a whole range of clinical mastitis incidences.

Besides the mastitis incidence of the currently available cows, a forecast for future mastitis incidence has to be made. With this information the most probable future values are taken from the database and the same procedure as described in Chapter 6 can be followed to determine the optimal policy.

5. Validation

Naylor and Finger (1967) developed a three-stage validation concept: 1) a rationalist stage of ensuring that assumptions are in accordance with the theory, experience and relevant general knowledge, 2) an empirical stage in which the model's assumptions are subjected to empirical testing where possible, and 3) a positive stage of comparing input-output transformations generated by the system to those in the real world. The first two stages are referred to as internal validation, and the last stage as external validation (Taylor, 1983).

During the development of the models tests were carried out frequently to ensure proper functioning of the model. So, much attention was paid to the internal validation. However, no external validation was carried out. Although it is an important point, the current optimization model could not be validated soundly with real farm data. Biological bias of data on farm level is already large and when the main interest is related to disease topics under a milk quota system it is very hard to standardize the circumstances of decision making. Moreover, the only result of a validation with field data might be that the replacement advice of the model does not always correspond with the decision of the farmer. It cannot tell what decision is the correct one, especially not for the cows which have already been culled at that moment. Actually, the only way to determine the power of the optimization model is to compare the results with the results of a simulation model. An experimental design is then needed for the external validation, but that was beyond the scope of this research.

6. Main conclusions from the study

- The hierarchic Markov process approach has shown to be very useful in optimizing large scale replacement problems. The method makes it possible to include health related topics in an optimization model and yet keeps the state space for other characteristics very detailed. The simultaneous evaluation of age, production, fertility, and mastitis aspects supported decisions related to 63% of all insemination and replacement decisions on a dairy farm.

- The total losses caused by clinical mastitis were found to be Dfl. 150 per average cow per year in a herd with average risk, and Dfl. 370 in a herd with twice the average risk (including 12.7% of the farms)
- The economic value of information on mastitis in making dairy cow replacement decisions depends heavily on the incidence of clinical mastitis. Farm-specific advice is necessary because a large variation of clinical mastitis incidence between farms was observed. On farms with twice the average risk, the losses from ignoring the history of clinical mastitis in insemination and replacement decisions were Dfl. 113 per average cow present in the herd per year. This was 7.6 times more than on farms with average risk.
- If the optimization criterion is maximization of income per kg of milk, then the opportunity costs of labour and housing have a significant influence on the optimal insemination and replacement policy. Under normal economic conditions the long-term optimal insemination and replacement policy does not change by introduction of a milk quota system.
- For economic decision support on clinical mastitis it is not necessary to include disease information of previous lactations. The occurrence of clinical mastitis in current lactation strongly affects the expected economic future value of a cow. For average farms, however, it most often does not change the optimal decision for single cows.
- The hybrid decision support system based on a genetic algorithm has shown to be a promising approach to including herd level restrictions and animal interactions in determining the optimal decision for single cows.

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Chapter 8

Summary

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Introduction

The research described in this thesis was directed towards decision support in dairy cow health management. The method was specifically worked out for clinical mastitis, considered to be the economically most important dairy health problem in many countries. The method is, however, general of nature and can also be used for other diseases and species.

Data analysis

A statistical analysis was carried out to obtain biological and economic parameters with respect to clinical mastitis which fitted in the state space definition of the dynamic programming model (Chapter 2). A stepwise least squares method was used to obtain unbiased estimates of milk, fat, and protein losses that were due to clinical mastitis and the carry-over effect from the previous lactation. Logistic regression was used to estimate the probabilities that a cow would have clinical mastitis in the next month.

The effect of clinical mastitis on production within one lactation was estimated at 527 kg of milk (8.1%), 22.7 kg of fat (8.0%) and 13.7 kg of protein (6.2%) for 3 or more clinical cases in the second lactation. One or two clinical cases in a lactation did not significantly affect the production in the next lactation. The negative carry-over effect of 3 or more clinical cases was estimated at 381 kg of milk (5.9%), 23.7 kg of fat (8.4%), and 10.1 kg of protein (4.6%) up to and including month 8 of the second lactation. The fat content in milk produced after the onset of mastitis decreased, and protein content increased.

The risk of clinical mastitis infection in the following month was influenced by month of lactation (a higher risk early in lactation), lactation number (risk increased with lactation number), production level (higher risk for high-producing cows), number of clinical quarter cases in the previous lactation, number of clinical quarters in the previous months of the current lactation, and occurrence of clinical mastitis in the current month.

Optimization model

Farmers frequently have to decide whether to keep or to replace cows that suffer from clinical mastitis. A dynamic programming model was developed to optimize these decisions for individual cows within the herd, using the hierarchic Markov process technique (Chapter 3). It provides a method to model a wide variety of cows, differing in age, productive performance, reproductive status, and clinical mastitis occurrence. The model presented was able to support decisions related to 63% of all replacements. Results - for Dutch conditions - showed a considerable impact of mastitis on expected income of affected cows. Nevertheless, in most cases, the optimal decision was to keep and treat the cow rather than to replace her. Clinical mastitis occurring in the previous lactation showed a negligible influence on expected income. Clinical mastitis in current lactation, especially in the current month, however, had a significant effect on expected income.

Sensitivity analysis

The economic value of including the history of clinical mastitis of a cow in insemination and replacement decisions was determined by the dynamic programming model (Chapter 4). Logistic regression was used to determine the between-herd variation in relative risk of contracting clinical mastitis. This variation was taken into account in the evaluation of the potential value of clinical mastitis in the replacement model. A large variation in relative risk was found: 12.7% of the farms ran more than twice and 3.5% more than three times the average risk. The total losses caused by clinical mastitis were found to be Dfl. 150 per average cow per year in a herd with average risk, and Dfl. 373 in a herd with twice the average risk. On farms with twice the average risk, the losses from ignoring the history of clinical mastitis in insemination and replacement decisions were Dfl. 113 per average cow present in the herd per year. This was 7.6 times more than on farms with average risk. Information on clinical cases in previous lactation showed to be of no value in the decision-making process. These calculations showed that it may be misleading to give all farmers advice that was based only on farms with average health problems.

Optimization criteria

The effect of maximization of income per unit of physical output (i.e. milk) instead of maximization per cow in the context of inclusion of opportunity costs of labour and housing was described in Chapter 5. Attention was particularly focused on the effect of including opportunity costs of labour, housing and other non-yield related costs on the optimal strategy. In the dynamic programming model, cows differed in age, productive performance and reproductive status.

If opportunity costs of labour, housing and other non-yield related costs were included, then the optimal insemination and replacement decisions to maximize the expected net returns per cow were the same as those to maximize the expected net returns per kg of milk. However, when the combination of net returns to labour, housing and management was maximized, and thus no attention was paid to the number of working hours that were necessary and to the housing capacity needed, then selecting the right optimization criterion was important. In this situation the optimal policy for maximizing the expected net returns per cow differed from that of maximizing the expected net returns per kg of milk (6.1% more voluntary replacements when maximizing expected net returns per cow). Total net returns were Dfl. 0.32 per 100 kg of milk higher when maximizing the expected net returns per kg of milk.

Link between decisions at animal and herd level

A hybrid decision support system for culling decisions was developed consisting of the dynamic programming model integrated with a genetic algorithm (Chapter 6). In the decision support system a genetic algorithm was used to adjust and fine-tune the culling advice calculated by the dynamic programming model. The approach was used to include herd level effects, such as shortage of replacement heifers and milk quota. Results for a small farm (i.e. 16 cows) showed that the genetic algorithm was very capable of finding the decision set which minimized the levy to be paid for exceeding of milk quota and maximized total future herd income. The model most often advised to reduce the herd size to meet quota restrictions by culling cows with the lowest future value. In more extreme situations however also cows with a high future value were culled first. Results of this decision support system method were robust and it was illustrated that the system can be used for large farms without running into problems of combinatorial explosion.

Main conclusions

- The hierarchic Markov process approach has shown to be very useful in optimizing large scale replacement problems. The method makes it possible to include health related topics in an optimization model and yet keeps the state space for other characteristics very detailed. The simultaneous evaluation of age, production, fertility, and mastitis aspects supported decisions related to 63% of all insemination and replacement decisions on a dairy farm.
- The total losses caused by clinical mastitis were found to be Dfl. 150 per average cow per year in a herd with average risk, and Dfl. 370 in a herd with twice the average risk (including 12.7% of the farms)
- The economic value of information on mastitis in making dairy cow replacement decisions depends heavily on the incidence of clinical mastitis. Farm-specific advice is necessary because a large variation of clinical mastitis incidence between farms was observed. On farms with twice the average risk, the losses from

ignoring the history of clinical mastitis in insemination and replacement decisions were Dfl. 113 per average cow present in the herd per year. This was 7.6 times more than on farms with average risk.

- If the optimization criterion is maximization of income per kg of milk, then the opportunity costs of labour and housing have a significant influence on the optimal insemination and replacement policy. Under normal economic conditions the long-term optimal insemination and replacement policy does not change by introduction of a milk quota system.
- For economic decision support on clinical mastitis it is not necessary to include disease information of previous lactations. The occurrence of clinical mastitis in current lactation strongly affects the expected economic future value of a cow. For average farms, however, it most often does not change the optimal decision for single cows.
- The hybrid decision support system based on a genetic algorithm has shown to be a promising approach to including herd level restrictions and animal interactions in determining the optimal decision for single cows.

Chapter 9

Samenvatting

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Inleiding

Het in dit proefschrift beschreven onderzoek had als doel om een systeem te ontwikkelen ter ondersteuning van beslissingen op het gebied van produktie- en gezondheidsmanagement op melkveebedrijven. De gehanteerde methode is specifiek uitgewerkt voor beslissingen gerelateerd aan klinische mastitis. Mastitis is een ontsteking van het uier en wordt in veel landen beschouwd als de economisch meest belangrijke gezondheidsstoornis bij melkkoeien. De ontwikkelde methode is echter algemeen van opzet en kan daardoor eveneens gebruikt worden voor andere ziekten en diersoorten.

Data analyse

Om het optimalisatiemodel te voeden met relevante biologische en economische parameters werd een statistische analyse uitgevoerd (Hoofdstuk 2). De hiermee verkregen gegevens sloten beter aan bij de gewenste opbouw van het optimalisatiemodel (Hoofdstuk 3) dan de gegevens die via de literatuur beschikbaar waren. Er werd gebruik gemaakt van een stapsgewijze schattingsmethode om zuivere schattingen te verkrijgen voor aan mastitis gerelateerde melk-, vet- en eiwitverliezen. Daarnaast was er speciale aandacht in de analyse voor het effect van klinische mastitis op de produktie in de volgende lactatie. De invloed van allerlei dierspecifieke factoren op de kans van optreden van klinische mastitis werd geanalyseerd met logistische regressie.

Uit deze data analyse bleek o.a. dat de produktie in de tweede lactatie bij drie of meer klinische kwartiergevallen met 527 kg melk (8.1%), 22,7 kg vet (8.0%) en 13.7 kg vet (6.2%) daalde. Een enkele of dubbele kwartierinfectie bleek geen significant effect te hebben op de produktie in de volgende lactatie. Indien echter 3 of meer klinische gevallen geconstateerd waren in de eerste lactatie dan daalde de produktie in de daaropvolgende lactatie met 381 kg melk (5.9%), 23.7 vet (8.4%), and 10.1 kg eiwit (4.6%). Direct na het optreden klinische mastitis nam het vetgehalte af en het eiwitgehalte toe.

Uit de logistische regressie bleek dat er diverse risicofactoren voor klinische mastitis waren. Vroeg in de lactatie was er een verhoogd risico, en dit nam toe bij een hogere leeftijd en een hoger produktieniveau. Daarnaast had klinische mastitis in een eerdere fase van de lactatie en in de vorige lactatie een duidelijk verhoogd risico in de huidige lactatie tot gevolg.

Optimalisatiemodel

Veehouders moeten in de praktijk frequent beslissen of een koe (al dan niet met klinische mastitis) aangehouden dan wel vervangen moet worden. Een optimalisatiemodel (waarbij de techniek van dynamische programmering is gehanteerd) werd ontwikkeld om alle effecten mee te wegen en zo voor individuele koeien de beslissingen te optimaliseren (Hoofdstuk 3). Door het gebruik van een speciale vorm van dynamische programmering (hiërarchische Markov proces techniek) was het mogelijk om de toestandsruimte van het beslissingsprobleem nauwkeurig te definiëren. Koeien konden variëren in leeftijd, produktiviteit, vruchtbaarheid en het aantal klinische mastitisgevallen. Het model was zodoende in staat om ca. 63% van alle afvoerbeslissingen te ondersteunen. De modelresultaten lieten zien dat, onder Nederlandse omstandigheden, dat de verwachte toekomstige opbrengsten sterk daalden ten gevolge van het optreden van klinische mastitis. In de meeste gevallen was het echter toch nog economisch aantrekkelijk om de desbetreffende koeien te behandelen en aan te houden. Klinische mastitis in de vorige lactatie had nauwelijks effect op de verwachte toekomstige opbrengsten.

Gevoeligheidsanalyse

Ter bepaling van de economische waarde van informatie over klinische mastitis in een beslissingsondersteunend model werd het optimalisatiemodel gebruikt voor een reeks van verschillende bedrijfssituaties (Hoofdstuk 4). Met behulp van het optimalisatiemodel konden technische en economische kengetallen behorende bij een bepaalde (sub)optimale strategie van een bedrijf, rechtstreeks bepaald worden. De gevoeligheidsanalyse was vooral gericht op het effect van mastitisincidentie op de economische waarde van informatie. Hiertoe werd eerst een logistische regressie uitgevoerd om inzicht te krijgen in bedrijfsgebonden variatie voor het risico van optreden van klinische mastitis. Er werd een sterke variatie aangetoond: op 12,7% van de bedrijven hadden de koeien meer dan 2 keer het gemiddelde risico om mastitis te krijgen en op 3,5% van de bedrijven was het zelfs meer dan 3 keer het gemiddelde risico. De totale verliezen veroorzaakt door klinische mastitis was voor een bedrijf met een gemiddeld risico 150 gulden per gemiddeld aanwezige koe per jaar. Voor een bedrijf met een dubbel risico was dit 373 gulden. Het volledig negeren van de klinische mastitis historie bij het nemen van inseminatie- en vervangingsbeslissingen kostte voor een bedrijf met een dubbel risico 113 gulden per gemiddeld aanwezige koe. Dit was een factor 7,6 keer hoger dan voor een bedrijf met een gemiddeld risico. Informatie over mastitis uit voorgaande lactaties bleek van minimaal belang te zijn. Uit deze resultaten kon afgeleid worden dat het gevaarlijk kan zijn om adviezen te baseren op gemiddelde bedrijven.

Optimalisatiecriterium

Bij een optimalisatiemodel draait het om het optimalisatiecriterium. Vóór de invoering van de melkquota was het streven naar maximale opbrengsten per koe het belangrijkste criterium. Echter sinds de invoering van het melkquotum is maximalisatie per kg melk een beter criterium. In Hoofdstuk 5 werd het effect van beide criteria op de optimale inseminatie- en vervangingsstrategie onderzocht. Daarbij was de aandacht vooral gericht op het meenemen van kosten voor arbeid, gebouwen en andere niet produktiegebonden kosten. In de analyse konden de koeien verschillen in leeftijd, produktiviteit en vruchtbaarheid.

Als ook de kosten voor arbeid, gebouwen en andere niet produktiegebonden kosten meegenomen werden dan was de optimale strategie bij het maximaliseren van de opbrengsten per koe hetzelfde als bij maximalisatie per kg melk. Dit betekende dat het melkquotum geen invloed had op het beleid. Als er echter geen alternatieve aanwending mogelijk was voor vrijkomende arbeid en gebouwen dan werden er wel verschillen gevonden tussen beide optimalisatiecriteria. Bij maximalisatie per kg melk werd er sterker op andere kosten gelet en daardoor nam het optimale vervangingspercentage met 6,1% af ten opzichte van de situatie waarbij de opbrengsten gemaximaliseerd werden per koe. De totale opbrengsten onder maximalisatie per kg melk waren 0,32 gulden per 100 kg hoger.

Verband tussen beslissingen op dier- en bedrijfsniveau

Om bedrijfsgebonden beperkingen en interacties tussen dieren mee te kunnen nemen werd een hybride optimalisatiemodel ontwikkeld (Hoofdstuk 6). Dit model was enerzijds gebaseerd op het dynamische programmeringsmodel en anderzijds op een genetisch algoritme. In dit hybride model werd het dynamische programmeringsmodel gebruikt om voor individuele dieren de toekomstige gebruikswaarde te bepalen en werd een genetisch algoritme gebruikt om het effect van beslissing bij andere dieren op de gebruikswaarde van betreffende koe te bepalen. Hierdoor was het mogelijk om beperkingen op bedrijfsniveau, zoals de beschikbaarheid van vervangende vaarzen en overschrijding van het melkquotum, mee te nemen bij beslissingen voor individuele melkkoeien. Resultaten voor een klein bedrijf (16 koeien) lieten zien dat het hybride model zeer goed in staat was om de optimale beslissingen te vinden waarmee het totale bedrijfsinkomen (inclusief superheffing) gemaximaliseerd werd. De optimale beslissingen betekenden soms het accepteren van een beperkte leegstand om zodoende het quotum niet te overschrijden. Echter in meer extreme situaties was het soms optimaal om koeien met een hoge gebruikswaarde voortijdig te vervangen. De resultaten bleken robuust te zijn en het bleek dat de aanpak ook voor grote bedrijven gebruikt kan worden, zonder direct tegen het probleem van de combinatorische explosie aan te lopen.

Belangrijkste conclusies

- De hiërarchische Markov proces techniek is erg bruikbaar bij het ontwikkelen van zeer grote optimalisatiemodellen. De methode maakt het mogelijk om aan gezondheid gerelateerde kenmerken in een optimalisatiemodel op te nemen en tevens voldoende ruimte over te laten voor een gedetailleerde opname van overige kenmerken. De simultane evaluatie van produktie-, vruchtbaarheid- en mastitisaspecten leidde tot ondersteuning van 63% van alle afvoerbeslissingen.
- Klinische mastitis bleek een schade te veroorzaken van in totaal 150 gulden per gemiddeld aanwezige koe per jaar. Op bedrijven met twee keer de gemiddelde mastitisrisico (12,7%) lag dit bedrag op 370 gulden.
- De economische waarde van het meenemen van historische informatie over klinische mastitis in de inseminatie- en vervangingsbeslissingen was sterk afhankelijk van de mastitisincidentie op het bedrijf. Bedrijfsspecifiek advies is noodzakelijk omdat een grote bedrijfsvariatie werd aangetoond in mastitisincidentie. Op bedrijven met twee keer het gemiddelde risico is het inkomensverlies veroorzaakt door het negeren van de klinische mastitishistorie 113 gulden per gemiddeld aanwezige koe per jaar. Dat is 7,6 keer zoveel als bij een bedrijf met een gemiddeld risico.
- Als de opbrengsten gemaximaliseerd worden per kg melk dan is het van belang om te weten in welk mate de opbrengsten uit alternatieve aanwending van vrijkomende arbeid en gebouwen meegenomen moeten worden. De omvang hiervan heeft dan een effect op het optimale inseminatie- en vervangingsbeleid. Echter onder normale economische condities (d.w.z. een volledige alternatieve aanwending van arbeid en gebouwen) bleek dat het inseminatie- en vervangingsbeleid niet gewijzigd hoeft te worden als onder quotumrestricties geproduceerd wordt.
- Op economische gronden is het niet noodzakelijk informatie over klinische mastitis uit de vorige lactatie mee te nemen bij de inseminatie- en vervangingsbeslissingen. Alhoewel de verwachte toekomstige opbrengsten door het optreden van klinische mastitis sterk dalen, is het nagenoeg altijd beter om tot behandeling en aanhouden over te gaan.

- Om rekening te houden met restricties op bedrijfsniveau en interacties tussen individuele dieren bij het nemen van beslissingen op dierniveau is een hybride modellering noodzakelijk. Het combineren van het genetisch algoritme en het dynamische programmeringsmodel blijkt hiervoor een veelbelovende aanpak.

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1990

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Curriculum vitae

Eric Hendrik Peter Houben werd op 1 juni 1966 geboren in Venray (Limburg). In 1984 behaalde hij aan het Boschveldcollege te Venray het diploma Atheneum-B. In september 1984 werd begonnen met de studie Zoötechniek aan de toenmalige Landbouwhogeschool (later Landbouwuniversiteit) Wageningen. Hij rondde zijn studie af in 1990 met als afstudeervakken Veefokkerij, Agrarische Bedrijfseconomie en Veehouderij. Zijn stage werd uitgevoerd bij VOC Nieuw Dalland en bij Danske Slagterier (Denemarken). In de periode september 1989 - februari 1990 werkte hij als toegevoegd onderzoeker bij de vakgroep Agrarische Bedrijfseconomie aan een oriënterende modelstudie naar de verspreiding en bestrijding van de ziekte van Aujeszky. Na zijn afstuderen in september 1990 was hij tot september 1994 werkzaam als Assistent in Opleiding (AIO) bij de vakgroep Agrarische Bedrijfseconomie van de Landbouwuniversiteit in Wageningen hetgeen heeft geleid tot dit proefschrift. Sinds oktober 1994 is hij werkzaam bij Houbensteyn Holding b.v. in Ysselsteyn (Limburg).