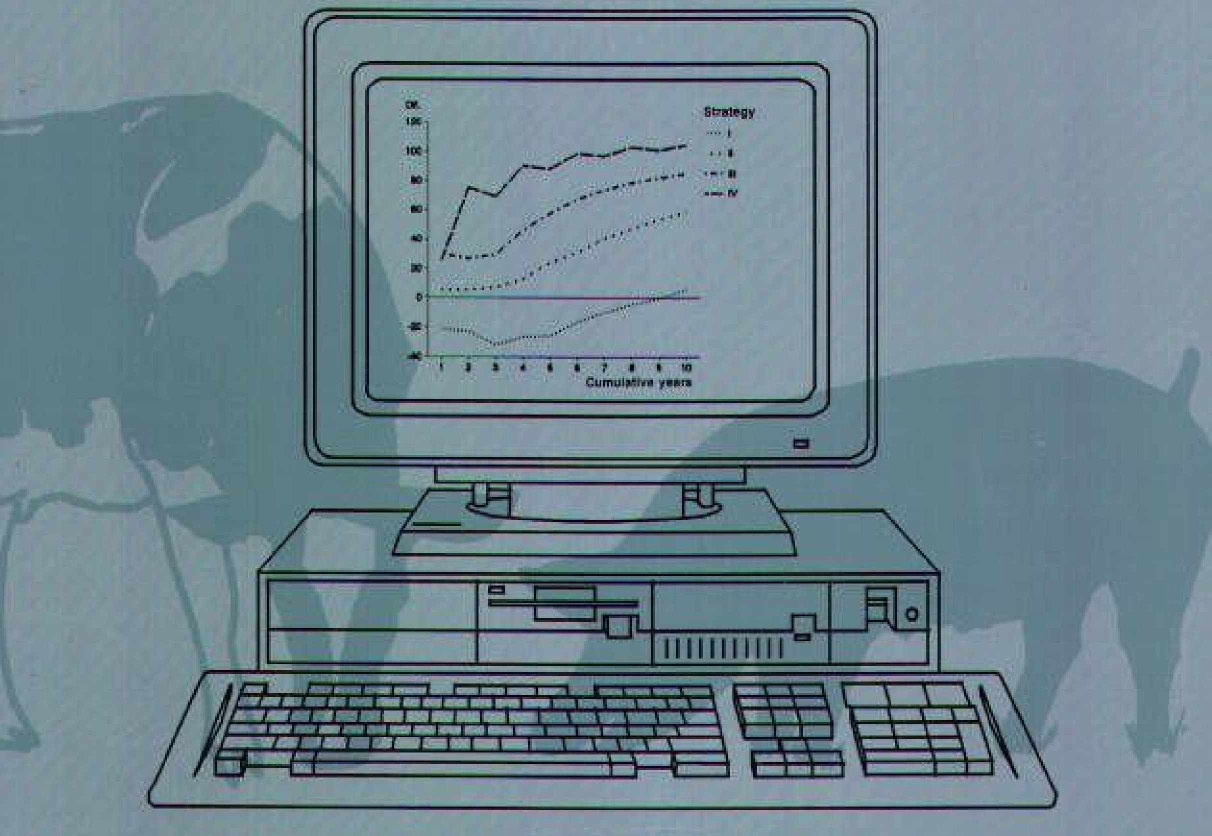
Dynamic livestock modelling for on-farm decision support

A.W. Jalvingh



Stellingen

1. Simulatiemodellen ter ondersteuning van managementbeslissingen op individuele veehouderijbedrijven vormen een zinvolle uitbreiding van de op dit moment beschikbare management-informatiesystemen.
   Dit proefschrift

2. Het veel gehanteerde kengetal "grootgebrachte biggen per zeug per jaar" is geen goede indicator voor het economisch effect van verschillen in het inseminatie- en vervangingsbeleid op zeugenbedrijven.
   Dit proefschrift

3. In onderzoek en voorlichting rond de economische aspecten van het afkalfpatroon bij melkvee wordt te weinig aandacht besteed aan de kosten van het daadwerkelijk verschuiven van dit patroon.
   Dit proefschrift

4. Een veestapel in evenwicht is één en al dynamiek.
   Dit proefschrift

5. Bedrijfsspecifiek toepasbare simulatiemodellen betekenen eerder een versterking dan een ondermijning van de positie van bedrijfsbegeleiders.

6. Een verbeterd management rond produktie, gezondheid en vruchtbaarheid op veehouderijbedrijven is niet alleen economisch aantrekkelijk, maar ook gewenst vanuit milieu-oogpunt. Belangentegenstellingen doen zich wel voor tussen dierlijk welzijn en milieu.

7. Een geïntegreerd gebruik van geografische informatiesystemen en simulatiemodellen in de bestrijding van besmettelijke dierziekten leidt tot zowel snellere alsook beter afgewogen beslissingen.
   Morris, R.S., Sanson, R.L. and Stern, M.W., 1992. EpiMAN - A decision support system for managing a foot-and-mouth-disease epidemic. Proceedings annual meeting VEEC, 5: 1-35.

8. Voorwaarde voor een succesvol ketenconcept voor verse agrarische produkten is, dat men erin slaagt de consumenten ervan te overtuigen dat de door hen gestelde eisen ten aanzien van produkt en produktiewijze zijn ingewilligd en dat het produkt de meerprijs waard is.

9. Met het oog op het toekomstig milieubeleid in de veehouderij is een mogelijke uitbreiding van het fokdoel met lichaamsgewicht een gewichtige zaak geworden.

10. Voor een succesvolle wetenschappelijke samenwerking is een goede persoonlijke relatie tussen de betrokkenen van essentieel belang.

11. Het organiseren van activiteiten als fokveedagen en dochtergroependemonstraties strookt niet met een verantwoord dierziektenbeleid, zolang een sluitende certificering op het gebied van diergezondheid ontbreekt.

12. Het feit dat een gehuwde vrouw bevoegd is de geslachtsnaam van haar man te voeren (Burgerlijk Wetboek, Boek 1, artikel 9 lid 1), geeft derden niet automatisch de bevoegdheid haar ook zo aan te spreken of aan te schrijven.

13. Mensen worden vaak op hun uiterlijke kenmerken beoordeeld zonder dat gelet wordt op het innerlijk. Met computermodellen is dat al niet veel anders.

14. Het negatieve imago van korfbal wordt gecreëerd en in stand gehouden door mensen die qua kennis van de sport al snel door de mand vallen.

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Dynamic livestock modelling for on-farm decision support
Wageningen, 21 september 1993

Dynamic livestock modelling for on-farm decision support

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Dynamic livestock modelling for on-farm decision support

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Abstract

Dynamic livestock modelling for on-farm decision support
Dynamische simulatie ter ondersteuning van managementbeslissingen op veehouderijbedrijven
Jalvingh, A.W., 1993.

The study described in this thesis focuses on the development and use of models that simulate herd dynamics in livestock. The models can be used to calculate the herd-specific technical and economic consequences of various management strategies. The thesis is composed of four parts. (1) Existing models from the literature simulating herd dynamics were described and discussed, including their possible role in on-farm decision support. (2) A modelling approach was developed to support decisions with respect to production, reproduction and replacement in swine herds. In this, probabilistic modelling using probability distributions was used to simulate herd dynamics and to evaluate various management strategies. (3) The approach developed for swine herds was modified and transformed to model similar decisions in dairy herds. Special attention was paid to the calving pattern of the herd. The model can be used to evaluate strategies in order to change a herd's calving pattern. Additionally, a method was worked out to determine the optimum herd calving pattern, which was based on the developed model and linear programming. (4) The possible path leading from the developed prototypes towards a successful implementation in the field as part of an integrated decision support system was discussed.

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Voorwoord

De openbare verdediging van dit proefschrift vormt de officiële afronding van mijn aanstelling als Assistent-in-Opleiding (AIO) bij de vakgroepen Agrarische Bedrijfseconomie en Veefokkerij van de Landbouwuniversiteit Wageningen. Tussen de start en finish van deze bijna gelopen race ben ik door vele mensen aangemoedigd. Daarvoor wil ik hen hartelijk danken. Vanwege hun speciale bijdrage wil ik enkele personen graag bij naam noemen.

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Alien

Contents

General introduction

1 INTRODUCTION

Management is becoming increasingly important in modern livestock farming. In the Netherlands, for instance, governmental regulations such as milk quotas and manure legislation limit the opportunities of expanding farms and increase the emphasis on a further reduction of the costs. Improving farmers' management is an option to reduce costs, and consequently to maintain farm income. Information technology can play an important role to improve management by providing accurate and consistent information for making decisions (Boehlje and Eidman, 1984).

In 1984 the Dutch Ministry of Agriculture, Nature Management and Fisheries started a program to stimulate the development and use of information technology in agriculture. A major activity consisted of developing the so-called information models for the various types of farming, primarily aimed at providing the essential standardization of definitions and algorithms to be used in management information systems (Verheijden et al., 1985; Brand et al., 1986). The information models also described the processes, such as nutrition and reproduction, about which sufficient knowledge was lacking and further research needed. Increased attention on computerized support for tactical planning was especially stressed, being the initial impetus for the project TACT-Systems. The need for this type of support came also from interviews with farmers (De Hoop et al., 1989).

The project TACT-Systems was started as a joint activity of the Wageningen Agricultural University, the Agricultural Economics Research Institute, research centres (dairy and swine), branch organizations and private software industry. The aim of the project was to develop simulation models as an extension of available management information systems. The extension with simulation models offers the possibility of providing the farmer beforehand with insight into the technical and economic consequences of various management decisions.

Within the farmer's tactical planning function many different processes can be distinguished. In the project TACT-Systems attention was paid to a selection of processes: roughage production, nutrition, reproduction and replacement for dairy, and reproduction, purchases and sales for swine. The intention of the project was not to develop one (big) single model, but a "tool kit" of smaller models. This should provide more flexibility in model configuration, serving a wider range of management questions. For the different processes at the farm separate models should become available, simulating the process in either a detailed or aggregated manner. Furthermore, the models should be able to carry out farm-specific simulations.

2 OUTLINE OF THE THESIS

Research in this thesis was carried out within the project TACT-Systems. Attention was focused on the development of simulation models to simulate the technical and economic consequences of management strategies related to decisions on production, reproduction and replacement in dairy cattle and swine. In the models simulating these consequences, dynamics of the herd over time play an important role.

Chapter 1 describes existing optimization and simulation models from the literature focusing on production, reproduction and replacement. Their possible usage in on-farm decision support is discussed.

After studying existing models that simulate herd dynamics, it was decided to develop new models, using the available knowledge in existing ones. At first, a model that simulates herd dynamics in a sow herd was developed (Chapter 2). The approach used to simulate herd dynamics is probabilistic modelling using the Markov chain approach and differs from the approach used in the existing models, to be described as probabilistic simulation involving random numbers (i.e. Monte Carlo simulation). The developed modelling approach was used to evaluate several management strategies on reproduction and replacement in sow herds (Chapter 3). General rules of thumb were compared with more detailed management guides, recently developed to economically optimize insemination and replacement decisions for individual sows within the herd (Huirne et al., 1991).

The modelling approach used for sow herds was modified and transformed to model similar decisions in dairy herds (Chapter 4). A new feature is the inclusion of the influence of season on herd dynamics and performance. Dairy farmers can increase their income by concentrating the production in those periods of the year that have highest revenues or lowest costs. The model was used to study the economic consequences of different herd calving patterns. The model was further extended in order to evaluate strategies that actually change a herd's calving pattern (Chapter 5). Strategies aiming at the intake of replacement heifers in the herd or at insemination and replacement of cows were compared.

The models described in Chapter 2 and 4 concentrated on the animal level. Chapter 6 shows how these models can be integrated with a linear programming model to take restrictions at herd level into account. This integration was worked out for the determination of the optimum calving pattern of a dairy herd.

The models described in the different chapters were designed for use in on-farm decision support, allowing for individual farm conditions to be included. The description of the models was mainly concentrated on the technique for simulating herd dynamics and on possible applications. The discussion chapter focuses on how to proceed towards a successful implementation of the prototypes in the field as part of an integrated decision support system. In addition, advantages and disadvantages of the Markov chain technique, which is used to simulate herd dynamics, over commonly used modelling approaches are discussed and evaluated.

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Chapter 1

The possible role of existing models in on-farm decision support in dairy cattle and swine production

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ABSTRACT

Current management information systems in (Dutch) livestock farming are not yet suited to support all important steps of the decision-making process. They should be extended with models that are able to calculate the technical and economic consequences of various decisions and management strategies over time for the farm as a whole or part of it. These models need to be farm-specific and available for use in the field. In this paper, a general outline is given of the framework in which these models can be used in on-farm decision support. Models available in the literature, primarily focused on reproduction and replacement in dairy cattle and swine, are studied to examine to what extent they are suitable for use in on-farm decision support. The structure of each single model and the differences/similarities between models are identified. An enormous variation in structure is observed. For on-farm use it is considered best to build new models using the available knowledge, rather than to adjust and combine existing ones. A possible outline for this is discussed.

1 INTRODUCTION

Management is becoming increasingly important in today's livestock farming. In the Netherlands, for instance, political measures such as milk quotas and manure legislation raise costs and limit the opportunities to expand farms. Improving farmers' management, therefore, is increasingly important for maintaining farm income. Management information systems can play an important role in this context.

Management implies decision-making. To make the right decisions, farm managers should have insight beforehand into the potential impact of various decisions on the results of the farm. Estimates of these impacts can be obtained from model calculations. A model is defined as a simplified representation of a system (e.g. the farm or a part of it), which can be used to predict the effects of changes in the system (Dent and Blackie, 1979; Spedding, 1988). Current developments in computers and advanced mathematical methods allow the consideration of more aspects of a decision and more alternative plans in these models. Computer-based models, therefore, have become promising tools in the field of farmers' management support.

Various computer-based models are described in literature. Use of these models has often ended in general rules of thumb applicable to all farmers. It is doubtful whether these general rules are indeed valid for all farmers. The profitability of the given support may be improved when this general advice can be replaced by recommendations from models that are tailored to individual farm conditions. The objective of this paper is to examine to what extent existing models can be used in this type of on-farm decision support. This will be studied especially in a field of livestock management with a high number of published economic models, i.e. reproduction and replacement in dairy and sow herds. Before addressing this main objective, a general outline will be given of the framework in which computer-based models can be used in on-farm decision support.

2 BASIC CONCEPTS OF MANAGEMENT AND MANAGEMENT INFORMATION SYSTEMS

Management can be described as the decision-making process in which limited resources are allocated to a number of production alternatives (Kay, 1986). This allocation of resources should be organized and operated in such a way that the firm's goals and objectives are achieved. As illustrated in Figure 1, the management process can be considered a cyclical process, including three basic or primary functions: planning, implementation and control (Boehlje and Eidman, 1984; Kay, 1986). Planning is the process of selecting a particular strategy or course of action from various alternatives. Depending on the planning horizon, strategic (long-term), tactical (medium-term) and operational (short-term) planning can be considered (Figure 1). Strategic planning concerns decisions related to the basic farm structure. The strategic plan has its effects in the long term and establishes the scope in which tactical planning

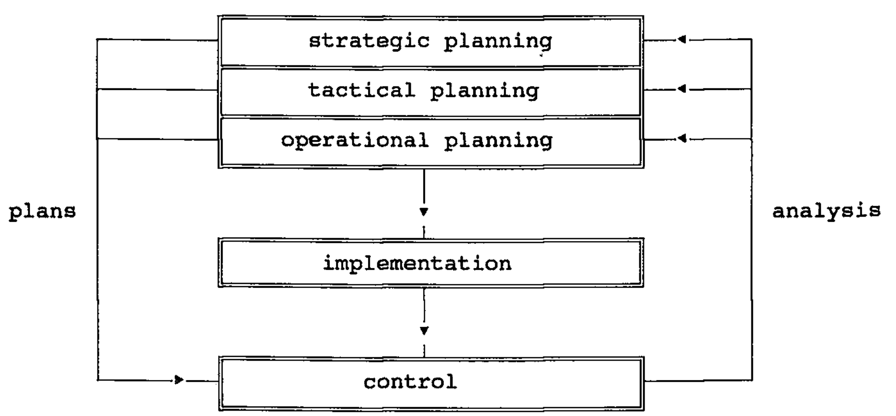

Figure 2.1. The management cycle (source: Huirne, 1990).

has to be carried out. Tactical or medium-term planning (year, season) is involved with obtaining optimal results within the given or proposed farm structure. Within the framework set by tactical planning, a more detailed plan can be produced. This operational or short-term plan (days, weeks) anticipates the actual situation on the farm. Implementation is the process of acquiring the resources needed and putting the chosen plan into action. Control involves the evaluation of performances, in order to determine whether or not they meet plans, and to decide whether corrective actions to improve performance are needed. The corrective actions resulting from the control function form the start of a new management cycle.

2.1 Computerized support of management

Information processing is an important activity for the farm manager, since it provides the essential information for making the right decisions (Boehlje and Eidman, 1984). Computers have become an essential part of organizational information processing because of the power of the technology and the volume of data to be processed. Furthermore, the ability to automate information processing has enabled an expansion in the use of formalized information (Davis and Olson, 1985). The current challenge in information processing is to use the capabilities of computers to support managerial activities and decision-making. The broad category of computer systems that realize the collection, maintenance and use of information for organizational purposes are classified as management information systems. Davis and Olson (1985) define a management information system as an integrated, user-machine system for providing information to support operations, management and decision-making functions in an organization. The system utilizes computer hardware and software; manual procedures; models for analysis, planning, and control and decision making; and a database.

The basic purpose of a management information system is to provide a way of supplying the decision maker with information for making decisions. Therefore, the components of a management information system should have a close relationship with the different steps of the decision-making process (Harsh et al., 1981). The decision-making process is commonly described in the following five steps (Boehlje and Eidman, 1984): (1) define the problem or opportunity, (2) identify alternative courses of action, (3) gather information and analyze each of the alternative actions, (4) make the decision and take the action, and (5) accept the consequences and evaluate the outcome.

Current management information systems in livestock farming are mainly focused on record keeping and primarily support operational management decisions (Corning and Van de Ven, 1989). To support more steps of the decision-making process these systems should be extended. Priority should be given to: (a) extension of the recordkeeping systems with modules for data analysis and (b) development of models to support tactical management decisions (Verheijden et al., 1985; Brand et al., 1986).

3 DAIRY CATTLE AND SWINE MODELS DESCRIBED IN LITERATURE

A fundamental principle of model-building is that the type of model to be constructed depends on its anticipated use: a model should represent those facets of the real system relevant to the model applications (Dent and Blackie, 1979). Models available in literature are studied to identify (a) the structure of each single model, and (b) the similarities and/or differences in structure between these models.

First of all three basic classifications are used to identify the overall structure of each model. A first feature to consider is optimization versus simulation. An optimization model determines the optimum solution given the objective function and restrictions, whereas a simulation model calculates the outcome of predefined sets of variables (Van Dyne and Abramsky, 1975). A second characteristic for the classification of models is deterministic versus stochastic (France and Thornley, 1984). A deterministic model makes definite predictions for quantities. A stochastic model contains probability distributions and/or random elements to deal with uncertainty in the behaviour of a system. With random elements, repeated runs of the model are necessary to provide insight into the potential variation in outcome. Finally, a model is either dynamic or static (France and Thornley, 1984). A static model does not contain time as a variable and is, therefore, not able to simulate the behaviour of a system over time, as opposed to a dynamic model. The way in which time is built into a dynamic model can vary (time-stepping versus event-stepping). In a model of the time-stepping type, time is advanced on a fixed unit basis. If time skips from the point at which one event occurs to the point when the next event occurs, the model is considered to be of the event-stepping type (Dent and Blackie, 1979). Furthermore, some characteristics more related to the contents of the model are used in identifying the structure.

As far as possible, we present these characteristics in the Tables, sudividing the models into those relating to dairy cattle (Table 1) and swine (Table 2).

Description of similarities and/or differences between model structures will be presented for dairy cattle and swine models separately.

3.1 Dairy cattle models

The structure of the available (nine) dairy cattle models focusing on reproduction and replacement has been studied and presented (Table 1). From Table 1 it can be concluded that although all models are focused on the same processes, they vary in almost all characteristics. Two classes of dairy cattle models are considered: (a) optimization models, and (b) simulation models.

The optimization models (Stewart et al., 1977; Van Arendonk and Dijkhuizen, 1985; Kristensen, 1987; Harris, 1988) determine the optimum culling policy for individual dairy cows using dynamic programming. The basic concepts of dynamic programming are those of the state of the system and the transition from one state to another over a number of stages. The variation among the models in state variables used to describe a cow and the length of a single stage, explain the differences in factors to be taken into account in the optimum policy. The models developed by Stewart et al. (1977) and Harris (1988) are restrictive in that culling decisions can only be made once per lactation, whereas Harris (1988) allows variation in lactation length. The model developed by Kristensen (1987) is quite similar to that of Van Arendonk and Dijkhuizen (1985). In both models decisions to cull animals can be made more than once per lactation, variation in length of calving intervals is possible, and the optimum insemination policy can also be determined. The major difference between Van Arendonk and Dijkhuizen (1985) and Kristensen (1987) is the algorithm used to determine the optimum policy; Van Arendonk and Dijkhuizen (1985) use value iteration and Kristensen (1987) combines value iteration with policy iteration into hierarchic optimization. In case of value iteration under an infinite planning horizon, it is not certain whether the absolute optimal solution is reached. Policy iteration gives the absolute optimal solution under a finite and an infinite planning horizon and uses matrix algebra. Hierarchic optimization is a method to reduce the size of the matrix used in policy iteration. The models of Van Arendonk and Dijkhuizen (1985; see Van Arendonk, 1988), Kristensen (1987) and Harris (1988) provide management guides for individual cows. The future profitability calculated from the optimal solution is used for ranking the cows within the herd. These management guides allow the farmer to inseminate and/or cull cows on expected future performance rather than on realized production. Van Arendonk and Dijkhuizen (1985) and Kristensen (1987) both use a separate

Table 1. Overview of characteristics of studied dairy cattle models[a].

Model[b]									Characteristic
I	II	III	IV	V	VI	VII	VIII	IX	
O	O	O	O	S	S	S	S	S	Simulation (S) or optimization (O)
S-P	S-P	S-P	S-P	S-R	S-R	S-R	S-R	S-R	Stochastic (S) or deterministic (D); when S: random elements (R) or probability distributions (P)
D-T-365	D-T-30.5	D-T-[c]	D-T-365	D-E-1	D-T-30	D-E-1	D-E-1	D-T-20	Dynamic (D) or static (S); when D: time-stepping (T) or event-stepping (E), and used time step (days)
N	N	N	N	Y-?	Y-A	Y-A	Y-A	Y-A	Able to follow changes in a herd over time (Y/N); if Y then initial herd generated from replacements (R) or age distribution (A)
(nr)	(nr)	(nr)	(nr)	?	Y	Y	Y	Y	Rearing of youngstock (Y/N)
Y	Y	Y	Y	Y	Y	Y	Y	Y	Involuntary culling (Y/N)
(nr)/10	(nr)/15	(nr)/∞	(nr)/?	?[d]	0/15	5/25	1/5	5/10	Length of stabilizing and experimental period in years
T/E-d	T/E-d	T/E-d	T/E-d	T[e]	T/E-d	T/E-d	T/E-d	T/E-d	Technical (T) and/or economic (E) calculations available; when E: does discounting (d) take place
?	M	?	?	?	M	M	?	?	Personal (P) or mainframe (M) computer
US	NL	DK	NZ	US	US	US	US	NL	Country of origin

[a] If a certain characteristic could not be obtained from the literature, this is indicated by a question mark. If a characteristic is not relevant this is indicated by (nr).

[b] I: Stewart et al, 1977; II: Van Arendonk and Dijkhuizen, 1985; III: Kristensen, 1987; IV: Harris, 1988; V: Oltenacu et al, 1980; VI: Kuipers, 1982; VII: Congleton, 1984; VIII: Marsh, 1986 (DairyORACLE); IX: Dijkhuizen et al., 1986b.

[c] Variable, but usually 56.

[d] 10 years in Rounsaville et al. (1979).

[e] Extended with milk production, feed intake and economic calculations in Oltenacu et al. (1981).

model to estimate performance, and costs and returns of cows during a given period depending on the state of the cow (Van Arendonk, 1985, and Kristensen, 1986 respectively).

All simulation models (Oltenacu et al., 1980; Kuipers, 1982; Congleton, 1984; Marsh, 1986 (DairyORACLE); Dijkhuizen et al., 1986b) have the objective of calculating the technical consequences of changes in biological and/or management aspects. Except for the model of Oltenacu et al. (1980), all models calculate additionally the technical consequences. Oltenacu et al. (1981) extended the model of Oltenacu et al. (1980) with feed consumption and milk production, making it possible to calculate economic results as well. In two cases (Oltenacu et al. (1980) and Marsh (1986)) reproduction is the key issue of the model structure. Both models have been used to study breeding management (Rounsaville et al., 1979; Oltenacu et al., 1981; Marsh et al., 1987). Marsh (1986) designed a species-independent skeleton model that can be combined with parameters which are species-specific to produce simulation models capable of predicting the characteristics of reproductive events in a number of mammalian species. In the remaining simulation models reproduction is also an important element in the simulation of the production cycle, but the applications of the models are not restricted to breeding management only. Dijkhuizen et al. (1986b) based their model on the work of Kuipers (1982), and both these models can be used to study management aspects related to production, reproduction and replacement (Dijkhuizen and Stelwagen, 1988). The model of Congleton (1984) is mainly focused on the calculation of consequences of aspects related to culling policies (Congleton and King, 1984; Congleton, 1988, Congleton et al., 1988).

All models studied describe the production cycle of cows during several lactations. The degree of detail of the description of the production cycle varies between these models. After an initial herd is generated, all simulation models, in contrast to the optimization models, are able to follow the changes in a herd over time. The simulated herd is composed of individual animals that, at least, show variation in age and reproduction status. Furthermore, in all simulation models replacement animals are raised to maintain herd size. Selection of youngstock and the way in which replacements enter the cow herd, however, differ among models.

Although important continuous processes, such as milk production and feed intake, have been described extensively in literature, the description of these processes in the models studied varies. These differences may be caused by (a) the possibility of more than one way to describe certain processes, (b) new developments as time proceeds, or (c) the purpose of the model. All models presented are stochastic, but of course not all factors in these models will be simulated in a stochastic manner. In general, milk production, reproduction and involuntary culling are simulated in a stochastic way, and factors like feed intake, body weight and prices are simulated deterministically. In simulating processes in a stochastic manner, all simulation models studied draw random elements from appropriate probability distributions to determine what happens to an individual animal. Therefore, processes as milk production and reproductive performance are unique for each individual animal. In the optimization models studied animals are distributed over the possible states they can be in using fixed probabilities. Consequently, fractions of animals instead of individual animals are considered in optimization models. For that reason milk production and reproductive performance vary among states.

The way in which time is built into the dynamic models studied varies. The models using event-stepping are in fact models that consist of event-stepping modules simulating, for instance, reproduction and time-stepping modules simulating continuous processes such as milk production. In a time-stepping model the size of the time interval will be directly related to the level of detail required in the model (Dent and Blackie, 1979). The fixed time-increment in the models of Kuipers (1982) and Dijkhuizen et al. (1986b) corresponds to the length of the oestrus cycle they consider.

3.2 Swine models

Seven swine models have been studied. Each was able to determine the effects of changes in reproduction and/or replacement. The structure of the models differs in various issues considering the model characteristics presented in Table 2. Two classes of models are considered: (a) optimization models, and (b) simulation models.

The structure and objective of the two optimization models (Dijkhuizen et al., 1986a; Huirne et al., 1988) are comparable to the dairy cattle optimization models discussed above. Both models determine the economically optimum replacement policy in sow herds, but the optimization techniques applied differ. Dijkhuizen et al. (1986a) use the marginal net revenue approach and Huirne et al. (1988) use dynamic programming. Dynamic programming has the advantage that it offers the opportunity to account for future variation in traits, such as piglet production of sows and replacement gilts (Van Arendonk, 1984).

The objective of all simulation models (Allen and Stewart, 1983; Marsh, 1986 (PigORACLE); Singh, 1986; Pettigrew et al., 1987; Houben et al., 1990) is comparable to that of the corresponding dairy cattle models, but with

Table 2. Overview of characteristics of studied swine models[a].

Model[b]							Characteristic
X	XI	XII	XIII	XIV	XV	XVI	
O	O	S	S	S	S	S	Simulation (S) or optimization (O)
D	S-P	S-R	S-R	S-R	S-R	S-R	Stochastic (S) or deterministic (D); when S: random elements (R) or probability distributions (P)
S	D-T-1pc[c]	D-E-1	D-E-1	D-E-1	D-T-1	D-T-7	Dynamic (D) or static (S); when D: time-stepping (T) or event-stepping (E), and used time step (days)
N	N	Y-R	Y-A	Y-A	Y-R	Y-R	Able to follow changes in a herd over time (Y/N); if Y then initial herd generated from replacements (R) or age distribution (A)
(nr)	(nr)	N	Y/0	Y/0	Y/6	Y/6[d]	Rearing of youngstock (Y/N)
Y	Y	Y	Y	Y	Y	Y	Involuntary culling (Y/N)
(nr)	50pc[c]	5-15	0-6[e]	1-10[f]	2-3	10-10	Length of stabilizing and experimental period in years
T/E-d	T/E-d	T	T/E-d	T/E-d	T/E	T/E	Technical (T) and/or economic (E) calculations available; when E: does discounting (d) take place
P	M[g]	?	P	?	?	M	Personal (P) or mainframe (M) computer
NL	NL	US	US	US	US	NL	Country of origin

[a] If a certain characteristic could not be obtained from the literature, this is indicated by a question mark. If a characteristic is not relevant this is indicated by (nr).

[b] X: Dijkhuizen et al., 1986a; XI: Huirne et al., 1988; XII: Allen and Stewart, 1983; XIII: Marsh, 1986 (PigORACLE); XIV: Singh, 1986; XV: Pettigrew et al., 1987; XVI: Houben et al., 1990.

[c] Production cycle.

[d] Also possible from birth or 10 weeks of age.

[e] Marsh (1988) uses real herd data as starting situation (Marsh (1986) gives only information about model structure, results are not given).

[f] 10 experimental years are used as 10 independent repeat calculations of 1 year each.

[g] In the meantime also available on PC.

the emphasis on somewhat different aspects. The logical structure of the pig herd model of Marsh (1986) is similar to that of the dairy cattle model described above, since it is based on the same skeleton model. Only a few interrelationships among biological, physical, economic and management factors were explored in the papers studied. Allen and Stewart (1983) compared alternative lactation lengths. Houben et al. (1990) determined the economic effects of various insemination and culling policies. Singh (1986) and Pettigrew et al. (1987) determined the effect of changes in various parameters, such as conception rate, litter size, mortality rate of piglets and feed cost.

All but one of the models studied describe the production cycle of an individual sow during several parities in a dynamic way. The optimization model of Dijkhuizen et al. (1986a) describes this in a static way. The degree of detail of the description of the production cycle varies among the models. All simulation models mimic changes in a herd over time. Pettigrew et al. (1987) define the herd as a combination of a breeding and a finishing herd with fattened hogs as output. All remaining simulation models mimic a breeding herd with feeder pigs as output. The method of obtaining replacement gilts varies in the simulation models from raising them from birth (Marsh, 1986; Singh, 1986) to replacing each culled sow with a newly purchased replacement gilt (Allen and Stewart, 1983).

For an efficient use of available housing facilities it is very important in commercial sow herds to plan production. Singh (1986), Pettigrew et al. (1987) and Houben et al. (1990) take this into account, but the implementation varies. Singh (1986) simulates synchronized groups of sows, with each group occupying one farrowing room. Furthermore, the model generates information about the magnitude and variability of the occupation of various housing facilities. Pettigrew et al. (1987) aim at a certain number of farrowings per week by allowing a certain number of breedings per week. Houben et al. (1990) also have the objective of achieving a constant flow of animals through the farrowing rooms. The number of breedings allowed per week is not fixed as in the model of Pettigrew et al. (1987), but is, among other factors, dependent on the number of breedings carried out in the preceding weeks. Allen and Stewart (1983) simulate floor space requirements without implementing any form of production planning.

The way in which various processes are simulated in the stochastic models, either stochastically or deterministically, is comparable to the situation in the corresponding dairy cattle models. Piglet production is simulated in a stochastic manner, just like milk production in the dairy cattle models. The description of processes, such as piglet production and feed intake, is less complex than the description of similar processes in the dairy cattle models, which corresponds to the actual differences in complexity of these processes.

The models of Pettigrew et al. (1987) and Houben et al. (1990) consider the pattern of weekly recurring activities in a sow herd. In order to do this Pettigrew et al. (1987) use a fixed time-increment of 1 day, which enables the assignment of activities to a certain day in the week.

4 DISCUSSION AND OUTLOOK

Management information systems can play an important role in the support of the decision-making process on dairy and swine farms. Current management information systems in livestock farming lack the ability to support important steps of decision-making, such as the analysis of alternative actions. Therefore, the development of models that are able to calculate the technical and economic consequences of various strategies is considered to be a very valuable extension of the current management information systems. Special attention should be paid to decisions concerning the tactical planning function of the farmer (Verheijden et al., 1985; Brand et al., 1986). These models should be able to calculate consequences of various management strategies, over time, for the farm as a whole or for a part of it. Furthermore, the results generated have to be tailored to individual farm circumstances. The models surveyed are primarily focused on reproduction and replacement in dairy and swine herds. They have been studied to examine their possible role in on-farm decision support. Despite the narrow field on which these studied models are focused, an enormous variation in structure is observed among the models.

It is not feasible to construct a model based on full knowledge of all biological and physical phenomena. The performance, in terms of output from the system in relation to inputs, can only be described by a model if simplifications are made. This can be achieved by limiting the boundaries of the model and by focusing only on important aspects (Dent and Blackie, 1979). The objectives of the initial model development, which often reflect the discipline interests of the modeller, will influence the balance of representation within the model (Bywater, 1990). All models studied are focused on animal activities and, therefore, processes related to these activities are described in detail. Descriptions of the remaining processes are simplified or even omitted. This is reflected, for example, in the absence of integration between animal activities and roughage production in the dairy cattle models studied. All models assume a given supply of roughage of a certain quality and price, despite the importance of and differences in roughage production in dairy farm management. In spite of these simplifications almost all models are able to generate meaningful technical and economic results for the farm. Various strategies concerning reproduction and replacement can be evaluated by the simulation models. This flexibility in evaluating various strategies does not apply to the optimization models, because they are usually structured around one specific optimization algorithm. For effective on-farm decision support, information about the consequences of suboptimum strategies should also be obtained. Therefore, simulation models can be a useful tool in this. Simulation models can also include the results of optimization models, such as management guides to support the insemination or culling decision for individual animals (e.g. Van Arendonk, 1988).

In general, the models studied were initially developed for specific research questions. The model builders did intend to create a model able to represent the situation on any individual farm or to evaluate a wide range of questions. The latter cannot be established by combining existing models in the field of reproduction and replacement with existing models focused on other processes of the farm. Combining them may lead to irrelevant results because of differences in underlying assumptions and ways of describing processes. Moreover, the models vary in programming language and in most cases cannot run on a personal computer, because of large memory requirements. Therefore, in case of development of a model of the whole farm to support tactical decisions, it is considered best to build new models, rather than to adjust and combine available models. Also, Bywater (1990) stated that the time and resource commitment necessary to restructure or reparameterise existing models may not be very different from the commitment necessary to build a new model. The possible role of existing models in on-farm decision support is limited to providing available knowledge when building new models.

When developing new models, it should be taken into account that the applicability of the model to the real world increases with the number of variables considered. But eventually the addition of new variables diverts attention from more important variables already present in the model (Rabbinge and De Wit, 1989). To avoid this problem separate submodels can be developed which simulate each process of the farm in both an aggregated and a detailed manner. Depending on the tactic to be evaluated, certain submodels are to be combined into a model of the whole farm or just part of it. To include aspects of risk and uncertainty in these models, relevant processes need to be simulated in a stochastic manner. All of the studied simulation models used random elements. The inclusion of random elements in models for on-farm decision support may lead to results that are difficult to interpret,

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Chapter 2

Dynamic probabilistic modelling of reproduction and replacement management in sow herds. General aspects and model description

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ABSTRACT

A dynamic probabilistic model has been designed for the personal computer to determine the technical and economic consequences of various biological variables and management strategies concerning reproduction and replacement in swine. In it, the Markov chain approach is used to simulate herd dynamics. The herd is described in terms of states animals can be in and the possible transitions between the states. The corresponding transition probabilities are derived from input values concerning biological variables and management strategies. The model has the property to calculate easily the herd structure in its stationary state. Sets of input values can be evaluated by comparing the results of the corresponding herds at equilibrium. Moreover, herd dynamics can be studied over a period of time to gain insight into how equilibrium is reached. Input values can be easily modified to be farm-specific. The number of states considered in the model is optional, making it possible to provide either aggregated or detailed simulations.

1 INTRODUCTION

Management is becoming increasingly important in livestock farming and with it its support. A critical aspect of good management is making the right decisions. The process of decision-making is commonly described in five steps (Boehlje and Eidman, 1984): (1) define the problem or opportunity, (2) identify alternative courses of action, (3) gather information and analyze each of the alternative actions, (4) make the decision and take the action and (5) evaluate the outcome. Current management information systems in livestock farming are restricted mainly to data registration and analysis, which especially support step 1 and partly step 2 of the decision-making process. The next step is to provide insight into the potential impact of various (management) strategies on the results of the farm. This insight can be obtained by combining the available management information systems with computer simulation (Jalvingh, 1992).

For effective on-farm decision support the input of the computer simulation has to be farm-specific, representing the actual situation on the farm, and the model should have the ability to evaluate a wide range of strategies. Furthermore, the created output needs to be recognizable to the user, for example according to the output of available management information systems. Management strategies can be evaluated using simulation or optimization.

Optimization models are generally developed for a specific situation and are, therefore, less suited to study the consequences of a wide range of management strategies. Therefore, simulation models are preferred, making it also possible to gain insight into the consequences of sub-optimum decisions. Of course it is possible to include results of optimization models in these simulation models.

This paper focuses on tactical management decisions concerning reproduction and replacement in livestock. The modelling approach presented is species-independent, and in this paper applied to swine. Reproduction and replacement are processes that can be manipulated by the farmer. Livestock production is a time-dependent process; at any point of time a herd is the outcome of reproduction and replacement in the past. In order to evaluate the consequences of decisions in livestock farming it is necessary to model herd dynamics. The technical and economic results are a function of herd dynamics. Reproduction and replacement depend on biological variables on the one hand, and management strategies on the other. The modelling approach presented in this paper is focused on studying their integration to determine the technical and economic consequences of decisions concerning reproduction and replacement for on-farm use.

In available simulation models focused on reproduction and replacement in livestock, herds are followed over many years in order to determine the effects of variables on the results (for an overview see Jalvingh, 1992). Individual animals are moved forward through time, modifying the status of each according to the outcome of various events and management decisions. In this, Monte Carlo simulation is used, which means that random elements are included. This may lead to confusion and reduction of the acceptability of the model to the user when used in on-farm decision support (Dent and Blackie, 1979). Another, simpler approach is assuming herd structure to remain in a stationary state, this being achieved by adjusting offtake so that inflows equal outflows (Upton, 1985). This can be established by modelling the herd dynamics using a Markov chain. The probabilistic nature of herd dynamics is taken into account in this approach.

The use of Markov chains in modelling animal production activities is not as common as in economics. In animal production they are mainly used to simulate the spread of contagious diseases (Carpenter, 1988; Dijkhuizen, 1989). Another common application of Markov chains is dynamic programming to determine the optimum culling decisions for dairy cows (Van Arendonk, 1985; Kristensen, 1987) and sows (Huirne et al., 1991). Azzam et al. (1990) modelled the culling strategy in beef cattle using a simple Markov chain in order to derive herd structure and cow herd life.

2 MODEL STRUCTURE

2.1 Basic principle

Central to the theory of Markov chain models are the concepts of states and state transitions. The distribution over states at a certain moment can be derived from the distribution at the moment before and the transitions possible for each state. The probability of making a transition to each state of the process depends only on the state presently occupied, the so-called Markovian property (Howard, 1971). Besides this a Markov chain has a finite number of states and a discrete time parameter (Hillier and Liebermann, 1980).

The distribution over states can be presented in a state vector **X**. A convenient notation for representing the transition probabilities is a transition matrix **P** with elements p_{ij}. In this, the transition probability p_{ij} refers to the probability that a process presently in state i will occupy state j after its next transition. The state vector at time n+1, $\mathbf{X}_{n+1}$, can be derived from the state vector at time n, $\mathbf{X}_n$, and the transition matrix **P**: $\mathbf{X}_{n+1} = \mathbf{P}\ \mathbf{X}_n = \mathbf{P}^n\ \mathbf{X}_0$. The initial state vector ($\mathbf{X}_0$) and the transition matrix **P** determine in fact the state vector at any subsequent moment. When all transition probabilities are stationary the distribution over the states will reach a limiting equilibrium distribution if the number of time steps is sufficiently large. When all states in the Markov chain are communicating, this equilibrium distribution is independent of the initial state vector. All states are said to communicate when each state can be reached from any other state in a finite number of steps. Instead of making a sufficiently large number of steps, a set of simultaneous equations can be solved to obtain the stationary state vector π ($\pi = \mathbf{P}\ \pi$ and $\Sigma_i \pi_i = 1$) (Howard, 1971).

The Markov chain approach is applied to herd dynamics. For this, the herd is described in terms of states animals can be in and the possible transitions between states and the corresponding probabilities. In this, input values concerning biological variables and management strategies are used. Next, the probability distribution over states at equilibrium is determined. For the obtained stationary herd structure the technical and economic results are calculated using additional input variables concerning performance and prices. Strategies involving modifications of certain input variables can be evaluated by comparing the herds at equilibrium. This procedure is illustrated in Figure 1. The Markov chain can also be used to study herd dynamics over time; for example, to study how a new equilibrium is reached when input variables, and thereby transition probabilities, are modified.

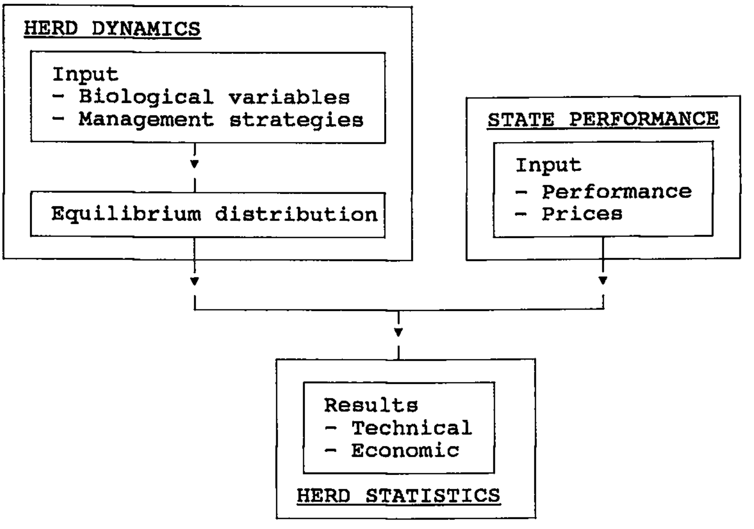

Figure 1. Overview of the modelling approach. Outcome of simulation of herd dynamics combined with state performance result in technical and economic results of the herd.

2.2 States

Choice of the number of states and the time interval between transitions involves a trade-off between complexity and precision, taking into account model objectives. In the presented model, transitions are made on a weekly basis, which closely connects to the pattern of weekly recurring activities in sow herds. States distinguished are related to the (re)production cycle of sows. In Figure 2 this cycle is represented schematically. Points at which decisions concerning reproduction and replacement should be taken are indicated: immediately after weaning, when sows do not conceive and replacement of culled sows by gilts.

A replacement gilt is bought at the age of 6 months and can stay in the herd until it is replaced or it has reached the maximum allowable litter. A cycle is defined as the period from weaning to weaning. The state variables used in the model to describe states sows can be in vary for different stages in the cycle. The relationship between state variable used and stage in the cycle is illustrated in Table 1. The number of inseminations per cycle varies between 1 and 4. Thus if a sow does not conceive from the fourth service, she will be replaced in any case. To cut down the number of states per cycle, the number of state variables used in the second part of the gestation period is reduced. Since information about these state variables is needed when generating results

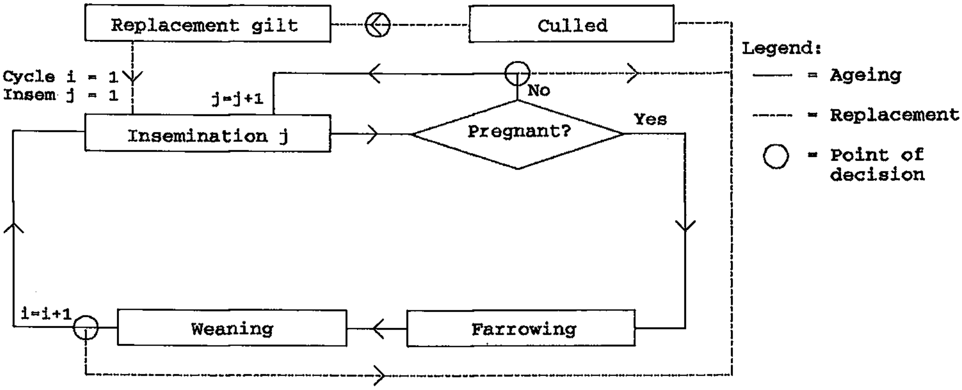

Figure 2. Schematic description of the (re)production cycle of sows. Points at which decisions concerning reproduction and replacement should be taken are marked. Only culling reasons related to these decisions are shown.

of the herd, it stays available for each remaining state as a weighted average of the original states. For some state variables the number of classes is fixed, as for suckling period (4 weeks) and gestation period (16 weeks). In other cases the number of classes depends on user-defined values (see Table 1). The maximum number of states per cycle is 156.

Furthermore, the state variable cycle number is used to represent sows of different ages, varying from 1 to 10. This leads to a maximum number of states of 10 * 156 = 1560. A gilt has cycle number 0 until the first insemination in life, when cycle 1 is started and the gilt becomes a sow. As the maximum number of cycles considered in the model is 10, all sows that have

Table 1. Possible values of the state variables used to describe states within a cycle of the sow (from weaning to weaning). State variables used are dependent on stage in cycle. Time unit in the model is 1 week.

Stage in cycle	State variables[a]					
	i[b]	j	k	l[b]	m[b]	n
Weaning - insemination	1-3					
Insemination - halfway gestation		0-6		1-4	1-12	
Halfway gestation - farrowing		7-16				0-1
Farrowing - weaning			1-4			

[a] The following state variables are used:
i : time after weaning;
j : time after insemination;
k : time after farrowing;
l : number of inseminations performed during this cycle;
m : interval weaning - insemination;
n : pregnant or not.
[b] Upper-limit number of classes depends on user-defined input values; given number is maximum.

produced 10 litters are replaced at the start of cycle 11. In this version of the model litter size of individual sows is only dependent on cycle number. However, production level of individual sows can also be considered, by adding two state variables: production level at last farrowing and production level at second last farrowing. Both state variables can vary from 4 to 16 pigs born alive. These state variables are chosen this way in order to be able to use the results concerning optimum culling decisions of individual sows generated by the dynamic programming model of Huirne et al. (1991). If production level of individual sows is taken into account, the maximum number of states in the model increases considerably (13 * 13 * 10 * 156 = 263640).

For gilts the state variable time after purchase is used to define the states from purchase till first insemination in life. The state variable time after weaning is used to define additional states for piglets after weaning till the end of the nursery period. These additional states are necessary to be able to determine results such as number of feeder pigs sold. Until weaning, litters are included in the states for lactating sows. At weaning the number of litters is converted into the number of piglets. The nursery period is assumed to last 7 weeks.

2.3 Transitions

For each state mentioned above, the probability of making the next transition to each other state has to be specified. Herd dynamics is a result of the interaction between biological variables and management strategies. Therefore, transition probabilities for all kinds of events are determined by these variables. Three categories of transition probabilities are considered in the model: (1) reproduction, (2) involuntary disposal and (3) production level. The given basic values for biological variables are assumed to represent typically Dutch herds. All values can easily be modified to suit different conditions.

Reproduction

Table 2 presents the basic values of the biological variables that determine transition probabilities concerning reproduction. The relationship between these biological factors and the transition probabilities itself is illustrated in Table 3. The length of the oestrus cycle is 3 weeks.

The distribution of first observable oestrus and oestrus detection rate before first insemination determine the probability of the first insemination in the different weeks after weaning. The first insemination will only be performed if the maximum allowable interval between weaning and first insemination is not

Table 2. Basic values of biological input variables that determine transition probabilities concerning reproduction.

Variable	Basic value	Code[a]
Distribution of first observable oestrus		(A)
week 1 after weaning	80	
week 2 after weaning	20	
week 3 after weaning	0	
Oestrus detection rate (%)		
before first insemination	98	(B)
after first insemination	90	(C)
Farrowing rate (within cycle) (%)		(D)
after insemination 1	85	
after insemination 2	65	
after insemination 3	50	
after insemination 4	40	
Distribution over "reasons" not conceiving		
in oestrus after 3 weeks	90	(E)
in oestrus after 6 weeks	0	(F)
abortion	7	(G)
not pregnant in farrowing house	3	(H)

[a] Code is used in Table 3 to refer to the biological variables.

exceeded. This maximum interval is an input value reflecting the management strategy under consideration, and can never exceed 3 weeks.

The variable farrowing rate determines if an insemination will result in a litter. If an insemination is not successful sows can come in oestrus after a certain period of time, abort or be still open at farrowing. The sows are distributed over these options according to specified probabilities (Table 2). In the model sows can come in oestrus at two moments, 3 and 6 weeks after an unsuccessful insemination. In case oestrus is detected, another insemination will be performed only if allowed by the management strategy. This is in fact

Table 3. Relationship between transition probabilities concerning reproduction and original biological variables.

Transition probability	Biological variable[a]							
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
Insemination 1 in week i after weaning	*	*						
Insemination j (j > 1), last one 3 weeks ago			*	*	*			
Insemination j (j > 1), last one 6 weeks ago			*	*	*	*		
Culling in week 11 after insemination because heat was not observed			*	*	*	*		
Abortion in week 11 after insemination				*			*	
Not pregnant in farrowing house				*				*

[a] Codes refer to overview of biological variables given in Table 2.

the number of inseminations allowed within a cycle. In the model this number is transformed into a maximum allowable interval from weaning to insemination, assuming reinseminations to be possible at intervals of 3 weeks. A maximum number of 1, 2, 3 or 4 inseminations allowed corresponds with a maximum interval from weaning to insemination of 3, 6, 9 or 12 weeks respectively. The number of inseminations allowed can be dependent on cycle number only, or also on production level of previous litters. If oestrus is not detected at 3 or 6 weeks after an unsuccessful insemination, sows are discovered still open and culled for that reason 11 weeks after insemination. Abortion takes place 11 weeks after insemination and these sows are culled immediately. At the time of - supposed - farrowing, sows are culled immediately when still open at that moment. If the management strategy does not allow insemination at all, sows are culled immediately after weaning.

Replacement gilts are inseminated at their second oestrus. In week 4 and week 5 after purchase, 80% and 20% of the gilts come into their first oestrus, respectively. All gilts are assumed to have their oestrus detected and are inseminated. From this point on gilts become sows and the transitions as described for sows are used.

Involuntary disposal

Disposal because of reproductive failure or insufficient production, which is controlled by management, is considered in the model. It is a function of the technical variables and management strategies, which can be specified by the user. Disposal due to other reasons, e.g. leg problems, diseases and accidents, and mortality of the sow, will be referred to as involuntary disposal.

Rate of involuntary disposal per cycle is given in Table 4. In the model, half of the involuntary disposal takes place at weaning, reflecting the disposal of animals that should have been culled in an earlier stage, but were kept to finish their current cycle and raise a litter. The other half takes place 7 weeks after weaning. The observed interval weaning to culling in that case corresponds to the value found by Dijkhuizen et al. (1989). In cycle 1 all involuntary disposal takes place 7 weeks after first insemination. In cycle 0, some of the gilts are removed because of bad legs and constitution immediately prior to insemination.

Production level

Production level of the individual sows at the last and second last farrowing are used as state variables. This provides the opportunity to take into account variation and repeatability in production. In the model, production level can vary from 4 to 16 pigs born alive. At farrowing the litter size of the new litter is determined and the transition to the corresponding state is made.

Table 4. Cycle-specific input values concerning transition probabilities and technical and economic results.

Cycle number	Involuntary disposal (%)	Pigs born alive	Piglet mortality (%)[a]	Live weight sow (kg)
0	10			140
1	2	9.6	13.0	140
2	8	10.3	12.0	160
3	8	10.8	13.0	175
4	7	11.1	13.0	188
5	9	11.2	14.0	196
6	11	11.1	14.0	200
7	13	11.0	14.0	200
8	15	10.9	15.0	200
9	17	10.8	15.0	200
10	18	10.7	15.0	200

[a] Piglet mortality rate before weaning; mortality rate after weaning: 1.5%.

The approach used in calculating the transition probabilities originates from Huirne et al. (1988). They used it in a stochastic dynamic programming model to determine the economic optimal replacement strategy in sow herds. The biological variables involved are cycle-specific mean litter size (Table 4), repeatability of litter size and the standard deviation. The expected litter size of a sow (pigs born alive) is based on both the cycle-specific mean litter size (see Table 4) and the expected deviation based on past piglet production of the sow. The latter effect is calculated using multiple regression from the litter size at the 2 previous farrowings of the sow, expressed as a deviation from the cycle-specific litter size in these cycles. The regression coefficients are calculated from the repeatability, which is assumed to be 0.20 between 2 successive farrowings and 0.15 with 1 farrowing in between. The probability of each litter size is then calculated from the expected litter size and the residual standard deviation using a normal distribution. The standard deviation is equal to 2.78 pigs born alive. The residual standard deviation equals 2.72 and 2.71 when litter sizes in 1 and 2 previous litters are known, respectively.

2.4 Actual Markov chain

The proposed states and transition probabilities lead to a transition matrix that contains a very large number of rows and columns, each of which contains only a couple of non-zero entries. This is a result of the structure of the modelled process: animals are ageing and only a few transitions are possible. The matrix approach does not utilize this quality. Therefore, the Markov chain is programmed to account for these typical characteristics, reducing the computational demand considerably. The model is programmed in the Turbo Pascal language (Borland, 1989), and is suitable to be run on a personal computer.

In the presented model, replacement animals are bought instead of raised at the farm, being the common system in commercial Dutch sow herds. Herd size is constant at any time, realized by immediate replacement of culled animals by gilts. Because of the chosen structure all states are communicating. Therefore the equilibrium distribution over states is independent of the initial state vector. The equilibrium distribution is in fact the distribution of a replacement gilt over all possible states in terms of relative numbers. A similar approach has been suggested by Baptist (1990) in a model to evaluate breeding objectives for tropical livestock. He refers to this approach as the actuarial method of modelling demographic issues in population analysis (Caughley, 1977).

In the presented model, all states within one cycle are seen as a separate unit. For all combinations of cycle number and production level such a unit is created. The states within a unit and the units themselves are organised in the state vector in such a way that the flow of animals due to ageing is in one direction. The only flow in the other direction is the replacement of a culled animal by a gilt. For each state the transitions possible are programmed into the model. After determining the distribution of a gilt over all states in terms of relative numbers, these stationary-state probabilities are recalculated to represent 130 sows and additional gilts, being the number of sows that represents one labour unit.

As well as looking at the herd structure in its stationary state, herd dynamics can be studied over time. This is only of interest when the distribution over states differs from the equilibrium distribution belonging to the input values. The model can be used to evaluate how this equilibrium is reached. The pattern from a certain equilibrium to a new equilibrium can be studied in case input values concerning biological variables or management strategies are modified. Another application is putting real animals into the states and studying the herd over time, approaching the stationary herd structure. The transitions from week to week are also determined not using the transition matrix approach. Each week the process of determining transitions is started at the "oldest state", weaning after the maximum allowable litter. The new contents of this state are derived from those states from which transitions can be made to this one. This is executed for all states upwards until the replacement gilt just purchased. The new contents of this state are equal to the number of culled animals in this week.

2.5 Technical and economic variables

To evaluate the consequences of changes in herd structure, several technical and economic variables are derived from the distribution over states. Some variables are derived directly from the state-distribution, such as number of litters per sow per year and percentage reinseminations. For other variables additional technical and economic variables are needed, as in the case of returns and costs.

Returns included in the model are the value of piglets sold and the slaughter value of culled sows and gilts. Costs included are the variable costs of replacement gilts and feed costs, as is the case in common Dutch record keeping systems. To calculate returns and costs information is needed on piglet production, slaughter value, feeding regime, prices of feed and price of purchased replacement gilts. The given values of these technical and economic variables are assumed to represent typical Dutch herds.

The market price of feeder pigs equals Dfl. 105 per pig sold at 23.5 kg of live weight (Table 5). Piglet mortality rate before weaning depends on cycle number (Table 4). Since the number of suckling piglets influences the ration of the lactating sows, it is assumed that 75% of pre-weaning mortality occurs at the end of the first week after birth. In the next weeks 15, 7 and 3% occurs, respectively. Piglet mortality rate after weaning is taken to be 1.5%. It is assumed that post-weaning mortality is equally distributed over the nursery period. Piglet production of a sow is dependent on cycle number and relative production level.

The amount of sow and pig feed consumed is derived using a standard ration with an average energy content (CVB, 1990). In Table 5 the energy content of the different feedstuffs is presented as energy value (EV) per kg of feedstuff. This energy value gives the amount of energy per kg of a feedstuff

Table 5. Economic input variables and their basic values.

Variable	Basic value
Feeder pig price (Dfl./head)	105
Feed price (Dfl./100 kg)	
gilts and non-lactating sows (EV/kg[a] = 0.97)	45
lactating sows (EV/kg = 1.03)	45
pigs	75
Slaughter value	
cycle 0	2.50
cycle 1	2.30
cycle 2 and higher	2.20
Price replacement gilts (Dfl./head)	500

[a] EV/kg = 1 = 8786 kJ net-energy for fat production.

to be retained at maximum by pigs in case of fat production (1 EV/kg = 8786 kJ/kg). The amount of feed consumed is expressed as energy value intake. Replacement gilts consume 2.6 EV per day. Daily feed consumption of pregnant sows depends on the stage in gestation, from the start to week 8 after insemination 2.3 EV per day, from week 9 to week 12 2.7 per day and from week 13 to the end 3.2 EV per day. The daily amount for lactating sows equals 2.0 EV per day and additionally 0.5 EV per piglet. In the first week after weaning the ration is 3.5 EV per day and in the next weeks 2.3 EV per day. Piglets up to feeder pig weight (23.5 kg live weight) consume in total 30 kg of feed. The prices of the different feedstuffs are presented in Table 5. For culled animals it is assumed that they are culled at the end of the week and their feed consumption until that moment is taken into account.

Live weight and corresponding slaughter value of sows increase with cycle number. The price per kg live weight for replacement gilts is Dfl. 2.50, for young sows Dfl. 2.30 and Dfl. 2.20 for old sows (Table 5). Additional financial loss associated with involuntary disposal is built into the model to account for losses such as decreased slaughter value and death. The basic value is Dfl. 25 per sow culled because of involuntary disposal.

The purchase price of a replacement gilt is assumed to equal Dfl. 500 at an age of 180 days.

3 MODEL BEHAVIOUR

The number of states to consider in the model is optional, making it possible to provide either aggregated or detailed simulations. Including the production level of individual sows, in particular, results in considerable expansion of the model. In this first analysis, model behaviour is presented with a version in which there is no variation in production, other than due to differences in cycle number.

3.1 Description basic situation and sensitivity analysis design

At first, model behaviour is studied by evaluating a basic situation, representing typically Dutch herds. The biological variables that influence herd dynamics are presented in Tables 2 and 4. The management strategies involved are a maximum allowable interval between weaning and first insemination of 3 weeks and a maximum number of inseminations per cycle number as given in Table 6.

Table 6. Number of inseminations allowed per cycle number.

Cycle number	1	2	3	4	5	6	7	8	9	10
Number of inseminations	2	3	3	3	3	2	2	1	1	1

Besides the evaluation of the basic situation, a sensitivity analysis is carried out to gain insight into the impact of various input values. In this case the effects of changes in major biological, production and price variables on the stationary herd structure are analyzed. In Table 7 the variables are mentioned for which this analysis is made. Most alternative values are at a 20% higher and a 20% lower level than the basic values. Only one variable is modified at a time, while for other variables the basic values are used.

Furthermore, the herd dynamics over time going from the equilibrium in the basic situation to the equilibrium of an alternative situation will be studied. After creating the equilibrium distribution for the basic situation, the input values concerning farrowing rate are set at 100%. Subsequently the transition probabilities concerning reproduction are recalculated and used to determine the herd dynamics over time, approaching the new equilibrium distribution.

3.2 Results: basic situation

The technical and economic results of the herd are derived from the stationary herd structure and converted to an annual basis. Technical and economic results for the basic situation are presented in Table 8. In the stationary state, 130 sows and 9.8 gilts are present in the herd. Per sow 2.32 litters are

Table 7. Production and price variables used in the sensitivity analysis; basic and alternative values.

Variable	Low	Basic	High
Farrowing rate (%)[a]	68/52/40/32	85/65/50/40	100/-/-/-
Oestrus detection rate (%)			
before first insemination	78.4	98	100
after first insemination	72	90	100
Involuntary disposal	-20%	[b]	+20%
Litter size (pigs born alive)	-20%	[b]	+20%
Price replacement gilt (Dfl.)	400	500	600
Feeder pig price (Dfl.)	84	105	126
Slaughter value (Dfl./kg)[c]	2.00/1.84/1.76	2.50/2.30/2.20	3.00/2.76/2.64

[a] Farrowing rate for 1st, 2nd, 3rd, and 4th insemination, respectively.
[b] Basic values are summarized in Table 4.
[c] Slaughter value per kg live weight for cycle, 0, 1, and ≥ 2 respectively.

produced per year. The average number of pigs born alive per litter is 10.6, with 21.0 piglets sold per sow per year. The annual culling rate is 49.4%, of which 43.1% for reproductive reasons. The returns and variable costs result in a gross margin per sow per year of Dfl. 1078.

Model behaviour is compared with results from real farms. Herd performances obtained at 615 farms during the period June 1989-July 1990 which use a common management information system are given in Table 8 (CBK, 1990). The simulated results agree closely with these results. Dijkhuizen et al. (1989) analyzed sow culling data of 1617 sows culled during 1985 and 1986 on 12 farms using the VAMPP herd health and management information system.

Table 8. General results of sow herd in the stationary state belonging to the basic situation and comparison with results from other sources.

Variable	Model	CBK[a]	VAMPP[b]
Technical results			
Average number of sows	130.0	154	145
Average number of gilts	9.8		
Litters per sow per year	2.32	2.23	2.22
Pigs sold per sow per year	21.0	20.4	20.2
Pigs weaned per sow per year	21.3	20.7	
Pigs born alive per litter	10.6	10.6	10.3
Pigs weaned per litter	9.2	9.4	9.1
Pre-weaning mortality rate	13.3	12.5	12.0
Mortality rate after weaning	1.5	1.9	
Culling rate sows	49.3	48	50
Non-productive sow-days per culled sow	38	46	40
Weaning - first insemination interval	8.4	7.6	
Farrowing interval	151	157	
Percent reinseminations	11.5	11	
Percent replacement gilts	49.3	52	
Percent litters from cycle 1	19.4	21	
Distribution over culling reasons			
Old age	11.1		11.0
Reproduction	43.1		34.2
no heat	8.7		9.0
repeat insemination	23.5		25.0
abortion/open at farrowing	10.9		
Others	45.8		48.6
Insufficient production	0		6.2
Economic results (Dfl. per sow per year)			
Returns sold piglets	2204		
Returns culled sows and gilts	216		
Costs replacement gilt	274		
Feed costs sow	591		
Feed costs pigs	476		
Gross margin	1078		

[a] 615 farms using CBK (CBK, 1990).
[b] 12 farms using VAMPP (Dijkhuizen et al., 1989).

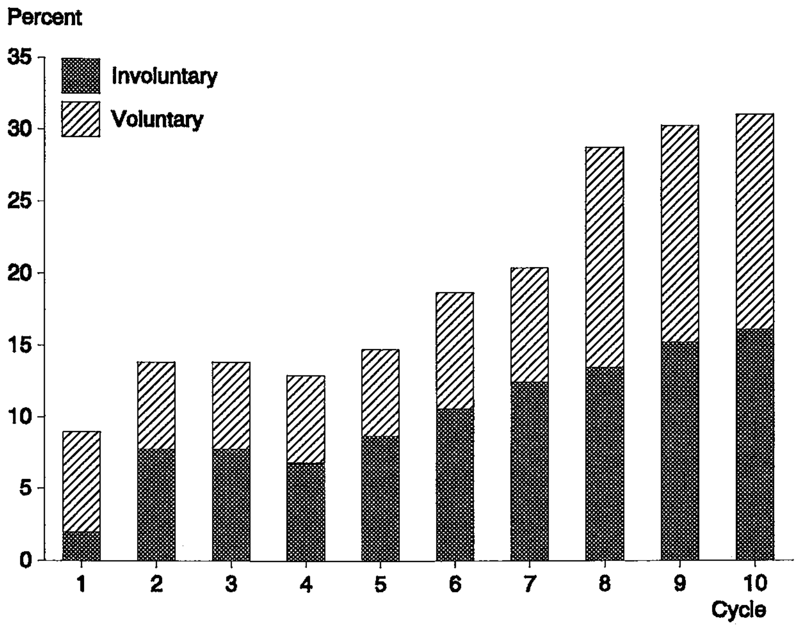

Figure 3. Voluntary and involuntary culling rates per cycle number (basic situation at equilibrium).

Some results are given in Table 8. The distribution over culling reasons in the model agrees closely with results from the analysis of Dijkhuizen et al. (1989).

The voluntary and involuntary culling rates are outlined in Figure 3. The values are calculated using the age structure of culled sows and their distribution over culling reasons per cycle. Since the maximum allowable farrowing interval is reduced when the cycle number rises, the voluntary culling rate increases with cycle number. Since all sows in cycle 11 are culled immediately after weaning, culling rate is 1 in that case.

3.3 Results: sensitivity analysis

The influences of changes in various factors are summarised in Table 9. The most relevant variables are presented.

When farrowing rates are reduced, the annual culling rate in the herd increases, since more sows are culled for reproductive reasons. Culling rate is

Table 9. Results of the sow herd in its stationary state when variables vary according to Table 7. Values are presented as the difference from the basic situation (alternative minus basic).

	Litters pspy		Pigs sold pspy		Culling rate		Gross margin	
Basic situation	2.32		21.0		49.3		1158	
Alternatives[a]	low	high	low	high	low	high	low	high
Farrowing rate	-0.148	+0.098	-1.5	+1.0	+19.9	-9.9	-159	+94
Oestrus detection rate								
before first ins.	-0.049	+0.005	-0.8	+0.1	+32.1	-2.8	-132	+12
after first ins.	-0.015	+0.006	-0.2	+0.1	+2.4	-1.1	-17	+7
Involuntary disposal	+0.006	-0.006	+0.1	-0.1	-2.8	+2.9	+13	-13
Litter size	0	0	-4.2	+4.2	0	0	-319	+319
Price replacement gilt	0	0	0	0	0	0	+54	-54
Feeder pig price	0	0	0	0	0	0	-441	+441
Slaughter value	0	0	0	0	0	0	-44	+44

[a] Most alternatives concern input value(s) at a 20% lower (low) or 20% higher (high) level than the input values in the basic situation.

very high when oestrus detection rate before first insemination is reduced, since in the model this factor determines directly the number of sows that are culled because of showing no heat. The economic relevance of oestrus detection rate after first insemination is rather low, since it affects only a fraction of the sows; those that do not conceive after first insemination and will come in oestrus again.

Input values concerning prices and herd performance, such as litter size, do not influence transition probabilities, and therefore do not influence herd dynamics as such. Naturally, returns and costs are influenced by changes in these variables. Changes in litter size and piglet price have a large effect on gross margin per sow per year. Changes in costs of replacement gilts and slaughter value of culled sows and gilts have a much smaller effect on gross margin. This is consistent with results found by Huirne et al. (1988; 1991).

3.4 Results: herd dynamics over time

Figure 4 presents the average results from year 0 (basic situation) to year 20 of the strategy (i.e. farrowing rate is 100%) for culling rate of sows, number of litters per sow per year and margin per sow per year. Results are presented as deviations in terms of percentage from the results of the strategy's herd structure at equilibrium. The absolute values belonging to both equilibrium situations can be found in Table 9. It is obvious from Figure 4 that it takes

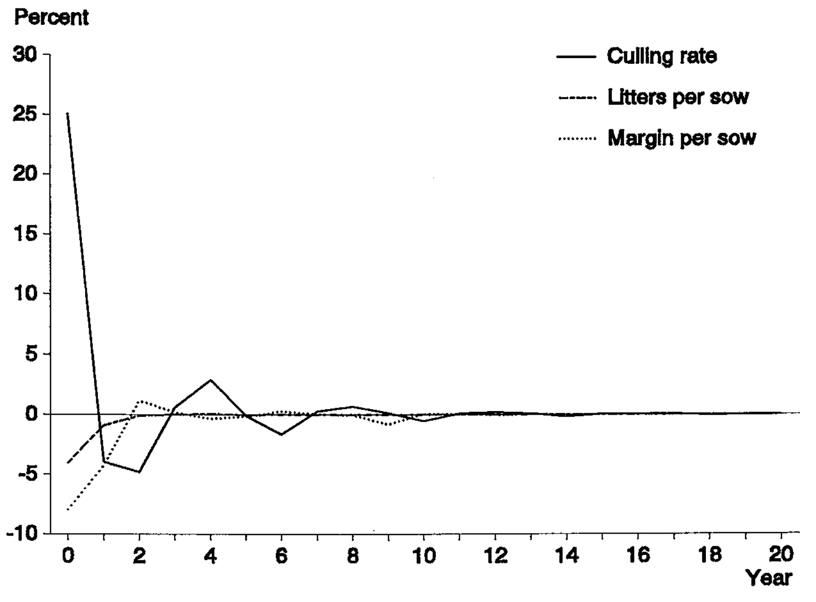

Figure 4. Results of the strategy from year 0 to year 20. Presented as the difference in terms of percentage from the results belonging to the strategy at equilibrium. Results of the strategy at equilibrium are set on 0.

some time to reach the new equilibrium distribution. The number of litters per sow per year is at equilibrium within a few years (differences within .05% from year 3 on). For the culling rate of sows it takes more years to reach equilibrium. Because of the time lag between purchase and first insemination of gilts, it takes time before the number of gilts that become sows (at first insemination in life) each week corresponds with the number of sows culled from the herd. The total number of sows and gilts in the herd is constant over time. Due to the reduction in culling rate, more sows (+1.85) and fewer gilts (-1.85) are present in the herd at the equilibrium belonging to the strategy. In the sensitivity analysis presented before, the number of sows is constant, but the number of gilts is not. Therefore, if sows and gilts are competitors for the available places, a comparison of gross margin per place would be more appropriate.

In Figure 5 it is shown how the distribution of gilts and sows over cycle numbers approaches the new equilibrium. Sows are kept longer than before, because of the increase in farrowing rate. From figure 5 it is obvious that these animals gradually move on to cycle 10.

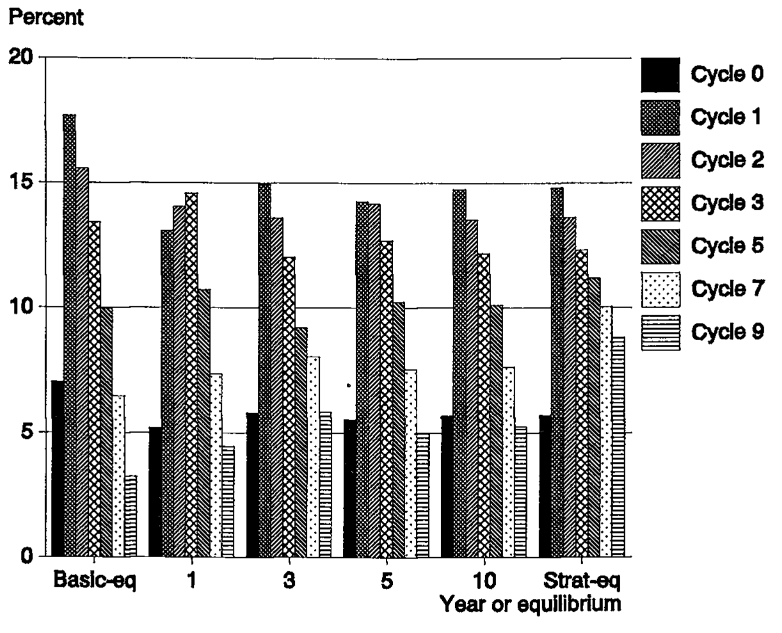

Figure 5. Distribution of animals over cycle numbers for (a) basic situation at equilibrium, (b) various years of strategy and (c) strategy at equilibrium.

4 DISCUSSION

The Markov chain approach has been shown to be useful in simulating herd dynamics. It enables easy modification of farm-specific input values that influence herd dynamics and its performance. Comparison of the results of herds at equilibrium is a good method for the evaluation of management strategies. Sensitivity analysis can be carried out to estimate the consequences of variation in farm-specific input values on herd dynamics and overall performance. The study of herd dynamics over time creates the possibility to gain insight into how an equilibrium is reached over time. This provides insight into possible extra costs or returns involved, since an equilibrium is never reached immediately. Compared to Monte Carlo simulation the Markov chain approach requires less computing time. When using Monte Carlo simulation, replicate calculations are required, providing insight into the variation present in the results. A model using the Markov chain approach will only provide the average results.

The property to create easily the stationary state of the herd structure originates from two assumptions in the model: (1) stationary transition probabilities and (2) constant herd size, realized by replacing culled sows immediately by gilts. The second assumption is not entirely in accordance to reality in sow herds. In reality culled sows are replaced by replacement gilts that have been purchased in batches. In that way, the farmer tries to maintain the size of the herd. Since the model has the same aim, it is very useful in comparing strategies despite no purchase of gilts in batches. The model, however, could be modified in this respect. The calculation of the equilibrium distribution over states has to be adapted, which cannot be done in a simple manner. This revised model can be used to evaluate management strategies concerning the purchase of gilts.

The objective of the model is to determine the technical and economic consequences of decisions concerning reproduction and replacement. The choice of the time unit of 1 week and the state variables reflect this objective. When studying management decisions influencing the interval from weaning to first insemination, a time unit of 1 day is more appropriate. However, converting the whole model to a time unit of 1 day would be excessive regarding other decisions to evaluate, and the number of states and thereby computer time would increase considerably. The present model can be used to study globally the variation in length of the interval from weaning to first insemination.

In the future, the model will be used to evaluate in more detail various management strategies concerning reproduction and replacement decisions, taking into account the production level of individual sows. As stated before, the number of states to consider in the model is optional, making it possible to provide either aggregated or detailed simulations. The presented modelling approach is not specific for swine, but can also be used to model herd dynamics of other species, such as dairy cattle and sheep.

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Chapter 3

An economic comparison of management strategies on reproduction and replacement in sow herds using a dynamic probabilistic model

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ABSTRACT

A dynamic probabilistic PC-model is used to compare six management strategies on reproduction and replacement in sow herds. The model uses the Markov chain approach to simulate herd dynamics, and derives from that technical and economic results of the herd. Under the studied circumstances, strategies based on the use of an economic culling index (I and II), including age and productive history of individual sows, are the best. In the basic situation annual culling rate (CR) amounts 47.4% and gross margin per sow per year (GM) Dfl. 1086. Economic differences between strategies depend mainly on realised differences in CR. Strategies that refer to guidelines given by extension service lead to an increase in CR (plus 5-6%) and a decrease in GM (minus Dfl. 15). The most strict strategy (no reinseminations) achieved the highest CR (+24.5%) and the lowest GM (minus Dfl. 62). A very liberal strategy, allowing in all cases 4 inseminations, resulted in almost the same results as strategy I and II. In case of low farrowing rates, low slaughter values or high prices of replacement gilts, differences between strategy I and II and more strict strategies increase. The model used is considered a useful tool in on-farm decision support, as an expansion of current management information systems. It allows for input modification, making it possible to study easily sensitivity for price and production circumstances.

1 INTRODUCTION

The average annual culling rate in commercial sow herds varies between 35 and 50% (Dagorn and Aumaitre, 1979; Kroes and Van Male, 1979; Dijkhuizen et al., 1989; D'Allaire et al., 1989; Stein et al., 1990; Ridgeon, 1991). Insufficient productive and reproductive performance account for more than half of the annual replacements. The decision to cull a sow because of these two reasons is usually based on economic considerations. A sow is replaced not because she is no longer able to produce in a biological sense, but because a replacement gilt is expected to yield more (Dijkhuizen et al., 1986). Economic calculations show a considerable increase in income if culling rates can be reduced (Bisperink, 1979; Kroes and Van Male, 1979; Dijkhuizen et al., 1986). The benefits of improved herd life are especially dependent on the replacement cost, which is the difference in price between replacement gilts and culled sows (Dijkhuizen et al., 1986; Huirne et al., 1991). A thorough consideration of this type of decisions is therefore important, and the more so since these decisions have to be made under varying production and price circumstances.

Current advice concerning decisions on reproduction and replacement usually involves general rules, which originate from experienced advisors (e.g. Ministerie van LNV, 1989) or from simple model calculations (e.g. Bisperink, 1979; Kroes and Van Male, 1979). Some of the available management information systems for sow herds allow for more detailed and farm-specific strategies on reproduction and replacement. However, the user does not yet have a tool to calculate and compare the technical and economic consequences of alternative strategies. This tool can be provided by combining the available management information systems with computer simulation (Jalvingh, 1992). In literature, various stochastic simulation models focusing on reproduction and replacement in swine can be found (Allen and Stewart, 1983; Marsh, 1986; Singh, 1986; Pettigrew et al., 1987; Houben et al., 1990; Pomar et al., 1991). Jalvingh et al. (1992) developed a dynamic probabilistic model to evaluate the consequences of decisions on reproduction and replacement in swine. In this model a Markov chain approach is used to calculate the expectation of technical and economic results. In this model, unlike in most other models, no replicated simulations are needed, which improves acceptability of the model when used in on-farm decision support (Dent and Blackie, 1979).

In this paper, the model of Jalvingh et al. (1992) will be used to compare different management strategies on reproduction and replacement. General rules will be compared to more detailed management guides, recently developed to economically optimize replacement and insemination decisions for individual sows within the herd (Huirne et al., 1991). Sensitivity analysis will be carried out to study the validity of the comparison when technical and economic parameters have changed. In this way, insight can be obtained into the potential benefits of using this type of simulation models in on-farm decision support.

2 MATERIAL AND METHODS

2.1 Model description

The dynamic probabilistic model of Jalvingh et al. (1992) focuses on evaluating the technical and economic consequences of decisions concerning reproduction and replacement. In the model, the Markov chain approach is used to simulate herd dynamics, and to derive from that the technical and economic results of the herd. The model can be used to calculate stationary state

Table 1. Basic input values concerning herd dynamics (biological variables), herd performance and prices[a].

Variable	Basic value
Distribution of first observable oestrus (%)	
week 1 after weaning	80
week 2 after weaning	20
week 3 after weaning	0
Oestrus detection rate (%)	
before first insemination	98
after first insemination	90
Farrowing rate (%)	
after insemination 1	85
after insemination 2	65
after insemination 3	50
after insemination 4	40
Piglet mortality rate after weaning (%)[b]	1.5
Repeatability of litter size	
two consecutive litters	0.20
one litter in between	0.15
Feeder pig price (Dfl.)[b]	105
Feed price (Dfl./100 kg)[b,c]	
gilts and sows	45
pigs	75
Slaughter value (Dfl./kg)[b]	
cycle 0	2.50
cycle 1	2.30
cycle 2 and higher	2.20
Price replacement gilt (Dfl.)[b]	500

[a] Basic input values represent typical Dutch herds.
[b] Input values concerning herd performance; these input values do not influence herd dynamics.
[c] The amount of sow and pig feed consumed is derived using a standard ration with an average energy content.

conditions in number of animals in each stage of the life cycle (i.e. equilibrium distribution over states), providing a solid base for comparing the technical and economic consequences of different management strategies.

The Markov chain approach requires the herd to be broken down into states animals can be in and the specification for each state of possible transitions and corresponding probabilities (Hillier and Lieberman, 1980). In the model transitions are made on a weekly basis. States are related to the (re)production cycle of individual sows in commercial herds. The transition probabilities are dependent on input values concerning biological variables such as farrowing rate, and on management strategies. These strategies include decisions on culling for production and reproduction (i.e. when to stop insemination). The number of states in the model is flexible, creating the possibility of detailed

Table 2. Cycle specific basic input values[a].

Cycle number	Involuntary disposal (%)	Pigs born alive[b]	Piglet mortality (%)[c,d]	Live weight sow (kg)[c]
0	10			140
1	2	9.6	13	140
2	8	10.3	12	160
3	8	10.8	13	175
4	7	11.1	13	188
5	9	11.2	14	196
6	11	11.1	14	200
7	13	11.0	14	200
8	15	10.9	15	200
9	17	10.8	15	200
10	18	10.7	15	200

[a] Basic input values represent typical Dutch herds.
[b] Cycle-specific litter size. Standard deviation: 2.78.
[c] Input values concerning herd performance; these input values do not influence herd dynamics.
[d] Piglet mortality rate before weaning; mortality rate after weaning: 1.5%.

simulation and aggregated simulation of the decision environment. In comparing management strategies in this paper the most extended version of the model is used, including 10 cycles, 13 classes of production level (4-16 pigs born alive) at last and second last farrowing. Strategies are compared for a herd with a constant number of sows (130), which is realized by immediate replacement of culled sows by gilts.

Some results can be derived directly from the distribution over states, such as the number of litters per sow per year. For other results, such as returns and costs, the distribution over states has to be combined with herd performance parameters, such as feed intake, and with prices. Returns included in the model are the value of piglets sold and the slaughter value of culled sows and gilts. Variable costs included are feed costs and the costs of replacement gilts.

Major input values concerning herd dynamics, herd performance and prices are given in Table 1 and Table 2. The given values are assumed to represent typical Dutch herds, but can be modified to represent other conditions. More detailed information on the structure of the model and its input is described elsewhere (Jalvingh et al., 1992).

2.2 Management strategies on reproduction and replacement

Six management strategies on reproduction and replacement with potential practical application will be compared. These management strategies, referred

Table 3. Strategy I: Optimal replacement. Number of inseminations allowed for sows with cycle number 4. Dependent on production level (PL) at last and second last farrowing.

PL second last farrowing	PL last farrowing					
	4[a]	5	6	7	8	9-16
4-5[a]	1[b]	2	2	3	3	4
6-7	2	2	3	3	4	4
8-10	2	3	3	4	4	4
11-12	3	3	4	4	4	4
13-14	3	4	4	4	4	4
15-16	4	4	4	4	4	4

[a] Number of pigs born alive.
[b] Number of inseminations allowed.

to as insemination strategies, vary in the way factors such as the sows' age and productive history are taken into account. The corresponding equilibrium distribution over states is used to compare the strategies. In creating this equilibrium the input values of the basic situation given in Table 1 and Table 2 are used.

In this paper an insemination strategy is represented by the maximum permissible number of inseminations within a cycle, which can vary from 0 to 4. In the model this number is transformed into a maximum permissible interval between weaning and insemination, assuming reinseminations to be possible at intervals of 3 weeks. This means that a maximum of 1, 2, 3 and 4 inseminations corresponds with a maximum permissible interval from weaning to insemination of 3, 6, 9 and 12 weeks respectively. If no inseminations are allowed, sows are culled immediately after weaning.

Strategy I: Optimal replacement

The optimal replacement strategy uses a management guide, the so-called Retention Pay-Off index (RPO-value), to determine the maximum number of inseminations allowed for each combination of cycle number, production level at last farrowing and production level at second last farrowing. The RPO-value equals the total extra profit to be expected from attempting to retain an individual sow for her optimal lifespan and not replacing her immediately. So, when the RPO-value of an individual sow falls below zero the (re-)insemination should not be carried out. The RPO-values are calculated for the default input values given in Table 1 and Table 2, using the stochastic dynamic programming model of Huirne et al. (1991), and transformed into the maximum permissable number of inseminations for single sow conditions. The outcome for cycle number 4 is illustrated in Table 3.

Table 4. Strategy II: Modified optimal replacement. Per insemination number the required minimum production level at last farrowing to allow this insemination.

Cycle	Insemination number			
	1	2	3	4
1	-[a]	-	-	-
2	-	-	-	-
3	-	-	-	-
4	-	-	5[b]	7
5	-	5	7	9
6	5	7	9	11
7	6	8	11	13
8	8	10	12	15
9	9	11	14	16
10	10	13	16	X[c]

[a] No minimum production level required.
[b] Required minimum production level at last farrowing, expressed as number of pigs born alive.
[c] This insemination number is in no case allowed.

Strategy II: Modified optimal replacement

This strategy is a simplified version of the previous one. The amount of information used in making insemination and culling decisions is reduced. Production level at second last farrowing is no longer taken into account, but assumed to be equal to the cycle-specific average litter size. The required minimum production level at last farrowing to allow a certain insemination for sows in the various cycle numbers is presented in Table 4.

Strategy III: Extension advice

An example of a strategy based on general rules, so-called rules of thumb, is the advice given by the extension service in the Netherlands (Ministerie van LNV, 1989). The given guidelines for selection of sows are based on the expertise of senior advisors. The guidelines given vary greatly with the cycle number of the sow. The guidelines can be taken into account in the model, with some minor adaptations. This results in a scheme as presented in Table 5. Production level at last and second last farrowing is only taken into account in the decision whether or not to inseminate and keep a sow after weaning. If a sow fails to conceive only age is considered in the decision to reinseminate the sow.

Strategy IV: Modified extension advice

This strategy is a modified version of the previous strategy. Production level is no longer taken into account in the decision whether or not to inseminate

Table 5. Strategy III and IV: Extension advice and modified extension advice (after Ministerie van LNV, 1989). Per cycle number is presented: (a) number of inseminations allowed, and (b) required minimum production level (PL) at last and second last farrowing to allow first insemination after weaning. Requirements concerning production level are not applicable to strategy IV.

Cycle number	Number of inseminations	Required minimum PL at both farrowings to allow first insemination	
		PL last farrowing	PL second last farrowing
1	2	-[a]	-
2	2	-	-
3	2	5	5
4	2	6	6
5-7	2	8	8
8-10	1	8	8
		or: 6	-

[a] No minimum production level required.

and keep the sow after weaning. The number of inseminations allowed is dependent only on the age of the sow. Comparison of the results of strategies III and IV will provide insight into the importance of culling under-productive sows immediately after weaning.

Strategy V: Very strict and Strategy VI: Very liberal

In these strategies the maximum permissible interval from weaning to insemination is independent of age and production level. In strategy V in all cases only one insemination is allowed, resulting in an interval from weaning to insemination which does not exceed 3 weeks. In strategy VI reinsemination is allowed up to the maximum value of this interval possible in the model (12 weeks), which corresponds with a maximum of 4 inseminations. These two strategies are rather extreme, and are included for reasons of comparison.

2.3 Sensitivity analysis

A sensitivity analysis will be carried out to gain insight into influences of changes of some input values on the technical and economic results of the strategies. Changes in input values may influence the ranking of the different strategies or the differences among the strategies. Insight into these influences is important, since in reality price and production circumstances vary across farms and years. Table 6 shows the alternatives which will be studied. In most alternatives 20% higher and 20% lower values compared to the basic situation

Table 6. Production and price variables used in the sensitivity analysis.

Variable	Low	Basic	High
Farrowing rate (%)[a]	68/52/40/32	85/65/50/40	100/-/-/-
Litter size (pigs born alive)	-20%	b	+20%
Price replacement gilt (Dfl.)	400	500	600
Feeder pig price (Dfl.)	84	105	126
Slaughter value (Dfl./kg)	2.00/1.84/1.76	2.50/2.30/2.20	3.00/2.76/2.64
Repeatability of litter size[c]	0.00/0.00	0.20/0.15	0.40/0.30

[a] Farrowing rate for 1st, 2nd, 3rd, and 4th insemination, respectively.
[b] Basic values per cycle number are summarized in Table 2.
[c] Repeatability between to successive litters and one litter in between, respectively.

are used. In the case of strategies I and II, for each alternative the corresponding optimal replacement strategy is re-calculated using the model of Huirne et al. (1991). Per alternative only one input variable is modified, while for other variables the basic values are used.

3 RESULTS

3.1 Basic situation

Herd structure at equilibrium and the corresponding technical and economic results are calculated for the different strategies. In Table 7 the major technical and economic results are presented.

Culling rate varies from 44.3% (VI: Very liberal) to 71.9% (V: Very strict). This variation in culling rate is directly related to the strictness of the insemination strategy. For young sows especially, extension advice (strategy III/IV) is more strict than when the RPO-value is used (strategy I/II), resulting in a 5-6% higher culling rate. In Figure 1 the distribution of the culled sows over major culling reasons is given for all strategies. The proportion for insufficient litter size refers to the sows culled immediately after weaning. This proportion is therefore zero in strategies IV, V and VI. Sows which are not reinseminated after a failure to conceive are included in the reason reproduction. Differences in culling rate and distribution over culling reasons between strategies I and II are very small (Figure 1). The rules concerning production level for selection after weaning in strategy III apply only to a small fraction of the sows, since the difference in culling rate with strategy IV is small (1.1%). The difference in culling rate between strategy I and VI amounts only 3.1%. Evidently, for the majority of the sows the decisions taken are the same.

Table 7. Major technical and economic results of the different insemination strategies. The economic results of strategy II till VI are presented as the difference from strategy I.

Variable	Insemination strategy					
	I[a]	II	III	IV	V	VI
Technical results						
Average number of sows	130.0	130.0	130.0	130.0	130.0	130.0
Average number of gilts	9.5	9.4	10.7	10.5	14.3	8.8
Litters per sow per year	2.31	2.31	2.32	2.32	2.34	2.31
Pigs sold per sow per year	21.0	21.0	21.0	21.0	21.0	20.9
Pigs weaned per sow per year	21.3	21.3	21.3	21.3	21.3	21.2
Pigs born alive per litter	10.6	10.6	10.6	10.6	10.5	10.6
Pre-weaning mortality rate (%)	13.3	13.3	13.3	13.3	13.2	13.4
Mortality rate after weaning (%)	1.5	1.5	1.5	1.5	1.5	1.5
Interval weaning-1st insemination (days)	8.4	8.4	8.4	8.4	8.4	8.4
Farrowing interval (days)	151	151	150	150	148	152
Culling rate sows (%)	47.4	47.1	53.6	52.5	71.9	44.3
Non-productive sow days per culled sow	37	37	37	38	32	39
Percent litters from cycle 1	19.3	19.2	21.0	20.6	25.6	18.1
Percent reinseminations	14.7	14.7	9.8	9.7	0	15.7
Economic results (Dfl. per sow per year)						
Returns sold pigs	2206	-1	0	-3	-6	-11
Returns culled sows and gilts	209	-1	+24	+20	+95	-14
Cost replacement gilts	263	-2	+34	+29	+136	-17
Feed costs sow	590	0	+4	+3	+16	-3
Feed costs pigs	477	0	0	-1	-1	-2
Gross margin	1086	0	-15	-15	-62	-3
Gross margin farm	141124	-51	-1939	-1971	-8009	-320

[a] Numbers refer to insemination strategy; I: Optimal replacement, II: Modified optimal replacement, III: Extension advice, IV: Modified extension advice, V: Very strict and VI: Very liberal.

The number of pigs sold per sow per year varies slightly between the strategies; from 20.9 (VI) to 21.0 (other strategies). The number of pigs sold per sow per year is dependent on the number of pigs born alive per litter and the number of litters per sow per year. Differences in these two variables are small. Figure 2 shows for all strategies the number of piglets born alive per litter for sows of different ages. Selection of sows based on their productive ability, as in strategies I, II and III, leads to a higher number of piglets born alive per litter for older sows. Since this increase mainly concerns older sows, of which only a few are available in the herd, the effect on the average herd productivity is limited. The number of litters per sow per year is influenced by farrowing interval and number of non-productive days of culled sows, being the interval from weaning to culling. In this paper higher culling rates correspond with a more strict insemination strategy, resulting in a reduction in farrowing interval and non-productive days of culled sows (Table 7). Therefore, the number of litters per sow per year varies only from 2.31 (VI) to 2.34 (V).

Strategy I has the highest gross margin per sow per year (Dfl. 1086) (Table 7). Compared to strategy I, reduction in gross margin varies from Dfl. 0 (II)

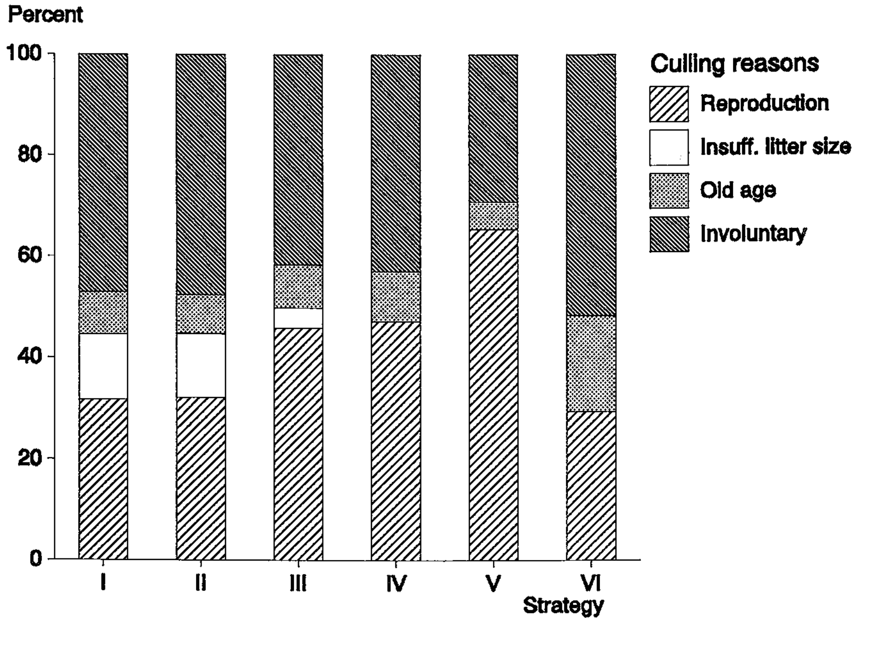

Figure 1. Distribution of culled sows over major culling reasons for the different insemination strategies.

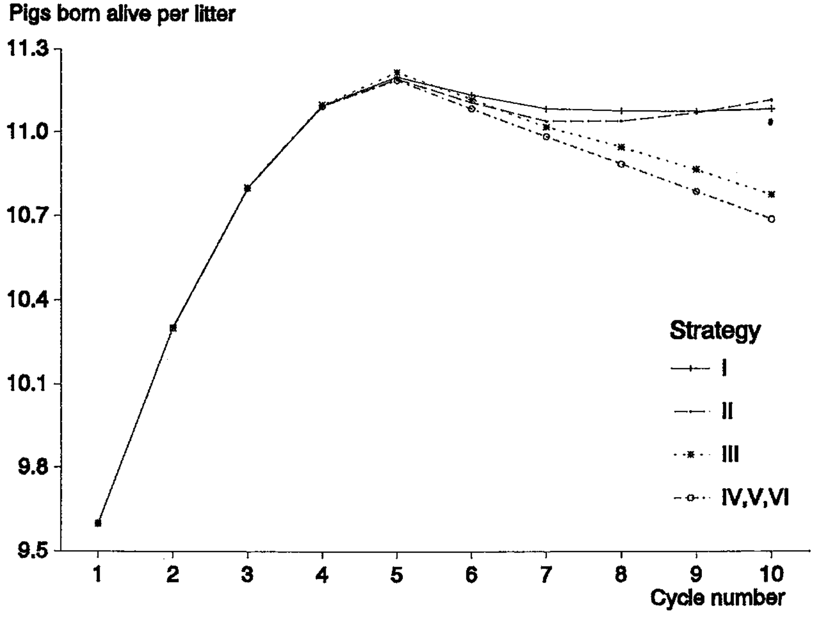

Figure 2. Per insemination strategy the average number of pigs born alive per litter for the different cycle numbers.

to Dfl. 62 (V) per sow per year. The strategies especially influence the economic results of the herd by the item costs of replacement gilts and returns of culled animals, which results from the observed variation in culling rate. Since the purchase price of a replacement gilt is higher than the slaughter value of a culled sow (approximately Dfl. 100), a higher culling rate results in a lower gross margin per sow per year. Although strategy VI has a lower culling rate than strategy I, the gross margin is lower due to a decrease in pigs sold per sow per year. Differences in gross margin per sow per year between strategies I and VI are small, however.

3.2 Sensitivity analysis

For all combinations of insemination strategy and modified input values, the most relevant results are presented in Table 8: the number of pigs sold per sow per year, the annual culling rate of sows and gross margin per sow per year. The description of these results is divided into two parts. First, the factors that influence the results for strategy I are described. After that, the ranking of the strategies and the size of the differences between strategies will be reported for the different factors.

Strategy I

All the alternatives have an effect on the optimal replacement strategy (I) calculated by the model of Huirne et al. (1991) and as a consequence on the distribution at equilibrium over states in the model of Jalvingh et al. (1992). Therefore, the number of pigs sold per sow per year, annual culling rate and gross margin per sow per year differ between alternatives, but the size of the differences depends on the input factor that has been changed (Table 8).

A reduction in farrowing rate results in a higher culling rate, as could be expected. Since it takes more time to achieve sow pregnancy, the farrowing interval increases (+4 days) as well as the number of non-productive days of culled sows (+22). Therefore, the number of litters produced per sow per year decreases from 2.31 to 2.15, resulting in a reduction in the number of pigs sold per sow per year (1.6). An increase in farrowing rate results in a decrease in culling rate and an increase per sow per year in the number of pigs sold and gross margin.

When the average litter size is changed the number of pigs sold per sow per year and the gross margin are influenced in the same direction, as expected. A decrease in slaughter value or an increase in price of a replacement gilt results in a higher culling rate, since more sows are culled voluntarily. Huirne et al. (1991) showed that optimal replacement decisions for individual sows are most sensitive to changes in the replacement cost, which is the difference between the price of a replacement gilt and the slaughter value of culled sows. A reduction of this difference results in a higher rate of voluntary replacement, as is also found in Table 8 for strategies at the herd level. Huirne et al. (1991) concluded that the optimal replacement decisions are not very sensitive to changes in feeder pig price and litter size, as is also found in Table 8 for strategies at the herd level. As expected, changes in these two factors have a considerable impact on gross margin per sow per year.

Doubling the repeatability leads to an increase in the required minimum production level to allow an insemination, since future litter size can be predicted more precisely. Therefore, the optimum replacement policy results in a 6% higher culling rate. The sows that are kept are on average better producers, so the number of pigs sold per sow per year and gross margin per sow per year (+ Dfl. 8) increase as well. If repeatability is set to zero, the

Table 8. Effects of variation in input variables on number of pigs sold per sow per year (pspy), culling rate of sows and gross margin pspy. Input variables are farrowing rate, litter size, price of replacement gilt, slaughter value, feeder pig price and repeatability of litter size. Input variables, excepting repeatability, are at a 20% lower level and a 20% higher level than in the basic situation (see Table 6)

	Pigs sold pspy			Culling rate (%)			Gross margin (Dfl. pspy)		
Farrowing rate	low	basic	high	low	basic	high	low	basic	high
I[a]	19.4	21.0	22.1	57.7	47.4	43.0	940	1086	1175
II	0	0	0	-.4	-.3	-.2	0	0	-1
III	+.1	0	-.1	+21.6	+6.2	-2.4	-42	-15	-3
IV	+.1	0	-.1	+20.7	+5.2	-3.6	-42	-15	-4
V	+.1	-.1	-.1	+72.2	+24.5	-3.6	-169	-62	-4
VI	-.1	-.1	-.1	-2.1	-3.1	-3.6	-1	-3	-4
Litter size	low	basic	high	low	basic	high	low	basic	high
I	16.9	21.0	25.1	47.5	47.4	47.1	771	1086	1398
II	0	0	0	-.3	-.3	-.4	0	0	0
III	0	0	0	+10.7	+6.2	+4.6	-21	-15	-14
IV *[b]		0			+5.2		-16	-15	-14
V *		-.1			+24.5		-62	-62	-60
VI *		-.1			-3.1		-2	-3	-3
Price repl. gilt	low	basic	high	low	basic	high	low	basic	high
I	21.1	21.0	21.0	51.5	47.4	45.6	1140	1086	1035
II	0	0	0	-.2	-.3	-.4	-1	0	0
III *		0			+6.2		-10	-15	-23
IV *		0			+5.2		-11	-15	-22
V *		-.1			+24.5		-36	-62	-91
VI *		-.1			-3.1		-8	-3	-1
Slaughter value	low	basic	high	low	basic	high	low	basic	high
I	21.0	21.0	21.1	45.8	47.4	50.7	1044	1086	1129
II	0	0	0	-.4	-.3	-1.0	0	0	-1
III *		0			+6.2		-21	-15	-11
IV *		0			+5.2		-20	-15	-12
V *		-.1			+24.5		-82	-62	-44
VI *		-.1			-3.1		-1	-3	-6
Feeder pig price	low	basic	high	low	basic	high	low	basic	high
I	21.0	21.0	21.0	46.5	47.4	48.2	645	1086	1527
II	0	0	0	-.5	-.3	-.6	0	0	-1
III *		0			+6.2		-15	-15	-15
IV *		0			+5.2		-15	-15	-16
V *		-.1			+24.5		-61	-62	-63
VI *		-.1			-3.1		-1	-3	-5
Repeatability of litter size	low	basic	high	low	basic	high	low	basic	high
I	20.9	21.0	21.3	45.0	47.4	53.4	1084	1086	1093
II	0	0	0	0	-.3	-.8	0	0	-1
III	+.1	0	-.2	+8.3	+6.2	+.5	-15	-15	-20
IV	+.1	0	-.3	+7.6	+5.2	-.8	-13	-15	-23
V	0	-.1	-.3	+26.9	+24.5	+18.5	-60	-62	-70
VI	0	-.1	-.4	-.7	-3.1	-9.0	0	-3	-11

[a] Numbers refer to insemination strategy; I: Optimal replacement, II: Modified optimal replacement, III: Extension advice, IV: Modified extension advice, V: Very strict and VI: Very liberal.

[b] When indicated with an asterisk this combination of option of the input variable and strategy does not influence the distribution over states. Therefore, the number of pigs weaned per sow per year and culling rate do not differ from the results in the basic situation.

optimal replacement policy from the model of Huirne et al. (1991) is independent of production level. This leads to a small reduction in culling rate, pigs sold per sow per year and gross margin per sow per year (- Dfl. 2).

The results for the different alternatives can also be used to determine the economic value of variables such as the number of pigs sold per sow per year and the number of open days. If litter size increases, the economic value of an extra pig sold per sow per year is Dfl. 76. Additional calculations show that financial loss caused by a delay in conception amounts to Dfl. 3.70 per open day. These values are in accordance to other sources (Dijkhuizen, 1989; Huirne et al., 1991)

Across strategies

In Table 8 the results for the remaining strategies are presented as the difference from strategy I for that same alternative. In cases an alternative does not influence the distribution over states for a certain strategy, the annual culling rate and number of pigs sold per sow per year do not change, and are therefore not presented in Table 8. In general, it emerges that the ranking of the strategies is not influenced by any of the alternatives, whereas the absolute differences are influenced.

If the farrowing rate is reduced, the differences in culling rate for strategies III, IV and V compared to strategy I become even more substantial, since fewer inseminations are allowed. The number of pigs sold per sow per year is 0.1 higher, as these strategies result in more litters per sow per year due to shorter farrowing intervals and less non-productive sow days than strategy I. Due to the increase in culling rate, the difference in gross margin between strategies I/II and the alternatives III, IV and V is higher. When the farrowing rate is "high" (i.e. 100%) the differences between strategies become smaller, since all animals are pregnant at first insemination.

Modifying litter size affects the distribution of animals over different production levels. Only when production level is taken into account in the strategy (I, II and III) herd dynamics are influenced. In general, the differences in results between the strategies remain the same (Table 8), except in the case of strategy III and a decrease in litter size. In strategy III decisions depend on absolute production level independent of the average production level of the herd. As a consequence culling rate increases when average litter size decreases which makes this guideline more costly under these circumstances.

Changes in prices for strategies III to VI do not affect the distribution over states but, as expected, do affect the derived economic results. If the culling rate is reduced for strategies I and II, the differences in gross margin with guides resulted in a 4-5% increase in net return to labour and management (basic level Dfl. 958; Van Arendonk, 1987).

4.2 Sensitivity analysis

Observed differences in technical and economic results between strategy I (Optimal replacement) and II (Modified optimal replacement) are under all studied conditions limited. Therefore, it can be concluded that taking into account production level at second last farrowing does not have any substantial technical and economic impact. This is even not the case with higher repeatabilities of litter size than assumed in the basic situation. When repeatability of litter size is set to zero, gross margin per sow per year in strategy I and II is only decreased by Dfl. 2. In that case, the optimal replacement strategy is independent of production level at last and second last farrowing. Consequently, in the basic situation an optimal replacement strategy based on cycle-specific average litter size only would suffice.

Repeatability of the interval weaning conception is not included in the model of Jalvingh et al. (1992) and Huirne et al. (1991). This may have resulted in overestimating the differences between strategy I and III (Extension advice), in case extension advice implicitly assumes a certain repeatability of this interval. Estimates found in literature on repeatability of interval weaning conception are rather small. Te Brake and Schuiling (1982) doubted the existence of this repeatability in case of early weaning (7 days); in case of late weaning (42 days) repeatability varied from 0.070 to 0.212, dependent on method of calculation. Extending the model in future research could be of interest from a scientific point of view, but a significant impact on the outcome is not expected.

Under certain price and production circumstances, the guidelines in strategies III, IV and V result in decision-making that is too strict. Compared to strategy I, the differences in gross margin per sow per year increased. This occurred especially in case of low farrowing rates (bad reproduction), but also with low slaughter value of culled sows and high prices for replacement gilts. Therefore, these rules of thumb should not be used under these circumstances. The management guides that can be derived from the optimal replacement decisions calculated by the model of Huirne et al. (1991) do take into account the circumstances under which the farmer has to make decisions. If simple guidelines are preferred instead of detailed management guides, the dynamic programming model of Huirne et al. (1991) could be used to derive these for different sets of circumstances.

4.3 Pigs sold per sow per year as economic indicator

The number of pigs sold per sow per year is often used as a starting point in evaluating the performance of sow herds. A difference in the number of pigs sold per sow per year can easily be transformed into differences in financial results. The studied strategies, however, do not influence the number of pigs sold per sow per year. Differences in economic results are mainly related to differences in culling rate. High culling rates affect productivity by shifting the herd age distribution towards younger sows with lower production levels. This effect is compensated, however, by less non-productive sow days. For example when studying the effect of changes in farrowing rate, the number of pigs weaned per sow per year was affected as a result of the changes in number of non-productive days of sows. It can be concluded that the number of pigs sold per sow per year has limited potential as an economic indicator in comparing strategies on reproduction and replacement.

4.4 Replacement gilts

The insemination strategies were studied under the condition that the size of the herd is constant at any time, which was realized by immediate replacement of culled sows. In reality, immediate replacement will be difficult to accomplish and may lead to a reduction in the average number of sows present in the herd, with an additional negative economic effect. The model of Jalvingh et al. (1992) can be used to determine this reduction in average number of sows and gross margin of the farm, in case replacement gilts are bought at specific intervals. Preliminary results show that the reduction in average number of sows and in gross margin of the farm amounts to 0.3%, 0.9% and 2.5% when gilts enter the herd at intervals of 2, 4 and 8 weeks, respectively. The negative effect could be outweighed by a reduction in the purchase price of replacement gilts (e.g. through the reduction in transporting costs). When annual culling rate is higher, gross margin of the farm will be further reduced since fewer sows are present in the herd. Therefore, the difference between strategy I and the more strict strategies (III, IV and V) would increase.

4.5 Concluding remarks

Results showed that the model of Jalvingh et al. (1992) is suitable to study the technical and economic consequences of different insemination strategies. The model can be a flexible tool in on-farm decision support since it offers the possibility to compare strategies under varying circumstances. In this study the model has only been used to compare strategies at equilibrium. The model can also be used to study the herd over time, which is illustrated by Jalvingh et al. (1992). In that case the model provides insight into how the equilibrium belonging to a new management strategy is reached, starting at the equilibrium distribution over states belonging to the current management strategy.

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ABSTRACT

A dynamic probabilistic model has been designed to determine the technical and economic consequences of various biological variables and management strategies concerning reproduction, replacement and calving patterns in dairy herds. The Markov chain approach is used to simulate herd dynamics. Herds are described in terms of states animals can be in and the possible transitions between the states. The corresponding transition probabilities are derived from input values concerning biological variables and management strategies. The model has the property of calculating easily the herd structure at equilibrium (steady state). Sets of input values can be evaluated by comparing the technical and economic results of the corresponding herds at equilibrium. Moreover, herd dynamics can be studied over a period of time to gain insight into how equilibrium is reached. Input values can be modified to be farm-specific. The model is used to compare different calving patterns of the herd under different circumstances. Results for Dutch conditions show that it is most profitable to have calvings concentrated in autumn.

1 INTRODUCTION

Insemination and culling are two important decisions in managing dairy cattle, both having a considerable economic impact. Dynamic programming models are available to calculate the optimum insemination and replacement decisions for individual dairy cows (Kristensen, 1987; Van Arendonk, 1988; DeLorenzo et al., 1992). The optimum decisions are influenced by factors such as age, stage in lactation, production level, calving interval and month of calving due to seasonal variation in performance and prices.

The influence of seasonal variation in performance and prices on technical and economic results of individual animals has been studied extensively (e.g. Van Arendonk, 1986; Strandberg and Oltenacu, 1989). However, studies at herd level focusing on optimum calving pattern are still in their early stage. DeLorenzo et al. (1992) made a start in determining the optimum calving pattern based on results from a dynamic programming model assuming immediate replacement of culled animals, i.e. maintaining constant herd size.

The approach commonly used in models simulating herd dynamics is dynamic stochastic simulation (i.e. Monte Carlo simulation) (see Jalvingh (1992) for an overview of these models). Individual animals are moved forward through time, modifying the status of each according to the outcome of various events and management decisions. Replicated calculations have to be carried out to obtain reliable average results. The resulting standard deviation of the average results can provide additional insight from a research point of view, but may be of little value in on-farm decision support (Dent and Blackie, 1979). Calculations with these models focus mainly on obtaining the results of an approximate steady state by simulating the herd during several years and determining the corresponding average results. The Markov chain approach offers the possibility of creating this steady state straightforwardly. In addition to the determination of the steady state, the Markov chain approach is able to follow a herd over time, which is also done by the models using dynamic stochastic simulation. Furthermore, the Markov chain approach provides the expected value of the results and only one run is needed to obtain these estimates. Recently, Jalvingh et al. (1992a) used the Markov chain approach to simulate sow herd dynamics, and to compare management strategies on reproduction and replacement (Jalvingh et al. 1992b).

The objective of this paper is to present and describe the components and results of a model that simulates herd dynamics in dairy cattle using the Markov chain approach. Compared to the swine model of Jalvingh et al. (1992a), an important new feature is the inclusion of seasonal variation in performance and prices, which has a large impact on model characteristics. The simulation of herd dynamics and technical and economic results takes into account management strategies with respect to insemination, replacement and calving pattern. The model is used to compare technical and economic results of herds with different calving patterns under different production and price circumstances.

2 MATERIAL AND METHODS

2.1 General

The modelling approach presented involves three separate models. A schematic overview is presented in Figure 1. The major component is a model that simulates herd dynamics using a finite-state Markov chain. Central to that theory are the concepts of states and state transition (Hillier and Lieberman, 1990). Using the three models, technical and economic results can be generated for a herd in its steady state or for different consecutive years of the herd. The latter offers the opportunity to determine the consequences when the herd approaches a new steady state.

Technical and economic results of the herd are calculated by combining the number of animals per state, with information on milk production, feed intake,

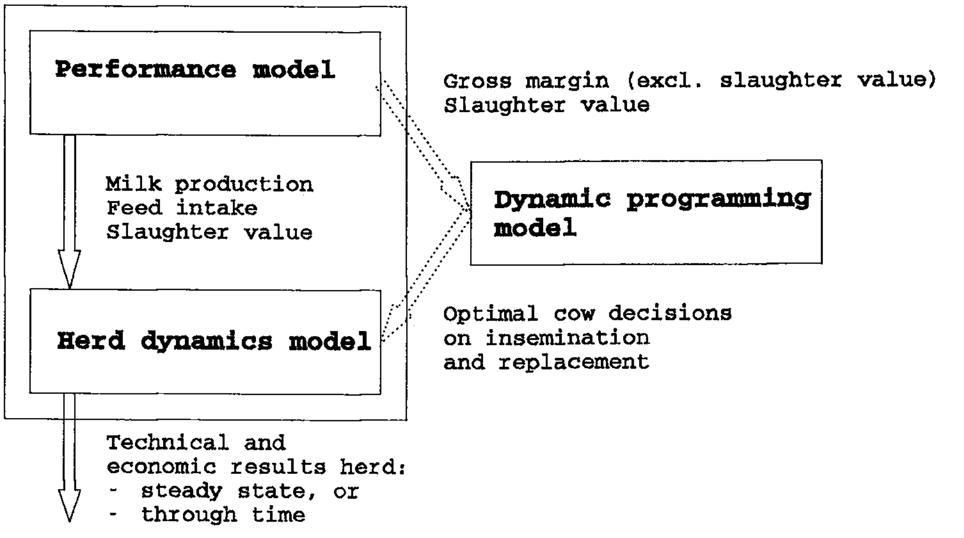

Figure 1. Schematic overview of modelling approach. The flow of information between the models is indicated by the arrows. Use of the dynamic programming model is optional.

slaughter value and prices. Milk production, feed intake and slaughter value per state are calculated by the performance model. Insemination and replacement of individual cows is determined by the outcome of a third model, i.e. a dynamic programming model that calculates the optimal insemination and replacement decisions for individual animals (Figure 1). The use of the results of the dynamic programming model in the herd dynamics model, however, is optional but used in all cases in this paper. The optimal decisions can be replaced by more simple rules, such as user-defined rules of thumb.

The herd dynamics model and the performance model are programmed in Turbo Pascal for the use on a PC. The dynamic programming model is available in Fortran on a main frame computer.

In this paper the states and possible transitions in the herd dynamics model are described, as well as the various possibilities of using the model. The performance model is largely based on two earlier published models (Van Arendonk, 1985a; Groen, 1988) and the dynamic programming model is based on Van Arendonk (1986).

2.2 Simulation of herd dynamics

A Markov chain has a finite number of states and a discrete time parameter (Hillier and Lieberman, 1990). The distribution over states at a certain moment can be derived from the distribution at the moment before and the transitions possible for each state. The probability of making a transition to each state of the process depends only on the state presently occupied, the so-called Markovian property (Howard, 1971).

States

Choice of the number of states and the time interval between transitions involves a trade-off between complexity and precision of the model, taking into account model objectives. Transitions are made on a monthly basis (30.5 days). State variables used are lactation number, stage of lactation, milk production level during the present lactation, time of conception and month of calving. The lactation number of a cow can range from 1 up to 10. For the production level 15 classes are distinguished, ranging from 70 to 130%. Insemination of a cow can occur at monthly intervals from 2 to 8 months after calving. A cow which remains open is allowed to stay in the herd up to a maximum of 17 months after calving. The state variable month of calving is included to account for seasonal variation in performance and prices.

Transitions

Uncertainty in future performance of the animals is represented in four groups of transition probabilities: reproduction, production, disposal and replacement. The transition probabilities in the model presented are dependent on input values concerning biological variables on the one hand, and management strategies on the other, as described in the following sections.

Reproduction

The marginal probability of conception of an open cow is calculated from the probability of first and/or later inseminations occurring and the probability that conception takes place after insemination. The conception rate of cows was assumed to be independent of production level and length of the previous lactation of the cow. See Van Arendonk and Dijkhuizen (1985) for a detailed description of the calculation of the marginal probability of conception. The input values needed in this calculation are given in the Appendix. Probability of conception is set at zero, when according to the insemination strategy an insemination should not be carried out. In this paper the optimal insemination decisions for individual animals calculated by the dynamic programming model are used as insemination strategy.

Production

The production of a cow is defined relative to its mature equivalent milk production during a one-year calving interval in the absence of genetic improvement and voluntary replacement. The probability for a heifer having a certain production level is calculated from a normal distribution using the limits of each class and the standard deviation of lactation production. The relative production level of a cow remains the same during the lactation period. Transition to other production levels occurs at the end of the lactation period. The probability of transition to each of the 15 production levels during the next lactation given the state of the cow, is calculated from the predicted value for the next lactation, the limits of each class and the residual variation in production. See Van Arendonk (1985b) for a detailed description of the calculation of the transition probabilities. Input values in this calculation are repeatability for lactation production at a one-year interval (0.55 for first parity cows and 0.60 for second and later parity cows) and variation coefficient of the within-age-and-herd lactation production (12%). As suggested by Van Arendonk (1986), repeatability for second and higher parity cows has been increased with 0.05 compared to Van Arendonk (1985b). This is done to compensate for the absence of production level in the previous lactation as state variable in the model, which would otherwise result in a rapid decrease in differences in production between low and high producing cows.

Disposal

Involuntary disposal is mainly caused by mastitis, lameness and death. The marginal probabilities of involuntary disposal per state are calculated from input values concerning probability of involuntary disposal per lactation number and proportion of involuntary disposal for each month in lactation (see Appendix). The calculation of marginal probabilities is given by Van Arendonk (1985a).

Voluntary disposal is considered after 2 months in lactation. Voluntary disposal of animals is determined by the replacement strategy used. In this paper, the optimal replacement decisions calculated by the dynamic programming model are applied.

Replacement

Animals that have been culled need to be replaced by heifers in order to maintain herd size. In the model, replacement of culled animals can be carried out in two different ways. In the first approach, the herd size is kept constant throughout the year by immediate replacement of all culled animals. This approach is similar to that used in the swine model of Jalvingh et al. (1992a) and the dynamic programming models of Van Arendonk (1986) and DeLorenzo et al. (1992). In the second approach, the herd size is kept constant on an annual basis, but may vary within a year. This approach allows for non-immediate replacement within a year. The distribution of replacement heifers over months is equal to the desired calving pattern for heifers. This pattern can be directly specified by the user or can depend on a specified herd characteristic, e.g. equal to the calving pattern of the whole herd (see further for more details). Herd calving pattern refers in all cases to all calvings in the herd (heifers and cows). Replacement heifers enter the herd in all cases at the age of 24 months.

Equilibrium distribution

When using stationary transition probabilities in a Markov chain, it is possible to determine the steady state herd structure. This means that after a sufficiently long period of time, the distribution over the states will reach a limiting equilibrium distribution (Howard, 1971). In that situation the distribution over states does no longer change over time. Due to inclusion of the state variable month of calving, the equilibrium distribution is not the same from month to month, but is the same for the same month in successive years.

For representing the Markov chain, the common matrix approach is not used because it results in matrices that are too large. The alternative approach described by Jalvingh et al. (1992a) is used, utilizing the special characteristics of the modelled process.

Because of the structure of the modelled process, it is not necessary to follow the herd during a large number of time steps to get the equilibrium distribution (Jalvingh et al., 1992a). The equilibrium distribution over states is equal to the distribution over all possible states in terms of relative numbers which originates from replacement heifers calving in different months of the year. An equilibrium distribution which originates from heifers calving in one single month of the year is referred to as a single-month equilibrium herd (SME-herd). Consequently, twelve different SME-herds can be determined, one for each month of calving of the heifer. The equilibrium distribution over states of an entire herd with a given heifer calving pattern can be obtained by weighing the SME-herds according to the proportion of heifers calving in each month.

With a fixed desired calving pattern of heifers, the corresponding equilibrium distribution can be calculated in a straightforward way. When the calving pattern of heifers depends on a characteristic of the herd, the corresponding equilibrium distribution needs to be calculated iteratively. At each iteration, the heifer calving pattern is compared with the desired pattern (e.g. calving pattern of the herd). This is repeated until the desired pattern is reached. This method is also used by DeLorenzo et al. (1992) in order to generate the post-optimization steady state herd structure assuming immediate replacement only.

The calculated equilibrium distribution for a herd, corresponds to the distribution which originates from one replacement heifer entering the herd. The sum of all state probabilities equals the average herd life of a cow in months and is also equal to the sum of monthly herd sizes. The resulting average herd size, however, is not yet equal to the desired average herd size. In order to obtain the desired average herd size, all state probabilities have to be multiplied by the ratio of desired herd size over the sum of all state probabilities divided by 12. The resulting number of heifers entering the herd each month, ensures a constant annual herd size in case of immediate and non-immediate replacement.

To obtain technical and economic results of the herd at equilibrium, the number of animals and events are combined with data from the performance model, concerning milk production, feed intake and slaughter value, as well as various prices. Several technical and economic results per month and per year are calculated.

Direct solution

In the method described above for calculating results belonging to the equilibrium distribution, two steps can be distinguished: (a) calculation of the distribution over all possible states, and (b) calculation of the technical and economic results by combining the contents per state with the outcome of the performance model. There is a faster way of obtaining the results belonging to a certain equilibrium, which will be referred to as "direct solution". Similar to the weighing of the SME-herds, the technical and economic results corresponding to these SME-herds can be weighed in order to get the results of a herd with a certain calving pattern at equilibrium. After creating the results of the twelve SME-herds, steady state results belonging to any heifer calving pattern can be calculated by solving the following equation:

$$\mathbf{A}\,\mathbf{x} = \mathbf{b}$$

in which:

x = vector with number of heifer calvings per month

b = vector with number of calvings per month

A = 12*12 matrix; each element a_{ij} gives the number of herd calvings in month i, belonging to SME-herd in which heifer calves in month j

Elements of **A** and **b** are given in number of calvings per month, but this can be replaced by other parameters, such as monthly number of cullings or milk production.

The direct solution can be applied in order to calculate **b** for a given **x**, but also to calculate **x** for a given **b**, by solving the equation $\mathbf{x} = \mathbf{A}^{-1}\ \mathbf{b}$. In case any $x_i \leq 0$ (i = 1..12), the given **b** cannot be realised by the biological input variables and management strategies. In some cases it is not possible to calculate $\mathbf{A}^{-1}$ because of singularity. In addition, iterations can be used to determine the herd at equilibrium in which $\mathbf{x} = \mathbf{b}$.

In case **x** is given or calculated, all technical and economic results of the herd at equilibrium can be generated by solving $\mathbf{A}\ \mathbf{x} = \mathbf{b}$, where elements of **A** refer to technical or economic results of SME-herds.

2.3 Simulation of performance, revenues and costs per state

Income on most Dutch dairy farms originates from three interdependent activities: grassland exploitation, rearing young stock and managing dairy cows. In the model replacement heifers are bought just before calving from the farm's young stock enterprise. Grass and silage consumed by the dairy cows is produced on the farm's land. Labour supplied by the farmer is not included in the calculation of the costs. Net revenues per cow originating from grassland exploitation and the dairy cow enterprise form therefore a compensation for the supplied labour and management.

Milk production and revenues

For each state milk, fat and protein production during the corresponding month are simulated based on the approach described by Van Arendonk (1985a). Relative monthly milk production is determined by the extended model of Cobby and Le Du (1978), including the effects of season and number of days open. These results are combined with the estimated lactation production in order to get monthly production. The lactation production is calculated from mature equivalent herd level, using correction factors for age, number of days open, month of calving and relative production level (see the Appendix for more information). The mature equivalent herd level is set at 7750 kg of milk, 4.35 % of fat and 3.39 % of protein. The average prices of milk, fat and protein are Dfl. -0.029, 8 and 14.50 per kg respectively. The monthly deviations in price per kg milk are presented in Table 1.

The influence of the previous number of days open on milk production during the lactation is formulated as an additive effect (see Appendix). The

Table 1. Per calendar month effect on (a) prices, (b) milk production and composition during lactation, (c) monthly milk production, (d) marginal probability of conception and (e) proportion of calvings corresponding with average Dutch calving pattern.

	Calendar month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Additive adjustment factors												
Prices (Dfl.)												
milk (100 kg)[a]	+3.7	+1.8	-0.7	-1.5	-4.5	-4.5	-4.5	-3.7	-0.7	+5.3	+7.3	+7.0
calves (kg)[b]	-1.18	-1.49	-1.66	-0.17	+1.76	+1.96	+2.05	+0.80	-0.08	-0.48	-0.72	-0.97
replacement heifer [b]	-37	-57	-66	-45	+13	+13	+27	+46	+44	+65	+20	-24
carcass weight (kg)[b]	-0.38	-0.23	+0.05	+0.07	+0.32	+0.33	+0.23	+0.15	+0.10	-0.03	-0.21	-0.30
Multiplicative adjustment factors												
Lactation production[c]												
milk (kg)	1.032	1.021	1.009	0.998	0.988	0.972	0.960	0.964	0.983	1.009	1.029	1.035
fat (%)	0.992	0.990	0.987	0.988	0.990	0.997	1.004	1.011	1.016	1.015	1.010	1.000
protein(%)	0.989	0.993	0.996	1.001	1.005	1.008	1.009	1.010	1.007	1.001	0.993	0.988
Monthly milk production[c]	0.95	0.97	1.00	1.03	1.05	1.07	1.06	1.03	1.00	0.96	0.94	0.94
Conception rate[d]	1.02	0.93	0.93	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.02	1.02
Others												
Proportion of calvings[e]	10.8	9.8	9.2	8.7	6.9	5.8	4.7	5.5	8.0	9.5	10.3	11.0

[a] Average of the monthly deviations of the three major milk processing plants in the Netherlands (KWIN, 1991).

[b] Monthly deviations estimated from weekly prices in period 1989 till 1991 (Boerderij, 1989-1991).

[c] Wilmink (1985).

[d] Average of seasonal influence on probability of conception after first insemination (Van Arendonk, 1986) and seasonal influence on oestrus detection rate (Elving and Van Eldik, 1990).

[e] Represents average calving pattern of the Netherlands. Based on 792712 calvings in lactation 1, 2 and 3 (H. Wilmink, personal communication, 1992).

additional energy requirements for the increase or decrease in milk production are calculated, assuming that weight at calving is independent of the previous number of days open. The additional energy requirements are assumed to be met by additional intake of roughage. The effects of the previous days open on milk production and roughage intake are assigned to the first month of lactation as done by Van Arendonk (1985a). The effects are weighed with the probability of survival during that lactation, to account for the fact that in reality the effects do not only take place in the first month, and that not all cows will realise the complete effect due to culling.

Feed intake and costs

The simulation of the monthly feed intake and costs is based on the approach presented by Groen (1988). The composition of the feed intake depends on energy intake requirements, dry-matter intake capacity and feed quality. Energy intake requirements consider maintenance, milk production, growth, pregnancy and mobilization and restoration of body(-fat) tissue. In determining dry-matter intake capacity the factors size and milk yield of the cow and composition and physical form of the diet are considered. Since energy from concentrates is more expensive than energy from roughage, intake of roughage is maximized. At least 30% of dry matter comes from roughage. The ration in summer (May to October) consists of grass and concentrates and in winter (November to April) of grass silage and concentrates. Energy content, fill value and prices of the different kinds of feed are presented in Table 2. Concentrates can be entered in the diet by units of 0.1 kg dry matter per day. The minimum daily intake is set at 0.5 kg during lactation. Using the original model of Groen (1988) it was not possible to define a ration for highly productive cows. To overcome this limitation, two modifications were made. First, the maximum decrease of live weight during lactation has been made dependent on the relative production level, since better producing cows are expected to loose more weight at the beginning of the lactation. Extra increase

Table 2. Characteristics of different kinds of feed.

	Energy content (VEM[a])	Fill value[b]	Price (Dfl./1000 VEM)
Grass	951[c]	1.00	0.22
Silage	850	1.13	0.30
Concentrates	1045	[d]	0.35

[a] VEM stands for Dutch Feed Unit; 1000 VEM = 6.9 MJ NE_L.
[b] Represents to what extent intake of a given feed takes up dry matter intake capacity of reference feed (Jarrige et al., 1986).
[c] Average energy content in summer. Values per month: 1013 VEM (May), 959 (Jun), 937 (Jul and Aug), 929 (Sep and Oct) (NVV, 1991).
[d] Fill value is dependent on amount of concentrates fed (see text).

or decrease is determined by using the phenotypic correlation and standard deviation of milk production and growth at the beginning of the lactation (r_p = -0.50, Van Arendonk et al., 1991). This results in an additional decrease in weight of 13.3 kg for each 1000 kg of extra milk. The average decrease in weight due to lactation is set at -25.0, -37.5 and -50.0 kg for first, second and later parities respectively (Groen, 1988). In the formula to simulate live weight, the mature live weight is set at 650 kg, and birth weight at 36 kg. Second, the substitution of concentrates for roughage (SR) is based on Hijink and Meijer (1987):

$$SR = (0.256 * CF + 0.023 * CF^2) * (EC/950) / (1 + (LP-6000)/15000)$$

in which:

CF = amount of concentrates fed (kg)
EC = energy content of roughage (VEM/kg dry matter)
LP = lactation production of the cow

Calves and calf revenues

Starting point in determining calf revenues is the selling of all calves one week after birth. Revenues are based on live weight, price per kg of live weight and survival rate. Birth weight of newly-born calves depends on sex of the calf and age of the dam. The average weight of female calves is 36, 39.75 and 41.45 for first, second and higher parity cows respectively. Male calves are 3.08 kg heavier (Meijering and Postma, 1985). Of the calves born 50% are females, 3% of the births concerns twins and 88% of first calving cows have calves that survive the first week. For older cows the survival rate is 96%. Base price per kg of live weight for female calves is Dfl. 6.60 and for male calves Dfl. 10.55. The price for calves is corrected for month of sale (Table 1). Monthly deviations are the same for heifer and male calves.

Slaughter value

The approach given by Van Arendonk (1985a) has been used. Slaughter value is calculated from live weight, dressing percentage and price per kilogram of carcass weight. The dressing percentage and the price per kilogram of carcass weight depend on age and stage of lactation (see Van Arendonk (1985a) for these parameters). All prices are expressed as deviations from the price per kg of carcass weight of a first parity cow 210 days in lactation which is set at Dfl. 6.40. The seasonal variation in this base price is presented in Table 1.

Others
The average price of a replacement heifer is set at Dfl. 2600. Monthly deviations are presented in Table 1. In case of involuntary culling, the financial loss due to a reduction in revenues of milk and other factors is taken into account, as described by Van Arendonk (1985a).

2.4 Dynamic programming model

The dynamic programming model of Van Arendonk (1986) is used to generate the economically optimum insemination and replacement decisions for individual animals. The dynamic programming model takes the same state variables into account as the herd dynamics model. The number of days-open classes in the original model of Van Arendonk (1986) has been extended from 6 to 7, in order to have the same number of classes as in the herd dynamics model. The performance model described in this paper is used to calculate gross margin and slaughter value per state. Parameters in the dynamic programming model were taken from the models for the simulation of herd dynamics and performance. The rate of genetic progress hardly influences the optimal decisions for individual animals (Van Arendonk, 1985), and has, therefore, been set at zero.

2.5 Alternatives to illustrate model behaviour

First, the profitability of the different months of calving will be calculated for individual animals to illustrate the outcome of the input variables for performance and prices. Results are presented for an average cow in which the results per lactation number are weighed using the herd composition based on marginal probabilities of involuntary and voluntary disposal given by Van Arendonk (1985b) ignoring seasonal variation.

Subsequently, steady state herd results are calculated for all twelve SME-herds. In this, the economically optimum insemination and replacement decisions for individual animals, calculated by the dynamic programming model, are used. The technical and economic results of the SME-herds are used to generate the results of four herds with a different calving pattern, using the direct solution approach. All herds have a heifer calving pattern that depends on a characteristic assigned to the herd. The following four alternatives are considered:

I: heifer calving pattern equal to herd culling pattern
II: heifer calving pattern equal to voluntary herd culling pattern
III: heifer calving pattern equal to herd calving pattern
IV: heifer calving pattern belonging to a given herd calving pattern (average calving pattern in the Netherlands, see Table 1)

The herd size in herd I is kept constant on a monthly basis, while in the other herds the size is kept constant on an annual basis.

Sensitivity of results at equilibrium for increased and decreased reproductive performance is also shown. For that purpose, the values of both conception rate and oestrus detection rate were relatively increased or decreased by 10%. The average interval of calving to first insemination with increased and decreased reproductive performance is set at 76 and 87 days respectively, instead of 81 days in the basic situation. In both alternatives, the optimal decisions on insemination and replacement of individual animals belonging to the basic input variables are used. The influence of reproductive performance is studied for the situation in which the heifer calving pattern is equal to the herd calving pattern (alternative III).

Sensitivity of results is also shown for situations in which seasonal variation in performance or prices is omitted in turn. Steady state herd results are calculated for all SME-herds. In this, the optimal decisions belonging to the modified set of input variables are used.

3 RESULTS

3.1 Influence of month of calving on costs and revenues

For all possible months of calving, costs and revenues during a lactation are presented for an average cow with a calving interval of 12 months (Figure 2). Attention is paid to milk and calf revenues, feed costs and resulting gross margin. Slaughter value and replacement costs are not taken into account in this case. Gross margin is highest for cows calving in October (Dfl. 4711) and lowest for cows calving in March (Dfl. 4434), implying a maximum difference of Dfl. 277. Gross margin for calving in the period May until August does not vary a lot and is only Dfl. 3 to Dfl. 22 below the average gross margin (Dfl. 4567). Milk revenues are highest for calvings in November and lowest for June (difference Dfl. 354). Feed costs are highest for calvings in November, and lowest for April (difference Dfl. 110). Calf revenues are highest for calvings in July, and lowest in March (difference Dfl. 148).

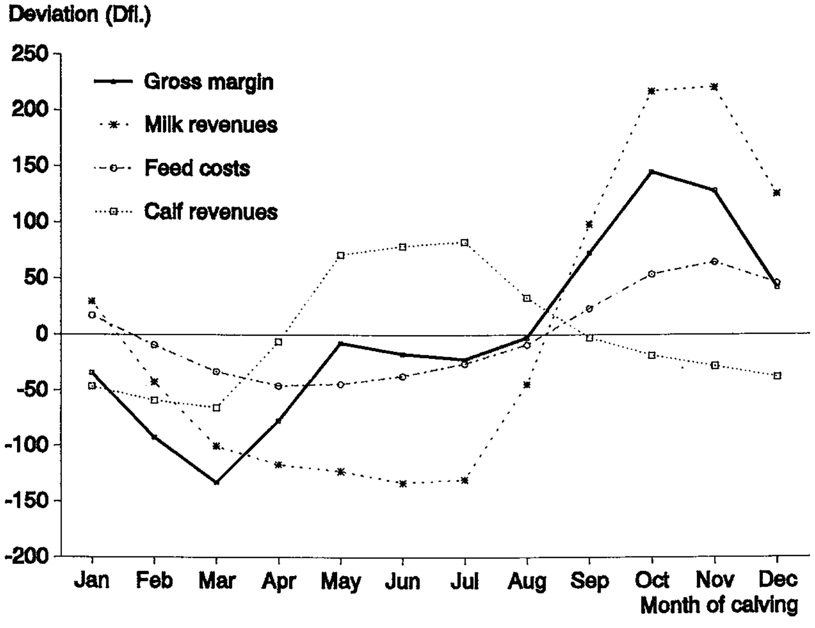

Figure 2. Effect of month of calving on revenues and costs (Dfl.) during a one-year calving interval, expressed as deviation from the mean (i.e., gross margin Dfl. 4567, milk Dfl. 5806, feed Dfl. 1582 and calves Dfl. 342).

3.2 Single-month equilibrium herds

The technical and economic results are generated for the twelve SME-herds. In Table 3, the resulting calving pattern for each equilibrium is presented. As could be expected, the majority of calvings for a certain equilibrium take place in the month in which heifers calve, i.e. more than 40% in all cases. There are no months without calvings. Besides that, the number of calvings and the average number of cows present in the herd resulting from one heifer calving are presented. The average number of cows varies from 2.45 (March) to 3.34 (October) and equals the average herd life of a heifer calving in the corresponding month.

In Table 4, technical and economic results are presented for each SME-herd. The annual culling rate of the herd varies from 30.0% (October) to 40.8% (March). The annual culling rate for heifers varies from 31.2% (October) to 60.0% (March). Milk production varies from 6,861 kg (July) to 7,242 kg (December) per average cow present in the herd. The average milk

Table 3. Distribution of calvings, including heifers, over calendar months per SME-herd. Total number of calvings and average number of cows present in the herd resulting from one heifer calving in a certain month.

Month of heifer calving	Proportion calvings (%)												Number of calvings	Average number of cows[a]
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		
Jan	49.0	11.5	6.7	4.1	2.5	1.4	0.7	0.4	1.0	2.2	5.4	15.1	3.12	2.67
Feb	14.5	50.7	10.6	6.8	4.3	2.5	1.4	0.7	0.7	0.9	1.8	5.1	2.95	2.49
Mar	4.8	13.9	49.7	10.9	7.7	4.5	2.6	1.5	1.1	0.8	0.8	1.7	2.94	2.45
Apr	1.6	4.7	12.9	48.5	12.2	7.9	4.7	2.9	2.1	1.3	0.7	0.7	3.07	2.57
May	0.6	1.5	4.3	13.0	48.0	12.1	7.8	4.9	3.8	2.3	1.1	0.7	3.30	2.79
Jun	0.6	0.7	1.6	4.8	14.5	45.9	11.5	7.6	6.0	3.9	2.0	1.0	3.44	2.92
Jul	0.9	0.6	0.6	1.7	5.2	14.0	44.1	11.4	9.8	6.3	3.4	1.9	3.55	3.03
Aug	1.6	0.9	0.5	0.7	1.8	4.9	13.1	43.2	14.5	10.2	5.6	3.2	3.67	3.16
Sep	2.7	1.5	0.7	0.5	0.7	1.7	4.7	13.8	46.3	14.1	8.5	5.0	3.67	3.17
Oct	4.5	2.6	1.2	0.6	0.5	0.6	1.6	4.5	17.6	46.1	12.4	8.0	3.79	3.34
Nov	7.5	4.5	2.2	1.2	0.7	0.5	0.6	1.5	7.1	17.0	45.2	12.2	3.59	3.16
Dec	11.8	7.9	3.9	2.4	1.4	0.7	0.5	0.5	2.5	6.3	15.2	47.0	3.38	2.95

[a] Average number of cows during a certain period of time is the ratio of total number of cow days and total number of days in that period.

Table 4. Technical and economic results per year of SME-herds.

	Month of heifer calving											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Technical results												
Number of cows	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Number of calvings	116.7	118.3	119.7	119.4	118.3	117.8	117.1	116.1	115.7	113.4	113.8	114.7
Culling rate herd (%)	37.4	40.1	40.8	38.9	35.8	34.3	33.0	31.7	31.6	30.0	31.7	33.9
Culling rate heifers (%)	50.1	57.1	60.0	56.6	49.1	47.0	44.8	40.8	39.9	31.2	35.4	40.5
Interval calving-culling (days)	194	191	180	171	165	161	159	162	169	189	197	198
Calving interval (days)	370	370	371	372	372	372	373	373	372	371	370	370
Milk per ave cow (kg)	7214	7150	7069	6997	6940	6893	6861	6891	6978	7116	7209	7242
Fat per ave cow (kg)	316	312	308	306	304	303	304	306	311	317	320	319
Protein per ave cow (kg)	245	243	241	240	238	237	236	237	240	244	246	246
Feed intake per ave cow (1000 VEM)	5686	5650	5612	5589	5577	5563	5556	5579	5622	5684	5714	5714
Average prices (Dfl.)												
Milk price premium (100 kg)	-0.69	-1.13	-1.18	-0.89	-0.40	0.21	0.84	1.32	1.56	1.44	0.85	0.03
Feed price (1000 VEM)	0.274	0.270	0.267	0.265	0.266	0.270	0.274	0.277	0.279	0.281	0.280	0.277
Calf revenues per calving	301	298	306	342	383	393	389	364	341	326	315	306
Price heifer	2565	2545	2535	2555	2610	2615	2625	2645	2650	2655	2620	2580
Slaughter value per culled cow	1603	1595	1571	1548	1524	1508	1500	1507	1515	1561	1589	1605
Economic results (Dfl./ave cow)												
Revenues												
milk	5855	5772	5708	5687	5694	5716	5749	5819	5907	6002	6011	5949
calves	351	353	367	409	453	463	456	423	394	370	358	351
culls	600	640	641	603	546	517	495	477	478	468	503	545
Costs												
feed	1556	1524	1497	1483	1486	1502	1520	1544	1567	1595	1602	1586
heifers	960	1021	1034	995	935	896	866	838	836	796	830	876
Gross margin												
absolute value	4290	4220	4185	4220	4273	4297	4313	4337	4376	4449	4440	4383
deviation from highest outcome	-159	-229	-264	-229	-176	-152	-136	-112	-73	0	-9	-66

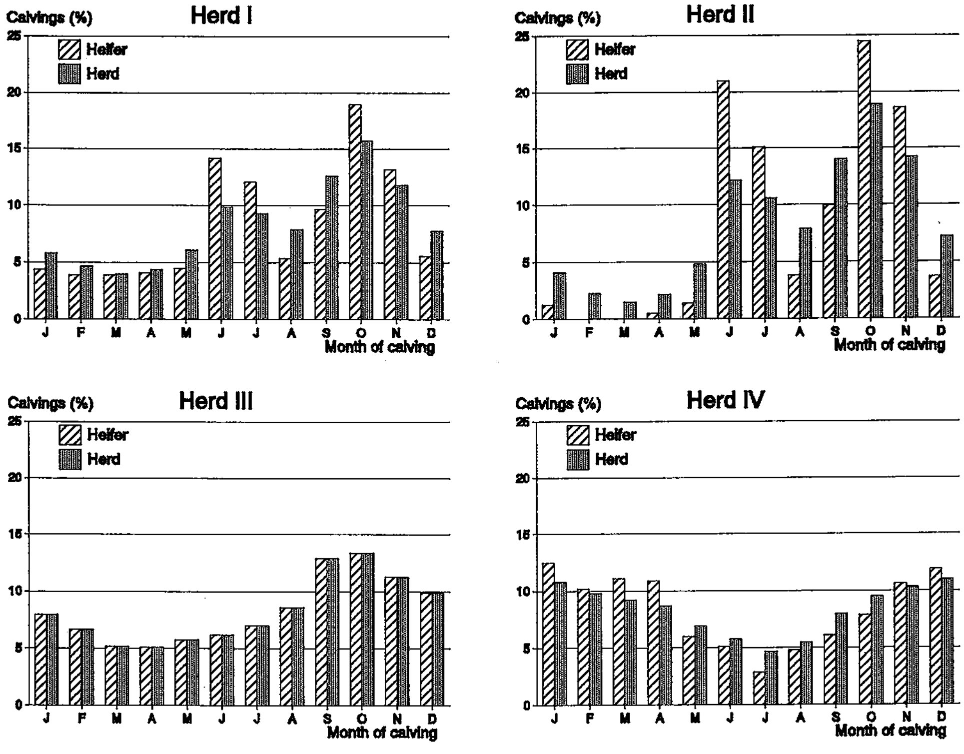

Figure 3. Calving pattern of heifers and herds for herds at equilibrium (heifer pattern equals pattern herd cullings (I), voluntary herd cullings (II), herd calvings (III), belongs to average herd calving pattern (IV)).

price premium received was highest for the September herd (Dfl. 1.56 per 100 kg milk) and lowest for the March herd (Dfl. -1.18). Gross margin per average cow is highest for the herd resulting from heifers calving in October (Dfl. 4449), and lowest for those calving in March (Dfl. 4185).

3.3 Alternative herds

Using the results of the SME-herds, the results of four different herds have been generated by using the direct solution approach. In Figure 3, the resulting heifer and herd calving patterns are presented. In herds I and II, heifer calvings are by far the highest in October. Moreover, there is a large proportion of heifer calvings in June, July, September and November. The heifer calving pattern in herds I and II is related to the culling pattern of the herd. Of the total number of cullings 65-70% and of the voluntary cullings even more than 90% take place in these months. Voluntary culling accounts for 52% of the total number of cullings. The proportion of heifer calvings in June is second largest. Cows that remained open after calving in autumn are kept until June. Keeping them until more profitable months later in summer is not profitable. The average interval of calving to voluntary culling is 190 days. In herds III and IV the course of heifer and herd calvings during the year goes more smoothly. This is in agreement with the presumption that the heifer calving pattern is related to the herd calving pattern in these cases.

In Table 5, technical and economic results of these herds are presented. The culling rate varies from 32.2% (II) to 35.2% (IV). Gross margin per average cow is highest for herd II. The difference between herd II and herd IV is

Table 5. Technical and economic results at equilibrium for four herds with different calving patterns.

	Herd			
	I[a]	II	III	IV
Technical results				
Number of cows	100	100	100	100
Number of calvings	115.9	115.4	116.0	116.6
Culling rate herd (%)	33.2	32.2	33.7	35.2
Culling rate heifers (%)	42.0	39.3	43.2	46.6
Interval calving-culling (days)	178	177	180	182
Calving interval (days)	371	371	371	371
Milk per ave cow (kg)	7039	7032	7060	7089
Fat per ave cow (kg)	311	312	312	312
Protein per ave cow (kg)	241	241	242	242
Feed intake per ave cow (1000 VEM)	5634	5636	5641	5646
Average prices (Dfl.)				
Milk price premium (100 kg)	0.64	0.90	0.50	0.04
Feed price (1000 VEM)	0.276	0.277	0.275	0.274
Calf revenues per calving	345	350	336	328
Price heifer	2617	2630	2609	2589
Slaughter value per culled animal	1546	1540	1554	1565
Economic results (Dfl./ave cow)				
Revenues				
milk	5864	5885	5866	5842
calves	399	403	390	383
culls	513	495	524	551
Costs				
feed	1553	1560	1554	1545
heifers	868	845	879	912
Gross margin				
average	4356	4378	4347	4319
deviation from highest outcome	-22	0	-31	-59

[a] I: heifer calving pattern equal to herd culling pattern;
II: heifer calving pattern equal to voluntary herd culling pattern;
III: heifer calving pattern equal to herd calving pattern;
IV: heifer calving pattern belonging to average herd calving pattern of the Netherlands.

largest and amounts to Dfl. 59. Approximately 80% of the difference in gross margin between herd II and the other herds originates from differences in milk, calves and feed. The remainder originates from differences in replacement costs (heifer costs minus revenues of culled animals).

3.4 Sensitivity analysis

Results at equilibrium have been calculated for the herds belonging to the three defined sets of reproduction parameters. In all cases, the heifer calving pattern is equal to the herd calving pattern (alternative III). The resulting calving patterns are presented in Figure 4. With an improvement of reproductive performance, the number of calvings in the more profitable autumn months increases. The opposite happens, when reproductive performance is reduced. The major technical and economic results are presented in Table 6. Since the proportion of calvings in autumn increases with the improvement of reproductive performance, milk production per average cow and the milk price premium increase as well. Gross margin per average cow per year is Dfl. 57 higher than in the basic situation. In case of a decrease in reproductive performance, gross margin decreases by Dfl. 83.

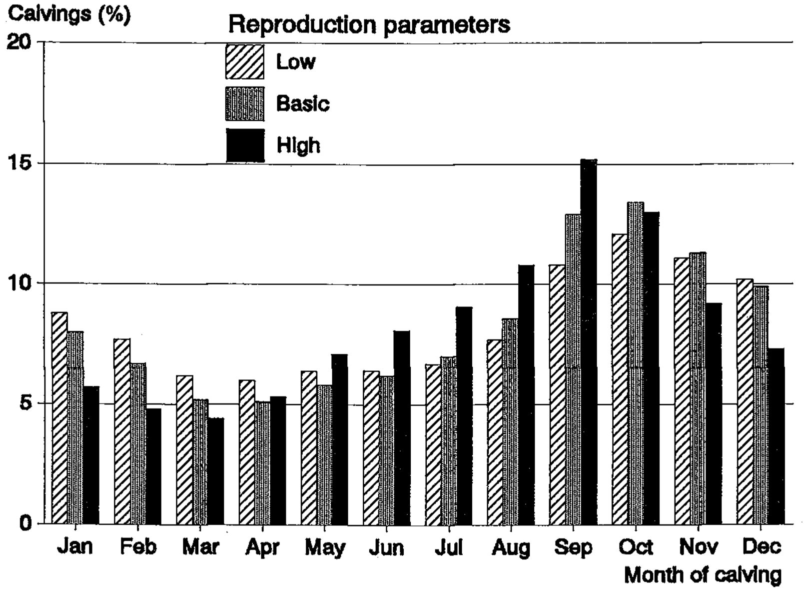

Figure 4. Heifer and herd calving pattern for herds with different reproduction parameters.

Table 6. Technical and economic results at equilibrium for three herds with different reproduction parameters (type equilibrium: heifer calving pattern = herd calving pattern).

	Reproduction parameters		
	Low[a]	Basic	High
Number of calvings	115.8	116.0	117.2
Culling rate herd (%)	38.0	33.7	31.0
Interval calving-culling (days)	187	180	169
Calving interval (days)	379	371	364
Milk per ave cow (kg)	6999	7060	7087
Ave milk price premium (Dfl./100 kg)	0.33	0.50	0.64
Revenues(milk+calves) - costs(feed) (Dfl./ave cow)	4652	4702	4744
Costs(heifers) - revenues(culls) (Dfl./ave cow)	387	355	340
Gross margin (Dfl./ave cow)	4264	4347	4404

[a] Low reproductive parameters: compared to the basic situation oestrus detection rate and conception rate have decreased relatively by 10%, and average interval calving to first insemination is increased by 6 days. The opposite is done in case of high reproductive parameters.

Results from SME-herds belonging to the alternatives that exclude seasonal variation in one or more traits or prices are presented in Table 7. Leaving out the seasonal variation in milk price has a large effect on the ranking of the SME-herds. The SME-herd with the lowest gross margin has shifted from March to August. Differences between SME-herds have become smaller. If seasonal variation in milk production is excluded, the ranking of the strategies also changes. The absolute difference between the SME-herd with highest (July) and lowest gross margin (February) is much higher than in the basic situation. The absence of seasonal differences in feed costs, slaughter value and heifer price influences the differences between months, but has no effect on the ranking.

4 DISCUSSION AND CONCLUSIONS

The presented Markov chain approach has shown to be very powerful in simulating herd dynamics and corresponding technical and economic results. The model offers the possibility of calculating the steady state distribution belonging to the implementation of the optimum insemination and replacement decisions determined by dynamic programming, as well as for any user-defined strategy. Although not presented here, the model can also be used to follow a herd through time, e.g. when moving to a new steady state distribution. Jalvingh et al. (1992a) illustrated this type of application for a swine model. Furthermore, the modelling approach allows farm-specific input values

Table 7. Differences in average gross margin per cow per year from SME-herds after exclusion of seasonal variation in different traits or prices.

	Gross margin (Dfl./yr)[a]	Month of heifer calving											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Basic situation	4449	-159[b]	-229	-264	-229	-176	-152	-136	-112	-73	0	-9	-66
Variation excluded in:													
(1) Production[c]	4482	-380	-390	-290	-186	-130	-49	0	-5	-28	-89	-186	-302
(2) Feed costs[d]	4473	-232	-339	-396	-372	-282	-242	-181	-133	-49	0	-5	-96
(3) Conception rate	4462	-148	-230	-269	-243	-217	-169	-154	-127	-85	-23	0	-58
(4) Milk price	4387	0	-21	-31	-28	-35	-81	-131	-191	-146	-77	-31	-1
(5) Slaughter value	4431	-137	-201	-225	-195	-139	-119	-113	-92	-52	0	-4	-56
(6) Heifer price	4462	-192	-273	-325	-272	-219	-187	-152	-118	-75	0	-13	-91
(7) Calf price	4472	-118	-165	-223	-269	-298	-295	-254	-174	-96	-20	0	-33
(8) (4)+(5)+(6)+(7)	4433	0	-17	-33	-81	-151	-247	-336	-305	-202	-105	-58	-15

[a] Value belongs to SME-herd with highest gross margin for a certain alternative.
[b] Difference in gross margin between this month and month with highest gross margin for this alternative.
[c] Milk, fat and protein production.
[d] Roughage intake and price.

that influence herd dynamics and corresponding technical and economic results. For effective on-farm decision support, the current model should be combined with the management information system of the individual farm in order to ease farm-specific input.

Genetic progress has been set at zero in all calculations. In reality, genetic progress influences the level of production and milk revenues over time. Purpose of the modelling approach is a comparison of the consequences of different management strategies. Without genetic progress, a change in production over time can directly be attributed to the chosen strategy, which enables a better interpretation of the results. The model can be used in a situation with genetic progress, but computation time would increase considerably. Van Arendonk (1985b) showed that rate of genetic progress hardly effects the optimum insemination and replacement policy. In conclusion, excluding genetic progress improves the interpretation of results and is expected to have little impact on the comparison of strategies.

From the results (Table 4), it is most profitable to have calvings concentrated in autumn. Changing the current calving pattern of an individual herd towards calvings concentrated in autumn, therefore, may be profitable. Such a change can be realised in various ways. When following the herd through time, the model could be used to compare different strategies for changing the calving pattern, as illustrated in the accompanying paper (Jalvingh et al., 1993). However, if the majority of farmers change the calving pattern towards autumn, price differences within the year will change. This can especially be expected for price differences in calves, culled cows and milk, since these prices are related to the supply pattern. From the results (Table 7), it can be concluded that seasonal variation in milk price is the major component that determines seasonal differences in herd results.

DeLorenzo et al. (1992) modified and implemented the dynamic programming model of Van Arendonk (1986) for US conditions. In addition, they determined the steady state distribution belonging to the use of the optimal insemination and culling policies and they refer to this as the optimized herd structure. Immediate replacement takes place, so that herd size is kept constant through time. Results in the current paper show that a herd with all heifers calving in October is most profitable. Here, the herd size remains constant on an annual basis, but varies within the year. Therefore, it is questionable whether the situation with immediate replacement is the optimized situation as suggested by DeLorenzo et al. (1992). The results from the current calculations show that it is profitable to leave a cow-place open after culling at certain moments, so that the heifer can enter the herd in a more profitable month of calving. This is especially the case for replacing involuntarily culled animals.

However, a herd with all heifers calving in October is not very realistic. The possibility of having all heifers calving in October is determined by the availability of the number of heifers in different months. The availability of heifers depends on the calving pattern of all cows during previous years, the selection of the heifer calves reared for replacement and the quality of reproductive management. Tuning of available heifers to desired calvings of heifers is an important element in this, and will be worked out in the accompanying paper (Jalvingh et al., 1993).

The calving pattern determines the pattern of monthly milk production, and need for roughage and labour. Having calvings concentrated in certain months, may lead to problems in the supply of roughage or interfere with the preferred pattern of labour supply. The model has the ability to show this type of consequence for any calving pattern. By trial-and-error and using the direct solution approach, a heifer and herd calving pattern which meets the various conditions can be determined. By combining the results of the SME-herds with linear programming, a method has been created that determines the optimum calving pattern taking into account several restrictions at herd level, such as milk quota, maximum herd size and labour supply. This method will be described in a future paper. The model presented in the current paper can, therefore, be used in various ways to support the farmer in choosing the calving pattern which is optimum given the situation at the farm.

ACKNOWLEDGEMENTS

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APPENDIX

Table A1. Per month of insemination or resulting calving interval: (a) proportion of first inseminations for heifers and older cows[a], (b) the relative conception rate for different months of insemination[a,b], (c) adjustment factors for the effect of the number of days open on milk production (multiplicative) and composition (additive) of the milk during the total lactation period (excl. seasonal variation)[c] and (d) additive effect of number of days open on milk production in next lactation[d].

		Month of insemination/ Resulting calving interval in case of pregnancy						
		2/11	3/12	4/13	5/14	6/15	7/16	8/17
Reproduction								
Prop. of first inseminations								
- heifers		44	41	11	4	0	0	0
- cows		49	38	10	3	0	0	0
Relative conception rate		0.97	1.02	1.02	1.00	0.97	0.92	0.90
Production								
Milk production	1[e]	0.932	1.000	1.057	1.106	1.149	1.187	1.221
	2	0.939	1.000	1.050	1.092	1.127	1.157	1.182
	≥ 3	0.944	1.000	1.044	1.080	1.110	1.133	1.151
Fat content	1	-0.027	0.000	0.024	0.044	0.061	0.076	0.089
	2	-0.025	0.000	0.021	0.039	0.053	0.066	0.076
	≥ 3	-0.023	0.000	0.019	0.035	0.047	0.057	0.065
Protein content	1	-0.018	0.000	0.015	0.027	0.038	0.046	0.053
	2	-0.017	0.000	0.014	0.024	0.033	0.040	0.046
	≥ 3	-0.016	0.000	0.012	0.022	0.030	0.035	0.040
Effect on milk production in next lactation (kg)		-106	0	+62	+113	+155	+190	+217

[a] Based on Van Arendonk (1985a).
[b] Relative to the average conception rate (see Table A2).
[c] Calculated using the extended model of Cobby and Le Du (1978) for lactations 1, 2 and 3 and higher.
[d] Based on Van Arendonk (1985a).
[e] Lactation number.

Table A2. Per lactation number: (a) average conception rate after first insemination[a], (b) probability of involuntary disposal[a,b], (c) multiplicative adjustment factors for age at calving on milk production and composition[c,d].

Lactation number	Conception rate	Probability of disposal	Milk	Fat content	Protein content
1	0.56	0.12	0.742	1.021	1.006
2	0.61	0.13	0.878	1.023	1.034
3	0.63	0.14	0.953	1.019	1.020
4	0.63	0.15	0.990	1.015	1.010
5	0.61	0.17	1.002	1.009	1.006
6	0.59	0.17	1.006	1.005	1.003
7	0.57	0.18	1.000	1.000	1.000
8	0.55	0.19	0.993	0.994	0.996
9	0.52	0.21	0.983	0.986	0.992
10	0.50	0.23	0.969	0.978	0.987
11	0.47	0.25	0.953	0.968	0.981
12	0.45	0.28	0.932	0.958	0.975

[a] Van Arendonk (1985a); oestrus detection rate is 70%.
[b] See Van Arendonk (1985a) for proportion of involuntary disposal per month in lactation.
[c] Wilmink (1985).
[d] See Wilmink (1985) for additive adjustment factors for the effect of month in lactation on fat and protein content.

Chapter 5

Dynamic probabilistic simulation of dairy herd management practices. II. Comparison of strategies in order to change a herd's calving pattern

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ABSTRACT

A dynamic probabilistic simulation model is further extended and used for a comparison of different strategies in order to change the calving pattern of a herd. The Markov chain approach is used to simulate herd dynamics. Strategies to change the calving pattern focusing on the farm's intake of replacement heifers, allowing a certain variation in age at first calving, are compared. A method has been developed which allows the tuning of the available replacement heifers to the desired heifer calving pattern, using linear programming. In the basic analysis a spring calving herd is changed into an autumn calving herd. The difference in gross margin per cow per year between the starting and the desired situation is Dfl. 115. The strategy that allows the largest variation in age at calving is fastest in changing the calving pattern. It takes 9 years to realise the desired herd calving pattern, while the desired heifer calving pattern is already reached after 2 years. This strategy is also the most profitable one. When considering a period of 10 years, this strategy on average yields Dfl. 105 per cow per year. In case of a strategy that does not allow changes in the initial age at calving, the increase is only Dfl. 6 per cow per year after 10 years, while in the previous years the costs of changing exceed even the benefits. An additional measure which does not allow cows to be inseminated in certain months during the first few years, shows not to be economically attractive.

1 INTRODUCTION

Dairy farmers can increase their income by producing particularly in those periods of the year that have higher revenues or lower costs. Jalvingh et al. (1993) developed a dairy herd simulation model and made static comparisons of seasonal herd calving patterns. They concluded that under the current Dutch conditions it is best to concentrate calvings in autumn, which is mainly due to seasonal variation in milk price.

The calving pattern of a herd can be changed in different ways, either focusing on cows or on young stock. Considering cows, the calving interval can be changed. With young stock, the age at first calving can be varied along with the proportion of newly-born heifer calves which are kept for replacement at different times throughout the year. Additionally, cows and young stock can be purchased or sold. From interviews with farmers, it became clear that they prefer actions with respect to young stock in changing the calving pattern.

Until now calculations on the profitability of changing the calving pattern were restricted to a comparison of the profitability of the starting and the desired situation (Mandersloot et al., 1987; Wunder and Orth, 1989), combined with an enumeration of costs of individual measures (e.g. costs of lengthening calving interval or the rearing period with one month) (Strandberg and Oltenacu, 1989; Schmidt, 1989). The objective of this paper is to investigate the importance of studying the consequences of actually changing the calving pattern of the herd as well. These consequences are difficult to judge beforehand, as they are revealed in various revenue and cost items and spread through time. A simulation model can offer help in determining whether it is profitable to change the calving pattern. In this paper, the model of Jalvingh et al. (1993) is extended and used for a comparison of strategies for changing the calving pattern. The model allows for a farm-specific approach taking into account biological variability and different management practices. The paper describes an integrated modelling approach that (a) simulates the herd in the starting situation, (b) determines the desired calving pattern and (c) examines the costs and benefits through time of strategies that can be used to change the calving pattern. The number of options to change the calving pattern, however, is too large to include them all. Attention, therefore, is limited to the strategies concerning the intake of young stock into the herd. The modelling approach as such, however, is flexible enough to include other strategies and conditions.

2 MATERIAL AND METHODS

2.1 General

For determining the consequences of a strategy that changes a herd's calving pattern, the situation where to start from (starting situation), the situation where to go to (desired situation) and the strategy to realise the desired situation need to be defined. The dairy herd model of Jalvingh et al. (1993) is used as a basis to simulate the consequences of a strategy. Some extensions were made to make the model more flexible for strategies concerning the farm's intake of replacement heifers, using the linear programming technique.

2.2 Replacement heifer model

In the dairy herd model, animals that are culled are replaced by springing heifers to maintain herd size. The herd size is kept constant on an annual basis but may vary within a year by allowing non-immediate replacement. The distribution of heifer calvings over calendar months depends on a given pattern. The number of replacement heifers entering the herd is calculated in such a way that given the calving pattern the herd size is kept constant on an annual basis.

The strategies to change the calving pattern focus on the intake of replacement heifers into the herd. In the original dairy herd model it is assumed that there are always enough heifers available for replacement. In changing the calving pattern, this assumption no longer holds; the available replacement heifers are required to originate from herd calvings in the past. Therefore, simulation of replacement heifers from birth to calving is added to the model in order to make the number of available heifers dependent on calves born in the past. Planning of the intake of replacement heifers is a complicated matter. Therefore, a method has been developed which allows the tuning of available replacement heifers to the desired calving pattern.

Simulation of young stock

Of the calves born in the dairy herd model, 50% are females, 3% of the births concerns twins and 88% of first calving cows bear a calf that survives the first week. For older cows the calves' survival rate is 96%. The remainder makes up the potential for replacement. During the rearing period 7.5% of the young stock is culled annually. In case the length of the rearing period is not modified intentionally, the remaining heifers calve at the age of 23, 24 and 25 months, at a rate of 25%, 50% and 25% respectively. At the moment of calving it is decided which heifers will enter the herd. For the economic calculations replacement heifers are valued at market (i.e. cost) price, implying that the rearing of young stock is not an activity included in the dairy herd enterprise (Jalvingh et al., 1993).

The tuning of available heifers to the desired calving pattern

When following the herd through time, the intake of replacement heifers per year is focused on keeping the average number of cows (ANC) present in the herd constant on an annual basis. At the start of each year calculations are carried out to determine this intake of heifers in terms of number of heifers calving per month. A schematic overview of these calculations is presented in Figure 1.

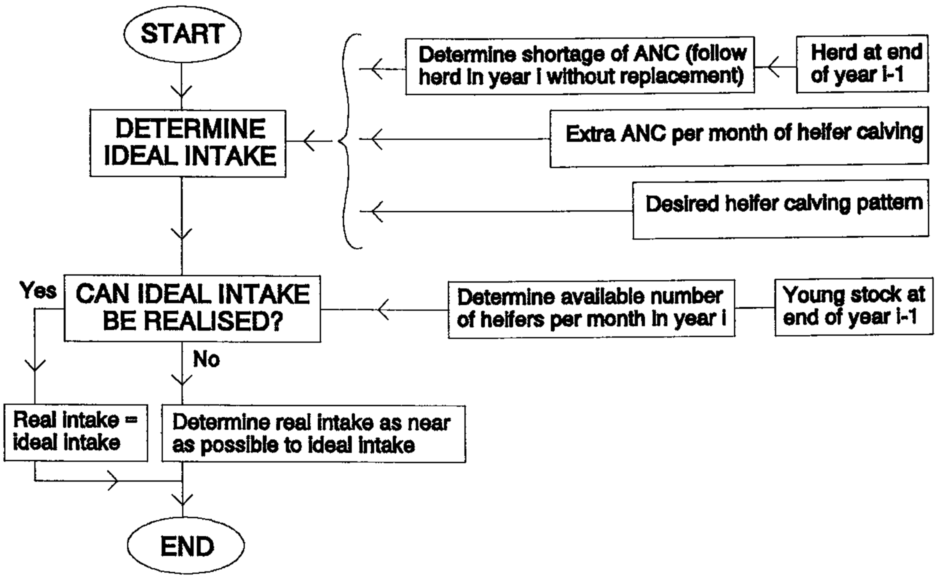

Figure 1. Schematic overview of calculations at start of year i to determine the intake of heifers per month in year i.

In the first step the ideal intake is calculated. The ideal intake represents the intake that keeps the average herd size constant on an annual basis and matches the desired heifer calving pattern. The herd is followed during one year without carrying out replacement of culled animals. The resulting shortage in ANC should be compensated for by the heifers that enter the herd during that year. For each calving month of a heifer the number of extra ANC a heifer realises in the rest of the year is known, taking into account the probability of disposal (see Table 1). The shortage of ANC, the extra ANC per heifer calving in a certain month and the desired heifer calving pattern, are combined into the ideal intake of heifers for each month of that year (Figure 1).

In the second step it is determined whether the calculated ideal intake can be realised with the available heifers. From available young stock at the beginning of the year, it is determined how many heifers might calve per month during that year. If there are enough heifers available in each month,

Table 1. Extra average number of cows in rest of the year when heifer calves in a specific month.

Apr[a]	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
0.75	0.71	0.66	0.60	0.54	0.49	0.46	0.40	0.33	0.25	0.16	0.08

[a]In the calculations a year runs from April to March

the ideal intake can be realised. Adjustments to the intake have to be made otherwise (Figure 1). These adjustments focus on trying to realise the ideal intake as much as possible. In the model two different ways have been defined to adjust intake: a) without and b) with changing the length of the rearing period of young stock.

Without changing the length of the rearing period

In case the calculated ideal intake cannot be realised and when the length of the rearing period is not changed, heifers calve in the calendar month they were originally assigned to at the age of either 23, 24 or 25 months. In one or more months a shortage of heifers can be observed. These shortages are eliminated by entering heifers in months with a surplus of heifers. To provide the future availability of heifers calving in months with a shortage, the intake is focused on heifers from surplus months, which on the long term results in the maximum number of calvings in months during which a shortage is observed. This is formulated as the following linear programming problem:

$$\text{Maximize } Z = \sum_{i=1}^{nr_{sp}} \sum_{j=1}^{nr_{st}} a_{ij} x_{ij}, \tag{1}$$

subject to:

(a) $\sum_{i=1}^{nr_{sp}} b_{ij} x_{ij} = \text{shortage}_j$, for all j

(b) $\sum_{j=1}^{nr_{st}} x_{ij} \leq \text{surplus}_i$, for all i

(c) $x_{ij} \geq 0$, for all i and j

In which:

nr_{st} = number of months with shortage of heifers

nr_{sp} = number of months with surplus of heifers

a_{ij} = number of herd calvings at equilibrium in shortage month j when one heifer calves in surplus month i; a_{ij} is obtained from single-month equilibrium herds (see Table 3 in Jalvingh et al., 1993)

x_{ij} = number of heifers calving in surplus month i, to eliminate (partly) shortage in month j

shortage_j = number of heifers short in month j

surplus_i = number of heifers surplus in month i

b_{ij} = scaling factor that assures that ANC is exactly constant on an annual basis and represents the quotient of extra ANC of a heifer calving in shortage month j and extra ANC of a heifer calving in surplus month i (see Table 1).

Especially in the case that shortages of heifers are countered by entering heifers in months at the end of the year, the scaling factor b_{ij} is relatively high, assuring that many heifers enter the herd. This will have a great effect on the number of heifers needed in the following year, since heifers entering during the last months of a year have only little impact on ANC in that particular year, but a great impact on ANC in the following year. To overcome these annual fluctuations in number of heifers entering the herd, the scaling factor b_{ij} is set at 1 in all cases.

With changes in the length of the rearing period

Modification of the length of the rearing period should be interpreted as delaying or advancing the age of first insemination and as a result of this the age at first calving. The initial age at first calving (23, 24 or 25 months) can be increased in the model by 6 months and decreased by 2 months at the maximum. A strategy to change the length of the rearing period is specified by limits for the minimum and maximum age at calving. In the model the maximum age at calving is set at 30 months, and the minimum age at 22 months. The user-defined limits are used to formulate which transitions from surplus months to shortage months are possible, taking into account the initial age at calving. The surplus of heifers from the previous year is also taken into account. At first it is tried to realise the ideal intake by modifying the length of the rearing period of heifers initially calving in surplus months so that they will calve in months with a shortage of heifers. This tuning of surplus heifers to the ideal intake is formulated as a two-step problem in linear programming. In the first step the number of heifers calving in months with a shortage is maximized. In formula:

$$\text{Maximize } Z = \sum_{i=1}^{nr_{sp}} \sum_{j=1}^{nr_{st}} \sum_{l=1}^{3} y_{ijl} \qquad (2)$$

subject to the constraints:

(a) $\sum_{i=1}^{nr_{sp}} \sum_{l=1}^{3} y_{ijl} \leq \text{shortage}_j$, for all j

(b) $\sum_{j=1}^{nr_{st}} y_{ijl} \leq \text{surplus}_{il}$, for all i and l

(c) $y_{ijl} \geq 0$, for all i, j and l

In which:

y_{ijl} = number of heifers changed from calving in age class l (l=1: 23, l=2: 24 and l=3: 25 months) in surplus month i to calving in shortage month j

$surplus_{il}$ = surplus heifers in age class l in surplus month i

In the second step, the priority given to the various changes in the length of the rearing period is taken into account in the objective function. The highest priority is given to little changes in the length of the rearing period. The outcome of the first step is added as an extra constraint to make sure that the maximum number of heifers calving in shortage months will be realised.

In case the ideal intake is not realised by changing the length of the rearing period of available heifers, an additional linear programming problem is formulated to make the actual intake as near as possible to the ideal intake. This is also formulated as a two-step linear programming problem. In the first step the number of calvings on the long term in months during which a shortage of heifers is observed is maximized. This is similar to formula (1), but now includes changes in the length of the rearing period.

$$\text{Maximize } Z = \sum_{i=1}^{(12-nr_{st})} \sum_{j=1}^{nr_{st}} \sum_{k=1}^{nr_{sp}} \sum_{l=1}^{3} a_{ij} v_{ijkl} \qquad (3)$$

subject to:

(a) $\sum_{i=1}^{(12-nr_{st})} \sum_{k=1}^{nr_{sp}} \sum_{l=1}^{3} v_{ijkl} \leq shortage_j$, for all j

(b) $\sum_{i=1}^{(12-nr_{st})} \sum_{j=1}^{nr_{st}} v_{ijkl} \leq surplus_{kl}$, for all k and l

(c) $v_{ijkl} \geq 0$, for all i, j, k and l

In which:

v_{ijkl} = number of heifers calving in month i to overcome shortage in month j; heifer was initially assigned to month of calving k and age class l.

To reduce the number of combinations possible for v_{ijkl}, combinations for which $a_{ij} > a_{kj}$ are allowed only.

In the second step, the priorities for the length of the change in the rearing period are taken into account. The highest priority is given to "no change" in the rearing period. The outcome of the first step is added as an extra constraint to ensure that the maximum number of calvings on the long term will be realised.

Table 2. Price correction of a replacement heifer depending on age at calving (Dfl). Base price of a replacement heifer calving at the age of 24 months is Dfl. 2600.

Age at calving (months)								
22	23	24	25	26	27	28	29	30
-45	-33	0	8	16	24	36	48	60

The simulation model has been programmed in Turbo Pascal and runs on the personal computer. The linear programming problems are solved by including the routines for the simplex method described by Press et al. (1989).

Changing the age at calving influences the performance in the first lactation. Heifers calving at an older age and higher live weight produce more milk, but need more feed for maintenance and may have more variable costs involved in rearing. Together this leads to the correction of the price of a replacement heifer when not calving at the age of 24 months as given in Table 2.

2.3 Analysis

In the basic analysis four strategies will be simulated and compared for one starting situation and one desired situation. In performing the simulation, the basic input variables for reproduction, disposal, milk production, feed intake, slaughter value and prices as described by Jalvingh et al. (1993) in the accompanying paper are used.

In the starting situation a spring calving pattern has been defined, with heifers calving from January to June at a monthly rate of 5%, 20%, 25%, 25%, 20% and 5% respectively. The desired pattern includes heifers calving in autumn at similar monthly rates, but now for the months August to January. The herd calving patterns in the starting and desired situation are a result of the heifer calving pattern and the transition probabilities that are used. The heifer calving patterns have been chosen in such a way, that they can be realised by raising and inseminating calves born in the herd. The average herd size is set at 100 cows.

Jalvingh et al. (1993) slightly modified the dynamic programming model of Van Arendonk (1986) to determine the optimum insemination and replacement decisions for individual cows, taking into account seasonal variation in performance and prices. These optimal decisions are used in (a) determining the herd at equilibrium belonging to the desired situation and (b) when following the herd through time to calculate the consequences of one particular

Table 3. Overview of strategies that will be compared.

Strategy	Length of rearing period	Minimum age at calving	Maximum age at calving
I	not changed	-	-
II	changed	23	25
III	changed	23	27
IV	changed	22	29

strategy. In the starting situation the optimal decisions are used belonging to the situation without seasonal variation in performance and prices.

The four strategies to be compared are presented in Table 3. In strategy I the length of the rearing period is not allowed to change. In the other strategies the length of the rearing period is allowed to change; the minimum and maximum age at calving vary. The herd will be followed over time during a period of 10 years. One year runs from April to March, which is the administrative period for the current EC milk quota system.

The following measure is used to summarize to what extent the realised and desired calving patterns deviate:

$$\sqrt{\sum_{i=1}^{12} (r_i - d_i)^2 / 12}$$

in which:

r_i = realised percentage of calvings in month i

d_i = desired percentage of calvings in month i

The economic consequences of the strategies are shown by comparing them with a strategy in which the desired situation equals the starting situation (strategy 0; no change of calving pattern). The strategies are compared for different time periods. The net present value of gross margin per cow per year is calculated by summing the discounted annual values of gross margin per cow per year for the period of consecutive years to which the present value refers. The discount rate is set at $0.96^{1/12}$ per month. Additionally, the net present value is converted into annual equivalent values by using the amortization factor procedure in order to make a good comparison possible at different points in time (Boehlje and Eidman, 1984). Unless stated otherwise, all revenues and costs mentioned in this paper refer to the annualized net present value.

Finally, a sensitivity analysis will be carried out. First, the consequences of an increase in the costs of changing the length of the rearing period is calculated. In case the age at calving deviates from 24 months, Dfl. 30 of extra costs are taken into account per month of deviation. The effects of extra actions taken in changing the calving pattern will be investigated. The extra actions consist of allowing no inseminations of cows in June and July in year 1 to 3, which results in no calvings of cows in March and April. Heifers can still enter the herd in March and April.

3 RESULTS

3.1 Starting and desired situation

In Figure 2, the heifer and herd calving patterns are presented belonging to the steady state herds in the starting and desired situation. As could be expected, the majority of herd calvings takes place in the same season as the majority of heifer calvings, but there are also cows calving in the less favourable months. In Table 4, the major technical and economic results of the two herds are presented. Gross margin per cow per year is in the desired situation Dfl. 115 higher than in the starting situation. This difference originates mainly from differences in milk revenues due to differences in average milk price premium received per kg of milk and the average milk production per cow. The interval between calving and culling in the desired situation is 16 days longer than in the starting situation, which is due to all voluntary cullings (210 vs. 178 days). This is a result of including seasonal effects in determining the optimal insemination and replacement decisions for individual cows in the desired situation.

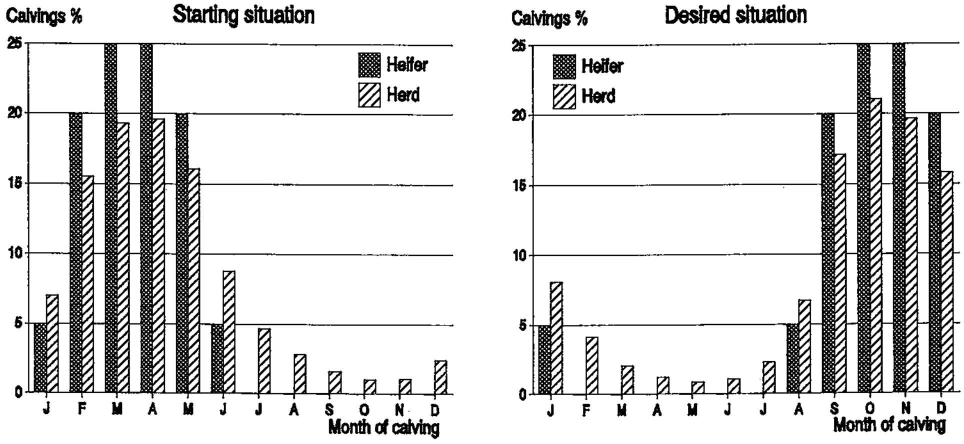

Figure 2. Calving pattern of heifers and herds in starting situation and desired situation.

Table 4. Major technical and economic results of herds belonging to starting situation and desired situation.

	Starting situation	Desired situation
Ave number of cows	100.0	100.0
Number of calvings	115.4	114.5
Culling rate herd (%)	31.0	31.9
Interval calving-culling (days)	171	187
Calving interval (days)	371	371
Milk per ave cow (kg)	7072	7128
Ave milk price premium (Dfl/100 kg)	-0.71	0.95
Economic results (Dfl/ave cow)[a]		
Revenues - milk	5867	6080
- calves	400	374
- culls	479	508
Costs - feed	1543	1617
- heifers	815	841
Gross margin	4388	4503

[a] Annualized net present value.

3.2 Strategies to change calving pattern

For strategy II, the heifer and herd calving patterns are illustrated in Figure 3, showing the change in calving pattern when going from the starting situation to the desired situation. The desired calving pattern for heifers is realised for the first time in year 9. The herd calving pattern belonging to the desired heifer calving pattern is not realised within 10 years. To what extent the realised calving pattern deviates from the desired calving pattern for all

Table 5. Deviation realised heifer and herd calving pattern from desired heifer and corresponding herd calving pattern in time for all strategies and year in which deviation becomes zero.

Year	Heifers				Herd			
	I	II	III	IV	I	II	III	IV
0	18.6	18.6	18.6	18.6	23.1	23.1	23.1	23.1
1	15.5	14.9	13.5	4.9	20.0	19.1	17.2	9.5
2	15.4	14.8	13.7	0.0	19.4	18.4	16.5	5.2
3	14.7	13.1	7.0	0.0	18.4	16.1	9.4	3.2
4	14.1	11.3	0.0	0.0	17.5	13.8	3.6	2.0
5	13.0	8.6	0.0	0.0	16.1	10.6	2.2	1.1
6	12.1	6.5	0.0	0.0	14.8	7.8	1.3	0.7
7	11.1	3.7	0.0	0.0	13.5	4.6	0.8	0.3
8	10.2	1.4	0.0	0.0	12.3	2.1	0.4	0.2
9	8.8	0.0	0.0	0.0	10.7	0.9	0.2	0.0
10	7.5	0.0	0.0	0.0	9.1	0.5	0.1	0.0
Deviation zero in year	17	9	4	2	20	14	11	9

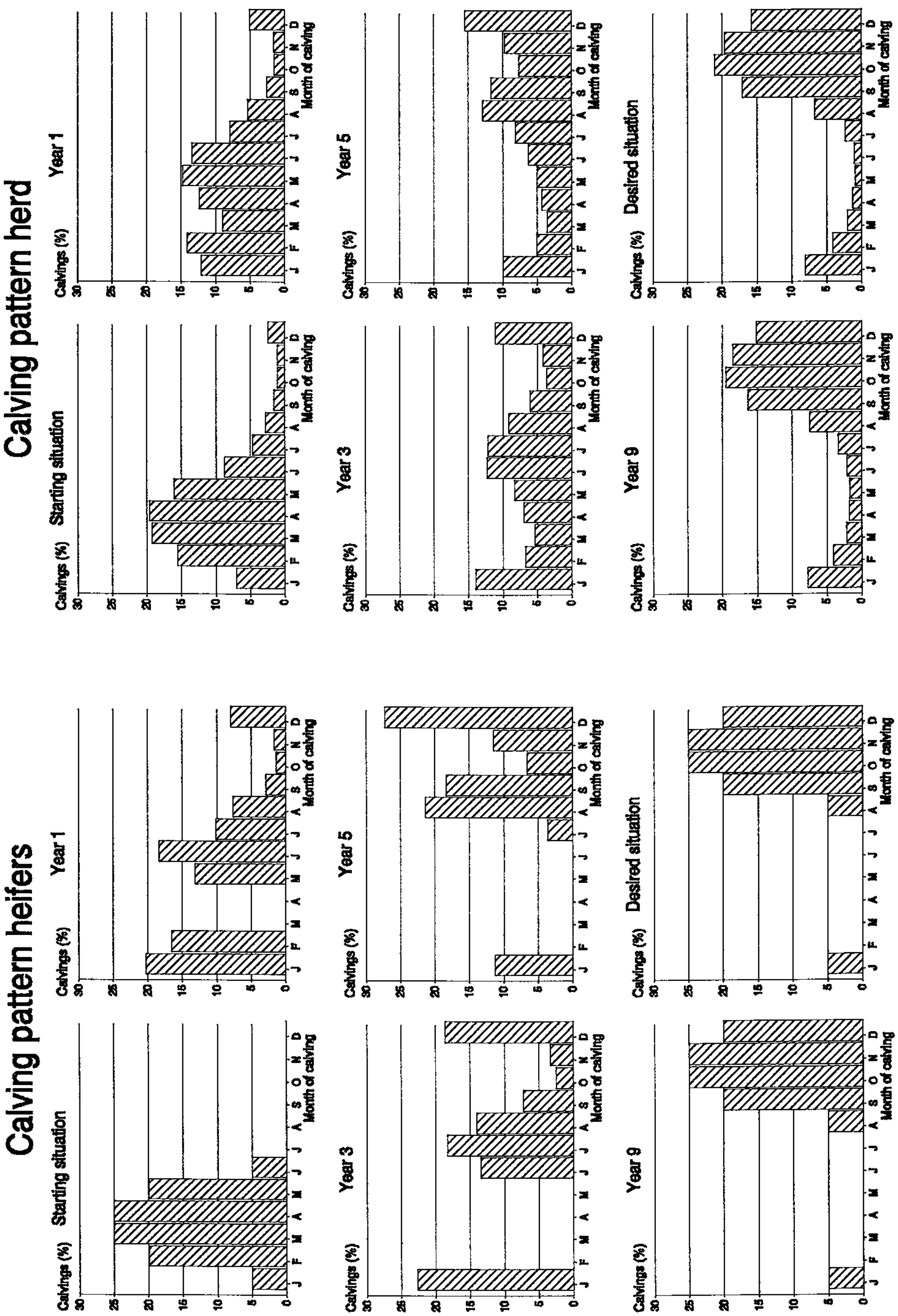

Figure 3. Heifer and herd calving pattern for starting situation, desired situation and period going from starting situation to desired situation in the case of strategy II.

Table 6. Major characteristics concerning replacement heifers entering the herd in specific years.

	Year	Strategy			
		I	II	III	IV
Replacement rate (%)	1	41.6	41.1	40.9	41.6
	2	37.4	36.5	35.1	31.1
	3	37.6	35.6	34.0	34.6
	5	35.9	32.6	31.6	33.5
	9	33.4	31.6	32.1	33.5
Ave age at calving (months)	1	24.0	24.1	25.5	26.3
	2	24.0	24.0	25.4	26.5
	3	24.0	24.1	25.4	24.9
	5	24.0	24.0	24.5	24.0
	9	24.0	24.0	24.0	24.0
Proportion of heifers with length of rearing period changed (%)	1	0.0	62.4	77.5	82.6
	2	0.0	59.9	77.6	78.3
	3	0.0	58.4	63.8	46.2
	5	0.0	42.3	26.0	11.0
	9	0.0	4.2	0.0	0.0

strategies in different years is presented in Table 5. The strategy that is the most flexible in changing the rearing period of young stock (IV) is the first to realise the desired heifer and herd calving patterns. Although the desired heifer calving pattern has already been realised in year 2, it takes several years more before the corresponding herd calving pattern is realised. Strategy I, allowing no change in the length of the rearing period, is the slowest to reach the desired calving pattern. Not until year 17 is the desired heifer calving pattern realised. The corresponding herd calving pattern is already realised 3 years later (Table 5), since the desired heifer calving pattern is approached more gradually than in the other strategies.

Table 6 shows some characteristics for all strategies concerning the replacement heifers that enter the herd in different years. The replacement rate in the

Table 7. Distribution of replacement heifers entering the herd in year 1 over age classes for all strategies (%).

Age at calving	Strategy			
	I	II	III	IV
22	-	-	-	16.4
23	25.6	41.9	28.4	11.0
24	49.6	7.8	7.8	7.8
25	24.8	50.3	4.5	3.7
26	-	-	4.1	0.2
27	-	-	55.1	3.6
28	-	-	-	3.7
29	-	-	-	53.6

first year is about 10% higher than in the starting situation, and gradually declines in the years after. The high increase in replacement rate in the first year is a result of the change in insemination and replacement strategy used. The new strategy focuses on realising calvings in autumn. In the first year many animals do not calve in the desired season, and many of them, therefore, are not inseminated but culled later on. In the first year of strategies II, III, and IV, the rearing period of the majority of heifers entering the herd is changed. This percentage declines later on. The rate by which it declines depends on to what extent the desired heifer calving pattern is realised. In Table 7, the distribution of heifers over age classes in year 1 is presented. The rearing period is lengthened or shortened as much as possible and as much as needed.

In Figure 4, the annualized net present value of gross margin per cow per year is presented for different periods of time and for all strategies. The given values are expressed as the deviation from the annualized net present value for strategy 0 (no change of calving pattern). Annual fluctuations in gross margin per cow per year are a result of annual fluctuations in number of replacement heifers entering the herd. Strategy IV is the most profitable strategy in

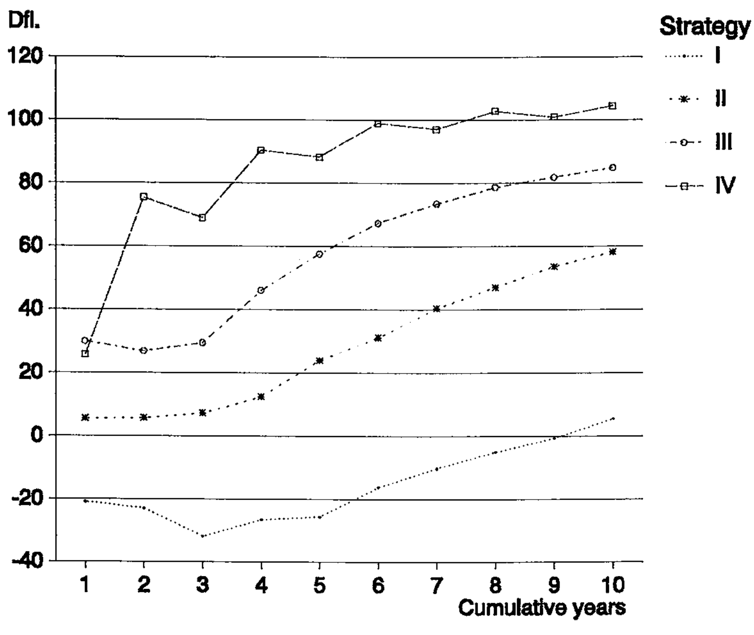

Figure 4. Annualized net present value of gross margin per cow per year for the respective cumulative years, expressed as deviation from strategy 0.

Table 8. Results strategy 0 and I to IV for year 1. Results for strategies I to IV are expressed as deviations from strategy 0 (no change in calving interval).

	Strategy				
	0	I	II	III	IV
Milk per ave cow (kg)	7072	+141	+174	+199	+269
Ave milk price premium (Dfl/100 kg)	-0.71	-0.05	+0.08	+0.30	+0.56
Economic results (Dfl/ave cow)[a]					
Revenues - milk	5867	+104	+138	+176	+245
- calf	399	+19	+17	+15	+10
- culls	479	+150	+141	+140	+109
Costs - feed	1543	+10	+18	+24	+44
- heifers	815	+284	+273	+276	+295
Gross margin	4388	-21	+6	+30	+26

[a] Annualized net present value.

changing the calving pattern when considered after a few years, and also when considered after 10 years. When the number of years considered increase, the benefit per cow per year realised by changing calving pattern also increases, until a certain maximum has been reached. Considering a period of 10 years, an increase in gross margin of Dfl. 105 per cow per year can be realised with strategy IV. In case of strategy I, the benefits amount to only Dfl. 6 per cow per year after 10 years (Figure 4), while in previous years the costs of changing exceed the benefits. The high increase in replacement costs in the first few years, due to the increase in culling rate, cannot be compensated for by extra milk revenues. It takes more time before heifers calve in months resulting in higher milk revenues. Table 8 presents, for all strategies, more precise information on annualized net present value of revenues and costs in year 1. The milk production per average cow present in the herd in year 1 is approximately 140 (strategy I) to 270 kg (strategy IV) higher than in the starting situation, due to the increase in the culling rate in year 1 (Table 8). The extra cows that are culled, mainly spring calving cows culled in autumn, contribute considerably to milk production in year 1. Since they are replaced by replacement heifers before reaching the period of low production or no production at all (dry period), a reduction in the average length of the lactation and in the average length of the dry period per lactation can be observed. Together with the increase in the total number of calvings, this results in the observed increase in milk production per average cow present in the herd. This increase is temporary; in the following years the milk production is approximately 150 (strategy I) to 200 kg (strategy IV) lower than in year 1. This can be explained by the reduction in the culling rate and the number of calvings and consequently more cows in the dry period. Also the proportion of younger, less productive animals present in the herd is higher in these years.

3.3 Sensitivity analysis

In Figure 5, the annualized net present value of gross margin per cow per year is presented for all strategies in case the costs of changing the length of the rearing period have been increased by Dfl. 30 per month of deviation from 24 months. As could be expected, gross margin decreases, especially the first few years. The highest decrease is found for strategy IV, since in this case the greatest changes in age at calving take place. In year 1, gross margin is decreased by Dfl. 38, and becomes lower than in strategy 0. Considering a period of 10 years, the gross margin decreases by Dfl. 10 per cow per year compared to the basic situation. For strategies I, II and III the gross margin per cow per year is decreased by Dfl. 1, 3, and 7 respectively.

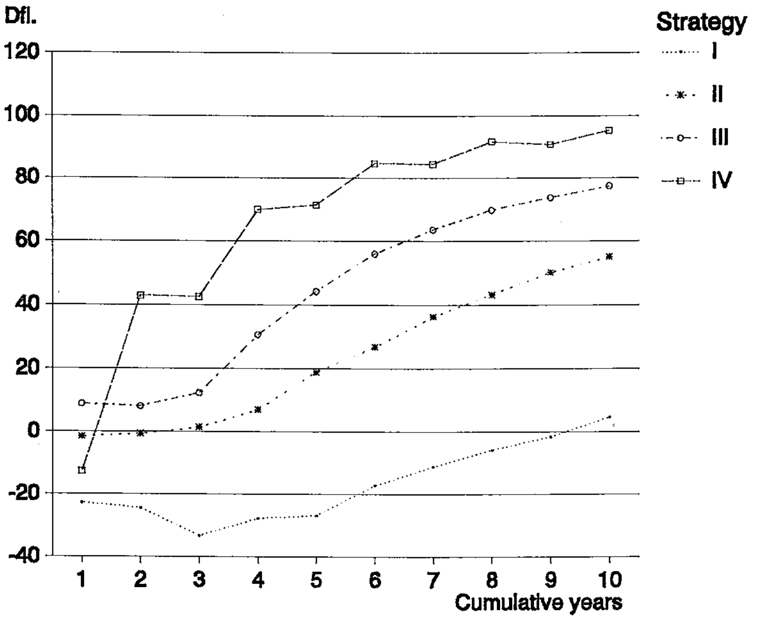

Figure 5. Annualized net present value of gross margin per cow per year for the respective cumulative years, expressed as deviation from strategy 0. Costs of changing the length of the rearing period have been increased.

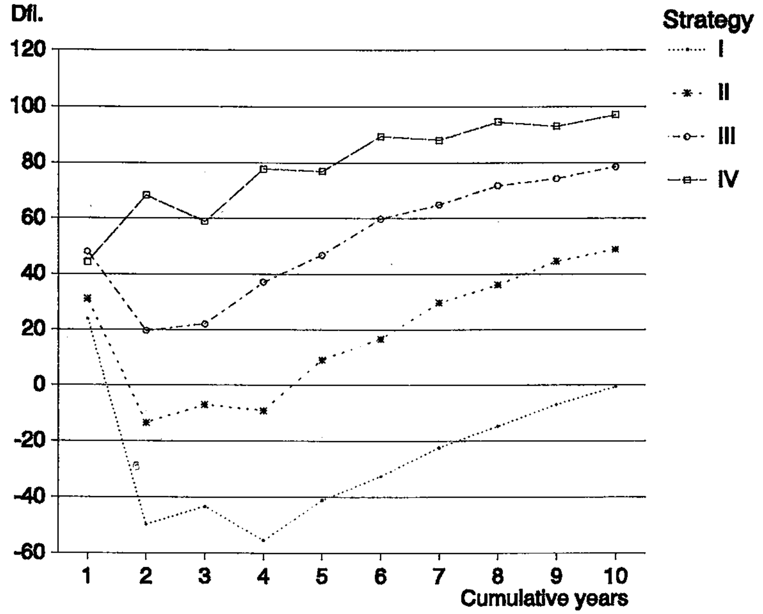

Figure 6. Annualized net present value of gross margin per cow per year for the respective cumulative years, expressed as deviation from strategy 0. In years 1 to 3 no inseminations are allowed in June and July.

In Figure 6, the annualized net present value of the gross margin per cow per year is presented for the situation in which, as an additional measure, cows are not inseminated in June and July during the years 1 to 3. In year 1, the gross margin per cow per year is for all strategies higher than in the basic analysis. The increase in replacement rate, from about 41% to 47%, results in higher replacement costs. This is, however, outweighed by higher milk revenues, since the increase in the culling rate results in a higher increase in milk production per cow. When considering 2 years, the reduction in the net present value in the case of strategies I, II and III is larger than in the basic analysis, because of lower milk revenues and higher replacement costs. The reduction in milk revenues can be explained by a higher decrease in milk production in both year 2 and the following years (300 (I) to 390 kg (III)) compared to the basic analysis, which is a result of the higher proportion of younger cows in the herd. Since the replacement rate in year 1 is very high, more heifers enter the herd in less desirable months, resulting in additional cullings and higher replacement costs in year 2 compared to the basic analysis.

Over a period of 10 years, the gross margin is decreased for all strategies by approximately Dfl. 7 per cow per year. "No inseminations in certain months of the year" as an additional measure in changing calving pattern, therefore, does not turn out to be economically attractive.

4 DISCUSSION AND CONCLUSIONS

The modelling approach presented in this paper is able to make both static and dynamic comparisons of herd calving patterns. Calculations so far on the profitability of changing the calving pattern were restricted to a comparison of the profitability of the starting and the desired situation (Mandersloot et al., 1987; Wunder and Orth, 1989), combined with an enumeration of costs of individual measures (Strandberg and Oltenacu, 1989; Schmidt, 1989). No attention was paid to the consequences of actually changing the calving pattern of the herd. The results of the current study show the importance of going beyond such a static comparison of calving patterns. The maximum possible profit to be obtained depends on the difference in profitability of the starting and desired situation. But, the profit that will actually be realised when changing the calving pattern, depends on the strategy applied and on the moment in time the profitability is considered. In the current study a spring calving herd is changed into an autumn calving herd by strategies focusing on the farm's intake of replacement heifers. The strategy that is able to realise this increase fastest turns out to be the most profitable one to change calving pattern. Each strategy approaches a certain maximum profit per cow per year but this is still lower than the difference in profitability of the starting and desired situation. The maximum value that can be realised with a certain strategy, depends mainly on the results obtained in the first few years.

The difference in gross margin between the starting and desired situation used in this paper amounts to Dfl. 115 per cow per year. In using strategy IV, the maximum profit to be realised is Dfl. 105 per cow per year. In the decision of farmers to actually change calving pattern, the level of this profit will be decisive, together with the amount of effort it will take to apply the strategy. The level of the total profit to be obtained in the basic analysis in this paper (Dfl. 115 per cow per year), can considered to be rather high when compared to other measures farmers can apply. Van Arendonk (1987) calculated that applying the optimal insemination and replacement decisions of individual animals lead to a Dfl. 46 higher annual income per cow than in the situation where all cows are inseminated and kept if they conceived. If the optimal decisions were compared with optimal decisions based on the expected milk revenues only, the profit was Dfl. 13 per cow. When all farmers decide to change the calving pattern, the seasonal differences in several prices may change, since the seasonal supply will then have changed. The modelling approach presented in this paper, can be used to determine the consequences of different price scenarios on the profitability of different calving patterns and on the profitability of actually changing the calving pattern. If seasonal variation in prices of milk, calves, heifers and slaughter value will disappear completely after a few years, the maximum profit to be realised will be Dfl. 50 per cow per year, which is considerably less than in the basic situation. However, it is still profitable to change the calving pattern to an autumn calving herd.

The strategies are compared for a herd with a good reproductive performance (average calving interval of 371 days). The modelling approach can also be used to simulate herds with poor reproductive performance. In case of the same starting and desired heifer calving patterns as in the basic analysis, the resulting herd calving pattern will be spread more widely. This means that differences in profitability between the starting and the desired situation will be smaller (Jalvingh et al., 1993). Moreover, these herds will have more difficulties in realising a heifer calving pattern concentrated in a few months, since not enough calves will be available in these months, and, therefore, changes in the rearing period have to be made continuously. Thus, more profit can be obtained by improving the reproductive performance before changing the calving pattern.

The strategies have been compared for a situation in which the average number of cows present in the herd is kept constant on an annual basis. The method which has been developed is flexible enough to carry out calculations for a situation in which, for instance, the annual milk production of the herd is kept constant or is even decreasing over time (quota system). Additional calculations have been carried out for the situation in which annual milk production of the herd is kept constant. The quotum is set equal to the annual milk production in the starting situation. At the start of each year, calculations are carried out to determine the intake of heifers resulting in a constant annual milk production of the herd, similar to the approach used in case of constant herd size (Figure 1). Calculations show the same results as in the case of a constant annual herd size, except for the years 1 and 2. Gross margin in year 1 is for all strategies approximately Dfl. 180 higher than in year 1 of that same strategy in the basic analysis. Due to the high increase in milk production per cow in year 1, part of the culled cows is not replaced by heifers, resulting in a smaller increase in replacement costs. In year 2 the milk production per cow is much lower, combined with the gap between the culling rate and the replacement rate in year 1, this results in a high increase in the replacement rate and costs in year 2. The gross margin per cow per year considered after 2 years is at the same level as in the basic analysis.

Starting point in defining the desired situation is the desired heifer calving pattern. However, the formulation of a desired herd calving pattern fits better in the farmers' perception, and is, therefore, more suitable for use in the field. In a future paper a method will be described for determining the farm-specific optimum herd calving pattern using linear programming and the technical and economic results of single-month equilibrium herds. In determining the farm-specific optimum calving pattern, various restrictions at herd level, such as milk quota, maximum herd size and labour supply, can be taken into account. After determining this optimum, the model described in the present paper can be used to compare different strategies to change the current calving pattern to the farm-specific optimum calving pattern.

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Chapter 6

Optimizing the herd calving pattern by using linear programming and dynamic probabilistic simulation

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ABSTRACT

Until now, little attention has been paid to the influence of seasonal variation in performance and prices on the optimal calving pattern of a herd. A method was developed to determine the farm-specific optimal herd calving pattern by using linear programming. The required technical and economic parameters are calculated by using a dynamic probabilistic simulation model of the dairy herd. The approach was illustrated by a situation in which the objective was to maximize the gross margin of the herd and the annual herd milk production was restricted, resulting in an optimal calving pattern: all heifers calved in August. When, in addition, only home-reared replacement heifers were allowed to enter the herd, heifer calvings took place from July to October. The gross margin was reduced by only Dfl. 0.13/100 kg of milk as a result of the additional constraint. The sensitivity of the optimal herd calving pattern was determined for lower reproductive performance and for a situation in which seasonal price variation was ignored. The method described in this paper is concluded to be a very flexible tool for determining the optimal herd calving pattern, taking into account farm-specific inputs and constraints.

1 INTRODUCTION

For individual animals, optimal decisions on insemination and replacement can be obtained by using dynamic programming (Van Arendonk, 1986; DeLorenzo et al., 1992) and taking into account seasonal variation in performance and prices. DeLorenzo et al. (1992) determined the optimal calving pattern based on the results from the dynamic programming model, assuming immediate replacement of the culled animals, i.e., constant herd size throughout the year. The restriction of constant herd size is a consequence of using the dynamic programming technique. Jalvingh et al. (1993a) developed a dynamic probabilistic simulation model and compared different herd calving patterns by using the decisions for insemination and replacement of individual animals calculated by the dynamic programming model of Van Arendonk (1986). This simulation model allowed for variation in herd size during the year. Jalvingh et al. (1993a) found that, for Dutch conditions, a herd with all heifers calving in October is the most profitable in case of maximization of the gross margin per average cow present in the herd. A herd with all heifers calving in October, however, is not very realistic. For farms using home-reared young stock, the availability of replacement heifers depends on the calving pattern of the herd in previous years, the selection of calves reared for replacement, and the quality of reproductive management. In addition, farmers may not prefer such a concentration in calvings because of restrictions, for example, in the amount of available labour or roughage supply. Until now, little attention has been paid to the determination of the optimal calving pattern of the herd, taking into account herd and farm restrictions.

In this paper, a linear programming approach is described to determine the optimal herd calving pattern, taking into account herd restrictions. The objective is to choose a calving pattern so as to maximize the gross margin of the herd. The maximization is carried out while annual milk production of the herd is restricted (quota system), but the maximization can also be carried out for a situation without output restrictions. In the situation with milk quota, the gross margin per kilogram of milk rather than per cow should be maximized (Gibson, 1989; Van Arendonk and Brascamp, 1990). Various types of additional constraints can be taken into account, e.g., cullings, calvings, and feed intake. The parameters of the objective function and constraints are obtained from the results of the dynamic probabilistic simulation model described by Jalvingh et al. (1993a). A few constraints are examined herein to illustrate the approach. Other applications of the model are discussed.

2 MATERIALS AND METHODS

2.1 The dynamic probabilistic simulation model

Jalvingh et al. (1993a) developed a dynamic probabilistic simulation model for dairy herds that simulates the technical (e.g., reproductive performance) and economic consequences of various decisions concerning production, reproduction, replacement, and calving patterns. Central to the simulation model is the simulation of herd dynamics, using the Markov chain approach (Hillier and Lieberman, 1990). In the herd dynamics module, the herd is described in terms of possible states for animals and transitions between these states. The time between the state transitions equals 1 month. The state variables that are defined in the model are lactation number, stage of lactation, time of conception, milk production level during present lactation, and month of calving. Uncertainty in future performances is included in four groups of transition probabilities: production, reproduction, disposal, and replacement. The transition probabilities depend on biological variables (e.g., conception rate and oestrus detection rate) on the one hand, and the farmers' management strategies (e.g., with respect to insemination and replacement), on the other.

The model has the ability to derive for a given set of biological variables and management strategies, the steady state of the herd representing the situation in which size and age structure of the herd are stable. Such an equilibrium distribution of animals over states is equal to the distribution of replacement heifers calving in different months over all possible states in the herd during their lifetime. A steady state herd is referred to as a single month equilibrium herd (SME-herd) when the herd originates from heifers calving in a specific month only. Consequently, 12 different SME-herds can be distinguished. The corresponding technical and economic results of an SME-herd are determined by combining the equilibrium distribution over states with information concerning milk production, feed intake, slaughter value, and prices. The information on milk production, feed intake and slaughter value is separately simulated by the performance module of the dynamic probabilistic simulation model. The technical and economic results of a herd with heifer calvings in more than one month, can be derived by weighing the results of the SME-herds according to the proportion of heifer calvings in each month for that herd (Jalvingh et al., 1993a). The technical and economic results of the SME-herds and the weighing of their results to derive the results of a herd with any calving pattern, are the major ingredients in determining the optimal calving pattern of the herd.

Input variables for reproduction, disposal, milk production, feed intake, slaughter value, and prices are taken from Jalvingh et al. (1993a) and are summarized in the Appendix. In simulating herd dynamics, the applied management strategies on insemination and replacement are based on the decisions for individual animals calculated by dynamic programming, taking into account the seasonal variation in performance and prices (Jalvingh et al., 1993a; Van Arendonk, 1986). In Table 1, the major technical and economic results of the 12 SME-herds are presented. Table 1 shows that a heifer calving in October realises, on average, 3.78 calvings in her life. The average herd life of the same heifer is 3.34 years. The average herd life is shortest when the heifer calves in March. The gross margin at the herd level is calculated as the difference between the revenues from milk, calves, and culled cows, on the one hand and the total costs for feed and replacement heifers, on the other. If the gross margin is considered per average cow present in the herd, the SME-herd for October has the highest gross margin and for March the lowest. When gross margin is considered per 100 kg of milk, the SME-herd with all heifers calving in August has the highest and February the lowest.

Table 1. Results belonging to single-month equilibrium herds.

	Single-month equilibrium herd											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Annual culling rate (%)	37.4	40.1	40.8	38.9	35.8	34.3	33.0	31.7	31.6	30.0	31.7	33.9
Calving interval (days)	370	370	371	372	372	372	372	373	372	371	370	370
Per calving heifer												
Number of average cows	2.67	2.49	2.45	2.57	2.79	2.92	3.03	3.16	3.17	3.34	3.16	2.95
Number of calvings	3.12	2.95	2.94	3.07	3.30	3.44	3.55	3.67	3.67	3.78	3.59	3.38
Milk production (kg)	19266	17825	17339	17969	19375	20110	20803	21750	22113	23740	22747	21336
Gross margin (Dfl.)	11456	10519	10264	10838	11927	12536	13078	13689	13869	14843	14010	12920
Per average cow												
Milk production (kg)	7214	7150	7069	6997	6940	6893	6861	6891	6978	7116	7209	7242
Gross margin (Dfl.)	4290	4220	4185	4220	4273	4297	4313	4337	4376	4449	4440	4385
Per 100 kg of milk												
Average monthly deviation in base price (Dfl.)	-0.69	-1.13	-1.18	-0.89	-0.40	0.21	0.84	1.32	1.56	1.44	0.85	0.03
Gross margin (Dfl.)	59.46	59.02	59.20	60.31	61.56	62.34	62.86	62.94	62.72	62.52	61.59	60.52

2.2 The linear programming approach

The technical and economic results of the 12 SME-herds, and the weighing of these results to obtain results for a herd with any calving pattern, form the basic ingredients of the linear programming approach. The monthly numbers of heifer calvings are used as decision variables in the linear programming approach. The objective is to choose the heifer calving pattern that maximizes the gross margin of the herd, taking into account herd and farm constraints. The parameters for the objective function and constraints are obtained from the technical and economic results of the SME-herds. Therefore, the influence of biological variables and management strategies on herd dynamics are taken into account in optimizing the herd calving pattern, but also the influence of seasonal variation in performance and prices. Different constraints can be used simultaneously, provided that the information for each constraint is calculated in the simulation model that generates the SME-herds. The optimal solution of the linear programming approach represents the optimal heifer calving pattern. The optimal herd calving pattern and the corresponding technical and economic results can be derived by weighing the results of the SME-herds according to the optimal heifer calving pattern.

In this paper, the gross margin per kilogram of milk is maximized, while the annual milk production of the herd is restricted to 500000 kg. The following linear programming problem is used to determine the optimal heifer calving pattern:

$$\text{Maximize } Z = \sum_{i=1}^{12} gm_i x_i$$

Subject to

$$\text{(a)} \quad \sum_{i=1}^{12} mp_i x_i \le \text{quota}$$

$$\text{(b)} \quad x_i \ge 0, \text{ for all } i$$

In which:

x_i = number of heifers calving in month i;

gm_i = gross margin of the SME-herd expressed per heifer calving, in case the heifer calves in month i (see Table 1); and

mp_i = milk production of the SME-herd expressed per heifer calving, in case the heifer calves in month i (see Table 1).

2.3 Sets of additional constraints

The linear programming problem just presented is referred to as set I. This set can be extended with additional constraints. For three different sets of additional constraints, the optimal heifer and herd calving patterns also are determined.

Set II

In set II, an additional constraint has been used, which specifies that all replacement heifers entering the herd should come from heifer calves that were born in the herd 24 months earlier.

(c) $\sum_{i=1}^{12} f_j y_{ij} x_i \geq x_j$, for all j

where

y_{ij} = number of herd calvings in month j in SME-herd corresponding to one heifer calving in month i, and

f_j = factor giving the number of 24-month-old replacement heifers per calving in month j that become available in month j 2 years later (f_j is set at 0.4 for all months).

All replacement heifers are assumed to calve at the age of 24 months, but this age at first calving can easily be changed to include variation.

Set III

A concentration of calvings within a few months results in a large fluctuation in the monthly herd size. In set III, variation in monthly herd size is restricted by using a lower and upper limit between which monthly herd size is allowed to vary. The limits are formulated in terms of a proportion of the average annual herd size. In formula

(d) $\sum_{i=1}^{12} hs_{ij} x_i \geq \sum_{i=1}^{12} \text{min } ahs_i x_i$, for all j

(e) $\sum_{i=1}^{12} hs_{ij} x_i \leq \sum_{i=1}^{12} \text{max } ahs_i x_i$, for all j

where

hs_{ij} = herd size in SME-herd in month j, in case one heifer calves in month i;

ahs_i = average annual herd size in SME-herd, in case one heifer calves in month i (see Table 1);

min = lower limit of the variation in herd size per month, expressed as a proportion of the average annual herd size; and

max = upper limit of the variation in herd size per month.

The lower and upper limits for variation in monthly herd sizes are set at 95 and 105% of the annual average herd size, respectively. The constraints used in set II also hold for set III.

Set IV

To study the impact of allowing for variation in herd size during the year, as is the case in the previous sets, the optimal herd calving pattern is determined in set IV for the situation in which all culled cows are immediately replaced, which is similar to the situation studied by DeLorenzo et al. (1992). A constant herd size can be formulated by the following constraint:

$$\text{(f)} \quad \sum_{i=1}^{12} c_{ij} x_i = x_j \text{, for all } j$$

where

c_{ij} = number of herd cullings in SME-herd in month j, in case one heifer calves in month i.

The linear programming model and the simulation model have been programmed in Turbo Pascal 6.0 (® Borland International, Inc., Scotts Valley, CA) and run on a personal computer. The linear programming problems are solved by the simplex method described by Press et al. (1989).

2.4 Sensitivity analysis

In the sensitivity analysis, the optimal herd calving pattern belonging to the four sets of constraints is determined in case of a lower reproductive performance of the herd. In that case, the initial conception rate after insemination and oestrus detection rate are reduced by 15%, and the initial average interval calving to first insemination is increased by 11 days (see the Appendix for initial values). Moreover, the optimal herd calving pattern is determined for a situation in which seasonal variation in prices for milk, calves, heifers, and slaughter value is ignored. Seasonal variation in milk production, feed costs, and reproduction, is still present. For both situations, the decisions on insemination and replacement of individual animals are recalculated using the dynamic programming model, and consequently the corresponding SME-herds are recalculated as well.

3 RESULTS

The optimal heifer and herd calving patterns for the different sets of constraints are presented in Table 2 with technical and economic results corresponding to the herds with the optimal calving pattern. As expected, the highest gross margin per 100 kg of milk is realised when only the milk production of the herd is restricted (set I). In that instance, all heifer calvings take place in August, which could be expected from the information presented in Table 1. The resulting herd calvings, including heifer calvings, take place mainly from July to October. The proportional monthly milk production varies from 4.3% in June to 11.3% in September. The variation in monthly milk production is much smaller than the variation in monthly herd calvings. The monthly herd size, expressed as a percentage of the average annual herd size, varies from 87% in July to 117% in August.

When the number of heifers calving per month is restricted by the number of heifer calves born in the herd in each month (set II), heifer calvings occur from August to October. The resulting herd calvings are still concentrated in the period from August to October. The gross margin is reduced by only Dfl. 0.13/100 kg of milk, which is Dfl. 651 at the herd level. The reduction in gross margin is a result of the reduction in milk and calf revenues. The milk revenues are reduced because of the reduction in average realised monthly deviation in base price of milk, whereas the revenues from calves are reduced because of the reduction in the number of calvings in the herd. In set II, the monthly herd size varies from 90% in June to 113% in September of the average annual herd size (Table 2).

In set III, the monthly herd size is restricted to vary between 95 and 105% of the average annual herd size, resulting in an optimal heifer calving pattern that is spread over a longer period than in set II. The gross margin is reduced by Dfl. 0.36/100 kg of milk compared with set I, which equals Dfl. 1784 at the herd level. In the case of immediate replacement (set IV), the heifer calvings occur in all months because culling takes place in all months. However, peaks in heifer calvings are observed in June, July, October, and November. These are the months with the highest proportion of voluntary culling, which makes up approximately 50% of all cullings. The gross margin is reduced by Dfl. 1.06/100 kg of milk, which is Dfl. 5304 at the herd level.

In Table 3, results are presented for the herd with lower reproductive performance. Compared with the basic situation, the average calving interval is increased by approximately 2 weeks to about 385 days. In set I, the optimal results are obtained when all heifers calve in July. The gross margin per 100 kg of milk is Dfl. 0.40 lower than in set I in the basic situation, mainly

Table 2. Results belonging to the optimum herd calving pattern for different sets of constraints for the basic situation.

	Set of constraints[a]			
	I	II	III	IV
Milk production herd (kg)	500000	500000	500000	500000
Calving pattern heifers (%)				
January	0.0	0.0	0.0	4.4
February	0.0	0.0	0.0	3.9
March	0.0	0.0	0.0	3.9
April	0.0	0.0	0.0	4.1
May	0.0	0.0	1.5	4.5
June	0.0	0.0	13.7	14.2
July	0.0	23.9	21.8	12.1
August	100.0	32.4	23.7	5.4
September	0.0	37.2	10.2	9.7
October	0.0	6.5	19.6	19.0
November	0.0	0.0	9.6	13.2
December	0.0	0.0	0.0	5.6
Calving pattern herd (%)				
January	1.6	2.1	2.6	5.8
February	0.9	1.1	1.5	4.7
March	0.5	0.6	1.0	4.0
April	0.6	0.8	1.6	4.4
May	1.8	2.1	4.3	6.1
June	4.9	5.5	10.6	9.9
July	13.1	16.4	15.0	9.3
August	43.2	22.2	16.4	7.9
September	14.5	25.5	15.5	12.6
October	10.2	13.2	16.8	15.7
November	5.6	6.6	10.1	11.8
December	3.1	3.9	4.6	7.8
Average number of cows	72.6	72.1	71.7	71.0
Range herd size (% of average)	87-117	90-113	95-105	100-100
Number of calvings	84.3	83.7	83.0	82.3
Annual culling rate (%)	31.7	31.8	32.0	33.2
Calving interval (days)	373	372	372	371
Milk per average cow (kg)	6891	6932	6972	7039
Average monthly deviation in base price milk (Dfl./100 kg)	1.32	1.31	1.06	0.64
Economic results (Dfl./100 kg of milk)				
Revenues - milk	84.44	84.37	83.98	83.31
- calves	6.14	6.00	5.95	5.67
- culls	6.93	6.94	6.99	7.28
Costs - feed	22.41	22.37	22.25	22.06
- heifers	12.13	12.10	12.06	12.30
Gross margin	62.97	62.84	62.61	61.91
Gross margin herd (Dfl.)	314843	314192	313059	309539

[a] Set I: only milk production herd constrained; Set II: I plus home-reared replacement heifers have to be available; Set III: II plus variation in herd size restricted; Set IV: I plus immediate replacement of culled animals.

Table 3. Results belonging to the optimum herd calving pattern for different sets of constraints for the situation with a lower reproductive performance.

	Set of constraints[a]			
	I	II	III	IV
Milk production herd (kg)	500000	500000	500000	500000
Calving pattern heifers (%)				
January	0.0	0.0	0.0	3.8
February	0.0	0.0	0.0	3.4
March	0.0	2.2	3.5	3.5
April	0.0	5.3	5.8	5.1
May	0.0	6.9	7.6	5.3
June	0.0	9.4	10.1	15.9
July	100.0	12.9	13.5	14.4
August	0.0	17.8	18.1	6.9
September	0.0	22.6	21.6	12.2
October	0.0	23.0	15.8	14.5
November	0.0	0.0	4.0	9.8
December	0.0	0.0	0.0	5.1
Calving pattern herd (%)				
January	2.1	3.6	3.5	5.7
February	1.4	2.7	2.7	5.0
March	0.8	2.9	3.5	4.4
April	0.8	4.2	4.6	4.9
May	1.8	5.5	6.0	6.0
June	8.0	7.4	8.0	10.7
July	44.3	10.2	10.7	10.9
August	12.7	14.1	14.3	9.3
September	10.6	17.9	17.1	12.0
October	8.4	18.2	15.3	13.3
November	5.5	7.8	8.8	10.3
December	3.6	5.5	5.3	7.5
Average number of cows	73.4	72.3	72.4	72.1
Range in herd size (% of average)	86-118	96-107	95-105	100-100
Number of calvings	83.8	82.1	82.2	82.0
Annual culling rate (%)	35.6	35.9	36.0	36.6
Calving interval (days)	386	385	385	385
Milk per average cow (kg)	6807	6911	6907	6933
Average monthly deviation in base price milk (Dfl./100 kg)	0.95	0.91	0.84	0.57
Economic results (Dfl./100 kg of milk)				
Revenues - milk	84.12	83.95	83.85	83.42
- calves	6.30	5.68	5.71	5.64
- culls	8.15	8.23	8.26	8.38
Costs - feed	22.30	22.24	22.21	22.10
- heifers	13.71	13.65	13.69	13.78
Gross margin	62.57	61.96	61.92	61.57
Gross margin herd (Dfl.)	312850	309818	309623	307827

[a] Set I: only milk production herd constrained; Set II: I plus home-reared replacement heifers have to be available; Set III: II plus variation in herd size restricted; Set IV: I plus immediate replacement of culled animals.

because of the reduction in milk revenues and the increase in replacement costs. With a constraint on replacement heifer availability (set II), heifer calvings take place in 8 different months, compared with only 4 months in the basic situation. Because of lower reproductive performance, the herd calvings and available replacement heifers resulting from a heifer calving are spread over a longer period, which directly affects replacement heifer availability. The reduction in gross margin per 100 kg of milk is Dfl. 0.61 compared with set I for the same low reproduction parameters. Because heifer calvings are distributed over more months in set II, the monthly fluctuations in the herd size are not as large as in the basic situation. Therefore, the difference in results between sets II and III is rather small (Dfl. 0.04/100 kg of milk) compared with that in the basic situation. With immediate replacement, the gross margin per 100 kg of milk is Dfl. 1.00 lower than in set I.

In Table 4, results are presented for the situation in which the seasonal variation in prices of milk, calves, heifers, and slaughter value is ignored. Seasonal effects on milk production, feed costs and reproduction are still present. In set I, all heifer calvings take place at the optimal moment, i.e., in March. Because the milk production per average cow in the herd is approximately 300 kg higher than in set I of the basic situation, fewer cows are needed to realise the same production of the herd. Because of the absence of the seasonal variation in the milk price, the revenues per 100 kg of milk are Dfl. 2.46 lower than in the basic situation, and the gross margin per 100 kg of milk is Dfl. 1.43 lower. With set II, heifer calvings take place from January to March. The gross margin per 100 kg of milk is reduced by only Dfl. 0.07. In case of immediate replacement, the gross margin is reduced by Dfl. 0.41. The reduction in the gross margin between set I and the other sets is much smaller than in the basic situation because of the smaller difference in gross margin per 100 kg of milk of the SME-herds. This difference is a direct effect of the lack of seasonal variation in prices. In the basic situation, the difference in gross margin per 100 kg of milk between the highest (August) and the lowest (February) SME-herd is Dfl. 3.92. With no seasonal variation in prices, the difference between the highest SME-herd (March) and the lowest (August) is Dfl. 1.50.

4 DISCUSSION

When only annual milk production is constrained, all heifers calve in August (set I). In case of set II (home-reared replacements only), heifer calvings take place from July to October and gross margin at herd level is reduced by Dfl.

Table 4. Results belonging to the optimum herd calving pattern for different sets of constraints for the situation in which seasonal variation in prices of milk, calves, heifers and slaughter value is ignored.

	Set of constraints[a]			
	I	II	III	IV
Milk production herd (kg)	500000	500000	500000	500000
Calving pattern heifers (%)				
January	0.0	21.7	27.2	10.7
February	0.0	42.9	3.1	8.1
March	100.0	35.4	26.5	6.1
April	0.0	0.0	6.4	6.5
May	0.0	0.0	2.0	5.6
June	0.0	0.0	0.0	4.3
July	0.0	0.0	0.0	4.1
August	0.0	0.0	0.0	4.0
September	0.0	0.0	0.0	4.4
October	0.0	0.0	6.4	10.2
November	0.0	0.0	17.9	21.3
December	0.0	0.0	10.5	14.7
Calving pattern herd (%)				
January	6.1	18.7	18.6	12.8
February	17.3	29.5	13.6	11.7
March	47.6	24.3	18.1	9.1
April	12.8	9.2	9.0	7.4
May	7.1	4.9	4.6	5.5
June	3.3	2.2	1.9	3.8
July	1.5	1.0	0.8	2.8
August	0.7	0.4	0.4	2.1
September	0.5	0.4	0.7	3.5
October	0.4	0.9	7.3	11.5
November	0.8	2.2	12.2	15.5
December	2.1	6.4	12.9	14.2
Average number of cows	69.9	69.6	69.7	70.2
Range in herd size (% of average)	83-115	86-111	95-105	100-100
Number of calvings	80.5	79.7	79.7	80.8
Annual culling rate (%)	32.9	31.5	31.2	32.6
Calving interval (days)	369	370	372	374
Milk per average cow (kg)	7149	7182	7170	7125
Average monthly deviation in base price milk (Dfl./100 kg)	0	0	0	0
Economic results (Dfl./100 kg of milk)				
Revenues - milk	81.98	81.97	82.13	82.29
- calves	5.49	5.44	5.45	5.52
- culls	7.2	6.79	6.68	6.97
Costs - feed	21.16	21.33	21.59	21.76
- heifers	11.96	11.4	11.32	11.89
Gross margin	61.54	61.47	61.35	61.13
Gross margin herd (Dfl.)	307708	307328	306727	305634

[a] Set I: only milk production herd constrained; Set II: I plus home-reared replacement heifers have to be available; Set III: II plus variation in herd size restricted; Set IV: I plus immediate replacement of culled animals.

651 for a herd with an annual milk production of 500000 kg (Table 2). This difference can be considered to be the maximum amount to spend on changing the rearing period of heifers to have enough replacement heifers available in August. In case of a reduction in reproductive performance, the difference between set I and set II is much larger (Dfl. 3032 at the herd level; Table 3). In case of reduced reproductive performance, fewer calvings occur in the month in which the heifer entered the herd. Modifications in the length of the rearing period of heifers might yield a larger profit in case reproductive performance is lower. However, this measure has to be repeated annually. An improvement in reproductive performance of the herd would be more effective and would yield a higher income because more cows could have a 1-year calving interval, and, consequently, more opportunities would exist to concentrate heifer calvings within a few months. In case modifications of the length of the rearing period are preferred, the linear programming approach will prove flexible enough to include these modifications. The heifer calving pattern will be optimized, taking into account differences in rearing costs of heifers that calve at different ages.

In the Netherlands, farmers are advised to produce the milk quota with as few cows as possible (Snoek, 1988). Based on the results in Table 2, when seasonal variation in performance and prices is taken into account, situations will exist in which keeping a few more cows for producing the milk quota is more profitable. In those cases, additional costs for maintenance are outweighed by the increased returns because of seasonality. Additional calculations in which the gross margin per average cow is maximized, while the annual milk production of the herd is still restricted, showed similar results. All heifer calvings now take place in October, which could be expected from the information in Table 1. The average number of cows needed to produce the quota in case of optimization per average cow is decreased by 2.3 compared with set I in Table 2 (maximization per kilogram of milk). Although fewer cows are required, the gross margin of the herd is decreased by Dfl. 2104 (compared with set I in Table 2).

In simulating herd dynamics in the SME-herds, the optimal insemination and replacement decisions calculated by the dynamic programming model derived from Van Arendonk (1986) have been used. In optimizing the individual cow-decisions, the dynamic programming model assumes immediate replacement. In the SME-herd culled animals are not replaced immediately, since all heifers calve in one specific month only. The assumption of immediate replacement in the dynamic programming model is inevitable, however, because the opportunity costs of postponed replacement have to be taken into account. Otherwise all cows would stay in the herd until their costs exceed their returns, which is not a realistic (i.e., profitable) option. Therefore, the use of decisions based on immediate replacement in a situation in which animals are not replaced immediately, seems justified.

In this paper, the linear programming approach is applied for a situation with output restrictions, where returns minus costs per kilogram of milk are maximized. In the underlying SME-herds, the insemination and replacement policy used for individual cows, however, is based on a maximization of returns minus costs per cow-place and is, therefore, not necessarily optimal for a situation with milk quota. Optimal insemination and replacement decisions for a situation with milk quota might be obtained when the objective function in the dynamic programming would be modified, for which Kristensen (1989) made a start. In the current paper, the dynamic programming model for a situation without quota is considered the best available option for individual cow advice, but the approach is flexible enough to include other strategies. If in the linear programming approach the basic constraint on annual milk production is replaced by a constraint on maximum herd size, the objective functions of the linear programming and dynamic programming are equal. The maximization of gross margin per cow-place results in immediate replacement of culled animals, which equals the situation assumed in dynamic programming. The resulting optimal heifer and herd calving patterns are equal to the patterns derived for set 4 in case of a maximization of gross margin per kilogram of milk and a constraint on maximum herd size (Table 2). The maximization of gross margin per cow-place equals the situation studied by DeLorenzo et al. (1992).

If gross margin is maximized per cow-place with a restriction on maximum herd size, instead of a restriction on annual milk production, immediate replacement of culled animals based on the optimal decisions calculated by the dynamic programming model results in the optimal heifer and herd calving pattern. In a situation with milk quota, however, it is most profitable to leave cow-spaces temporarily open for reasons of seasonality (i.e. non-immediate replacement). However, this results in variation in herd size, implying that more cow-places will be needed than are used on average. The linear programming approach is able to handle restrictions on cow-places (e.g., set III). In the comparison of sets I to IV, a large variation in herd size is observed (Table 2). The effect of this within-year variation on the economic results, through its effect on fixed costs, is not accounted for, since many farms under a quota system have excess facilities. In other situations, however, the opportunity costs for fixed assets should be included.

5 CONCLUSIONS

The approach described in this paper combines simulation and optimization and can be considered to be a promising tool in on-farm decision support. It provides the possibility of determining the optimal calving pattern of the herd, taking into account herd and farm restrictions. The impact of some possible constraints is illustrated in the paper. Additional constraints can be defined, such as restrictions on roughage supply or amount of available labour, provided that the monthly numbers of heifer calvings are used as decision variables and that the information about the parameters needed is calculated by the simulation model. If these precise coefficients are not available, estimates provided by the farmer or advisor can also be used. The approach offers the possibility of quantifying the economic consequences of various constraints and, moreover, of managing different objective functions. Based on the results of the calculations with different sets of constraints, the desired calving pattern of the herd can be defined. Subsequently, the model of Jalvingh et al. (1993b) can be used to compare strategies that actually change the current calving pattern of the herd to the desired one. The comparison of the current calving pattern and the optimal calving pattern results in the maximum possible benefits of a change. The strategy that is used to actually change the calving pattern, determines the final profit that can be realised to a large extent (Jalvingh et al., 1993b).

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APPENDIX

See Jalvingh et al. (1993a) for more details on input variables and for a complete overview. The given input values are assumed to represent typically Dutch herds, but they can easily be modified to suit other farm and price conditions.

Herd dynamics model

Proportions of first inseminations for mont 2 to 5 after calving are 44, 41, 11, and 4%, respectively. After second calving and later these proportions are 49, 38, 10, and 3%.
Conception rate after insemination depends on lactation number. Conception rate per lactation number weighed according to an average herd composition results in 62%.
Oestrus detection rate is 70%.
Probability of involuntary disposal is 12% in lactation 1 and increases to 23% in lactation 10.

Performance model

In Table A1 the base prices of milk, calves, replacement heifer and carcass weight are presented, together with the monthly deviation in prices. In Table A2 energy content and price of grass, silage and concentrate is presented. In summer (May-October) cows feed on grass and concentrates. In winter, the ration consists of silage and concentrates.

Table A1. Base price and monthly deviations in price of milk, calves, replacement heifer, and carcass weight.

	Base price (Dfl.)	Monthly deviations in price (Dfl.)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Milk, 100 kg[a]	-2.90	+3.7	+1.8	-0.7	-1.5	-4.5	-4.5	-4.5	-3.7	-0.7	+5.3	+7.3	+7.0
Calves, kg[b]	10.55	-1.18	-1.49	-1.66	-0.17	+1.76	+1.96	+2.05	+0.80	-0.08	-0.48	-0.72	-0.97
Replacement heifer	2600	-37	-57	-66	-45	+13	+13	+27	+46	+44	+65	+20	+24
Carcass weight, kg[c]	6.40	-0.38	-0.23	+0.05	+0.07	+0.32	+0.33	+0.23	+0.15	+0.10	-0.03	-0.21	-0.30

[a] Prices of milk, fat and protein are Dfl. 8.00 and 14.50/kg respectively. Price of 100 kg milk is based on the negative base price, the monthly deviation in base price, and the price of fat and protein contents in 100 kg milk. Mature equivalent milk production is set at 7750 kg of milk, 4.35% of fat, and 3.39% of protein.

[b] Refers to male calves. Base price for heifer calves is Dfl. 6.60.

[c] Refers to price of a kilogram of carcass weight of a first parity cow 210 days in lactation.

Table A2. Energy content and prices of different kinds of feed.

	Energy content (VEM)[a]	Price (Dfl./1000 VEM)
Grass	951	0.22
Silage	850	0.30
Concentrates	1045	0.35

[a] VEM = Dutch Feed Unit; 1000 VEM = 6.9 MJ NE_L.

General discussion

1 Introduction

The study described in this thesis focuses on the development and use of models that simulate herd dynamics in livestock. The models can be used to calculate the technical and economic consequences of management strategies with respect to production, reproduction and replacement. The thesis is composed of three parts. In the first part, existing models from the literature simulating herd dynamics were described and discussed, including their possible role in on-farm decision support (Chapter 1). In the second part, a modelling approach was developed to support decisions on production, reproduction and replacement in swine herds (Chapter 2). The model was used to evaluate various management strategies (Chapter 3). In the third part, the approach developed for swine herds was modified and transformed to model similar decisions in dairy herds (Chapter 4). Special attention was paid to the calving pattern of the herd. The model can be used to evaluate strategies in order to change a herd's calving pattern (Chapter 5). Based on the developed model, a method was worked out to determine the optimum herd calving pattern of an individual herd using linear programming (Chapter 6).

The models described in this thesis were designed for use in on-farm decision support, allowing for individual farm conditions to be included. The models are an extension of the current management information systems, which are still limited to registration and analysis of data. In the thesis, the developed models were used to obtain general knowledge and insight, mainly to illustrate the economic impact of alternative management strategies under consideration. So far little attention was paid to how the models should actually be used in on-farm decision support. In this discussion part of the thesis, therefore, an integrated decision support system, being the ideal framework in which the models should fit for use in on-farm decision support, is outlined and discussed. The path leading from the current prototypes of the models towards their implementation in an integrated decision support system, including the major (research) problems to be solved, is discussed. Attention is not focused on hardware- and software issues, but on aspects related to the contents of the models. Before that, the technique used to simulate herd dynamics is further discussed and evaluated against more commonly used modelling approaches.

2 Probabilistic modelling using probability distributions versus using random numbers

2.1 Background

Simulation models are a useful tool for studying herd dynamics. They are not only able to include and integrate many aspects of the system (i.e. herd) under consideration, but can also account for the fact that it often takes years before the full effects of management changes related to herd structure and dynamics become apparent. Herd dynamics are most often simulated using a dynamic probabilistic model with random numbers (Monte Carlo simulation) as observed in Chapter 1. In this type of models, individual animals are moved forward through time, modifying the status of each according to the outcome of various events and management decisions. Random number generators are used to create observations for individual animals, such as production, survival and conception. As a result of using a random number generator, multiple runs are needed to obtain a reliable estimate of the average results of the herd. Moreover, the inclusion of random numbers in models for on-farm decision support is a possible source of confusion and reduction in the acceptability of the model and its results to the user (Dent and Blackie, 1979), particularly when the number of replications is not large enough. For this reason, the probabilistic approach using random numbers, often referred to as stochastic simulation, was rejected in this thesis for simulating herd dynamics.

As an alternative for a probabilistic model using random numbers, a deterministic model could have been used. Deterministic models, however, do not take into account uncertainty (i.e. variation) associated with future events, which results in an oversimplification of the conditions under which real decisions have to be made. In this thesis, therefore, a finite-state Markov chain approach was used to model herd dynamics. The Markov chain approach, referred to as probabilistic modelling with probability distributions, combines features of the deterministic approach and the probabilistic approach using random numbers. Probability distributions are included accounting for uncertainty, while avoiding the need for multiple runs, since a single run gives the expected value (i.e. weighed average) of the results. The approach requires the definition of states in which animals can be and of possible transitions between these states. In order to generate technical and economic results of the herd, numbers of animals per state were combined with simulated performances per state. Based on the experiences acquired in this thesis in applying the probabilistic approach using probability distributions, some advantages and disadvantages of the approach will further be discussed below.

2.2 Simulation results

Compared with the deterministic approach, the approach using probability distributions and the one using random numbers, have the advantage that animals with different performances can be treated differently, e.g. a more liberal insemination and replacement policy for high-producing animals. Moreover, future performance can be related to current performance. Therefore, culling of animals with a low performance will influence the realised performance in later production cycles. In the deterministic approach this is not possible; the resulting average performance per production cycle is always equal to the input value.

An advantage of the approach using probability distributions is that there will be observations in all classes. Therefore, the model will exactly provide the expected value of the results and only one run is needed to obtain these results. In fact, the results of a very large herd are simulated, with animals available in all possible states. In the model using random numbers, the presence of observations in all classes is not assured. The larger the number of observations the better the average result will approach the real expected value. Replicated calculations are needed to obtain a reliable estimate of the average results.

An advantage of models with random numbers and multiple runs, on the other hand, is the available information about the expected standard deviation in the results, which allows for statistical tests and non-neutral risk analysis. Performing these tests and analyses requires a careful design and analysis of the modelling experiments in order to obtain reliable estimates of average results and standard deviations. By simply choosing a large number of replications, for instance, a difference between two strategies can always be made significant, due to the fact that the standard error of the mean will then be small. The herd dynamics models using random numbers and described in Chapter 1 are focused only on the comparison of average results, rather than on a trade-off between expected outcome and its variation (non-neutral risk analysis). Therefore, one could just as well apply the approach using probability distributions. Because one run supplies the expected value of the results, various sensitivity analyses can be carried out much easier than is the case with models using random numbers.

2.3 Steady state

An important feature of the model with probability distributions is the possibility of deriving the steady state of the herd, i.e., the situation in which size and age structure of the herd are stable. Results of steady state herds are a basis for a sound comparison of strategies; the results are not influenced by any initial situation nor by the length of the period of time for which they have been calculated (Upton, 1989). As described in Chapter 1, the majority of models simulating herd dynamics applies probabilistic modelling using random numbers and focuses on obtaining results for the steady state herd. The models simulate an approximation of the steady state herd by starting with an initial herd and using a stabilizing period of several years to approach the steady state situation. In the approach using probability distributions, the steady state of the herd is not approximated, but actually calculated. Therefore, the method using probability distributions is more rigorous, efficient, precise and formal (Baptist, 1992).

A steady state only occurs when transition probabilities remain constant over time, i.e. are stationary. This does not mean, however, that the developed Markov chain models could not handle situations where transition probabilities vary. A new steady state will not be reached as long as transition probabilities are not stationary, which was illustrated in Chapter 5. In changing the calving pattern of a dairy herd, the steady state of the starting herd no longer exists when it is decided to change the calving pattern. After a certain period of time, the desired calving pattern is reached and no extra actions have to be taken to change the calving pattern. The transition probabilities become stationary again and the new steady state herd will be reached.

2.4 Flexibility in model structure

A final issue in the discussion about advantages and disadvantages of probability distributions versus random numbers refers to the extension of the amount of information about individual animals when taking decisions. In that case, the model using probability distributions has to be extended with an extra state variable. An example is the inclusion of production level in the last lactation as an extra state variable in the dairy cattle model. In case n classes are considered for this state variable, the number of states in the modified model will be n times the number of states in the original model, which will increase memory requirements and the number of calculations to be performed. Consequently, the model will require more computing time resulting in longer response times and less user friendliness of the model. Adding an additional variable to the model with random numbers affects memory requirements to some extent but the influence on calculation time is relatively small. Therefore, in case of the model with probability distributions, the choice of the number of states (and the time interval between transitions) involves a trade-off between complexity and precision, in which model objectives must be taken into account. In the calculations in this thesis, extensive versions of the models were used. The models, however, were structured in such a way that it is easy to reduce the number of classes per state variable, e.g. for production level or fertility status or even to leave out variation in certain state variables, such as production level (see Chapter 2).

3 Integrated decision support systems

3.1 Introduction

Improving farmers' management is increasingly important in maintaining farm income. Computer technology can be helpful in providing the farmer with information that supports the farmer's decision-making process. The models described in this thesis could be used as a tool in decision-making. They can help to provide additional information or, at least, determine the potential impact of decisions on the results through sensitivity analysis ("what..if" calculations). Therefore, the developed models should be considered a component of a larger comprehensive information system, a decision support system.

The term Decision Support Systems (DSS) conveys a variety of meanings in the current literature. Sprague and Carlson (1982) characterized DSS as computer based systems that help decision makers confront semi-structured problems through direct interaction with data and models. A DSS consists of three major subsystems: a data base, a model base and the decision maker (Sprague and Watson, 1983). Of paramount importance is the management of subsystems and the interfaces between them. Figure 1 shows the three major components, software systems and linkages. This sophisticated level of integration is the goal to be achieved for a DSS to become user-friendly and widely accepted. A DSS with such a sophisticated level of integration is referred to as an idealized integrated DSS (IDSS) (Wagner and Kuhlmann, 1991).

Using the structure of an IDSS as presented in Figure 1, it will be discussed how the developed models fit into this structure. This discussion is focused on the contents of the models in relation to an IDSS, and not on the technical aspects of hard- and software.

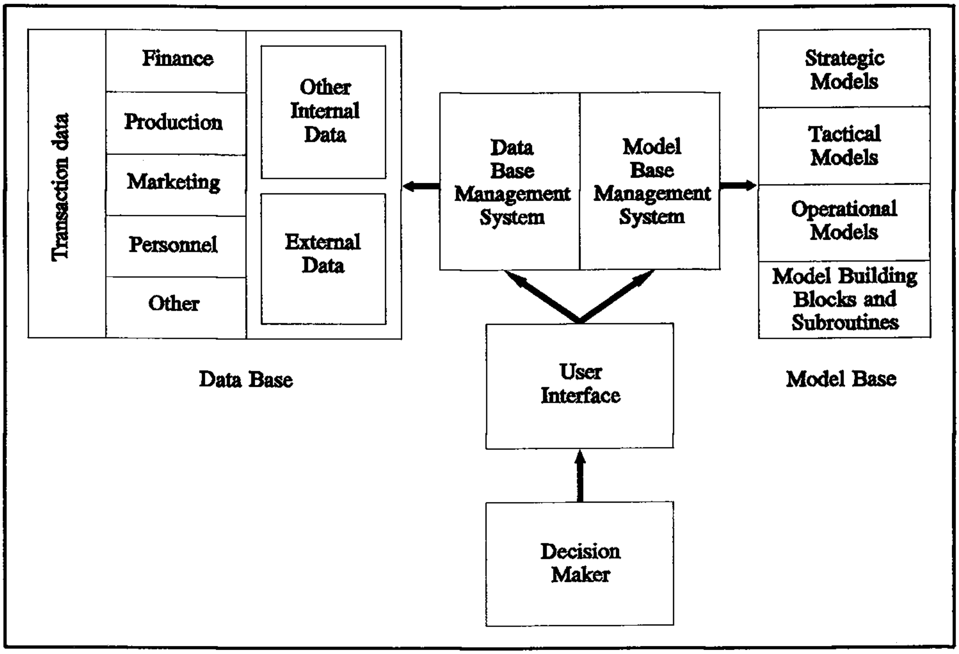

Figure 1. Components of an integrated decision support system (IDSS). (Source: Sprague and Watson, 1983)

3.2 Data base subsystem

The data base subsystem is used to store classes of data collected from internal and external sources. Data can be captured automatically (e.g. milking parlour and self feeder), extracted from other sources (e.g. milk, feed and slaughter plants) or entered manually. The data base management system (DBMS) can be used to create, restructure and update files, to select, retrieve and sort data, and to generate reports (Davis and Olson, 1984). The results of the actions of the DBMS can be used by the decision maker or serve as input for model calculations.

In developing the models described in this thesis, no integration with existing data bases was established yet. The current use of default data provides a concrete illustration of the models' input requirements and output possibilities and, therefore, is useful in getting started with the models. For on-farm decision support, however, the user may expect more farm-specific input and output; the acceptance of a model by the decision maker will increase if the model provides results that accurately reflect individual farm circumstances (King and Dijkhuizen, 1988). In order to obtain these farm-specific modelling results, a large amount of high-quality input data will be required. If the models are integrated with a data base, as in the IDSS, the requirement concerning the amount of farm data will most likely be met, but not, or at least not automatically, the requirement concerning data quality. Some of the aspects concerning data quality will be discussed here.

A first issue in simulating farm-specific performance is gaining insight into the decisions taken by the farmer. The management strategies underlying these decisions influence the technical and economic results of the farm and should, therefore, be part of the farm-specific input of the models. The strategies, however, cannot easily be perceived or measured. Farmers, for example, will not always apply standard rules when ceasing insemination or culling animals. Therefore, the strategies cannot easily be retrieved from available data nor from direct interviewing. A possible way of approaching the farm-specific strategy is the definition of some basic strategies by experts. The system could choose the basic strategy that goes best with the available data and may ask the farmer whether the chosen strategy matches the real strategy applied. The farm-specific strategy could also be approached the other way around; the decision maker chooses the basic strategy that reflects best the actual strategy. Subsequently, the system checks if the choice is consistent with the available data. Further research is needed to determine which approach is preferable.

A second question is the amount of historical data to be included in obtaining farm-specific input parameters of high quality. This question has two aspects. First, the input parameters should reflect the real situation on the farm, and second, these parameters should be associated with future performance. To reflect the real situation on the farm as accurate as possible, the inclusion of data concerning present performances is required. For reasons of variability in input parameters over time, however, it may be necessary to include also data about the past in order to obtain input parameters that are of value in estimating future performances. Because of differences in variability between herds or years, the approach of obtaining farm-specific input parameters may vary between variables, herds and years.

Not much is known yet about variability in input and output variables. Data from 81 randomly obtained sow herds using the CBK management information system (CBK, 1990) were used to show some of the issues in obtaining farm-specific input data. The analysis was carried out for records concerning average annual herd parameters on technical performance, available for the years 1988, 1989 and 1990. The mean and corresponding average annual standard deviation for some major technical parameters are presented in Table 1. The mean values presented are very similar to those given in Chapter 2 for 615 farms using CBK. As can be observed, the relation between mean and

Table 1. Average technical results and corresponding standard deviation of 81 herds for 1988 to 1990.

Parameter	Mean	Average annual S.D.	Within herds, between years		
			Average herd S.D.	Range herd S.D.	
				Min	Max
Number of sows	153.8	64.3	4.2	0.1	16.7
Pigs weaned per sow per year	21.4	1.5	0.9	0.1	2.2
Pigs weaned per litter	9.4	0.4	0.2	0.1	0.6
Pigs born alive per litter	10.6	0.4	0.3	0.0	0.7
Pigs born dead per litter	0.7	0.2	0.1	0.0	0.3
Pre-weaning mortality rate	12.0	2.3	1.3	0.1	3.8
Litters per sow per year	2.28	0.10	0.06	0.01	0.15
Int weaning-first insemination (days)	7.1	1.4	0.6	0.0	2.6
Int first-last insemination (days)	4.1	2.0	0.9	0.1	3.6
% Rebreedings	10.2	3.8	2.0	0.6	5.5
Interval between litters (days)	155.5	4.1	1.9	0.1	9.0
Culling rate sows	46.8	9.5	7.0	0.0	20.2
Non-productive days per culled sow	38.1	14.6	6.7	0.6	27.5

average annual standard deviation varies considerably between variables. Especially culling rate, number of non-productive sow days, percentage of rebreedings and interval between first and last insemination show much variation, as opposed to interval between litters, number of pigs born alive per litter and number of litters per sow per year (Table 1). Additional calculations showed that differences in standard deviation between years are small for all parameters.

For each herd, the mean and standard deviation of the technical parameters were calculated for each of the three years. The average standard deviation observed between years within herds (herd S.D.) is presented in Table 1, together with the observed range of herd standard deviations. The variation within herds is lower than the variation between herds for all parameters. Highest variation remains in culling rate and number of non-productive sow days. Additional calculations showed that for all parameters the average herd standard deviation of the 25 smallest herds is considerably larger than the average herd standard deviation of the 25 largest herds, due to the difference in number of observations included.

To illustrate the degree of association between technical parameters in consecutive years, the linear correlation coefficient was estimated (Table 2). Also the correlation coefficients for the average value over 1988 and 1989 and the parameter value in 1990 were determined. Almost all correlations are within the range of 0.60-0.80, indicating that for nearly all variables 40 to

Table 2. Correlation coefficients within technical parameters between years[a].

	1988-1989	1989-1990	(1988+1989)-1990
Pigs weaned per sow per year	0.69	0.65	0.66
Pigs weaned per litter	0.73	0.63	0.61
Pigs born alive per litter	0.69	0.49	0.45
Pigs born dead per litter	0.82	0.77	0.77
Pre-weaning mortality rate	0.67	0.67	0.66
Litters per sow per year	0.55	0.70	0.71
Int weaning-first insemination	0.71	0.75	0.79
Int first-last insemination	0.75	0.67	0.72
% Rebreedings	0.70	0.65	0.64
Interval between litters	0.78	0.81	0.74
Culling rate sows	0.39	0.26 *	0.24 *
Non-productive days per culled sow	0.71	0.81	0.80

[a] All correlation coefficients are significantly different from 1.00 at level $P < 0.001$. Correlations are also significantly different from 0.00 at level $P < 0.001$, except for coefficients indicated with * that are significant at $P < 0.05$.

60% of the variation between herds in a certain year can be accounted for by a linear function of the variable in the previous year. The correlation coefficient is lower for culling rates of sows and for the number of pigs born alive (in case of 1990). The correlation coefficients for 1988-1989 and 1989-1990 are fairly similar in most cases, except for the number of pigs born alive per litter, litters per sow per year, and culling rate. The effect of taking the results of 1988 into account when estimating the correlation coefficient with 1990 varies. In some cases it increases, in others it decreases. Multiple regression may improve the prediction for the results of 1990, but the question then remains how stable such a prediction equation is over time or for a different set of herds.

Further research is needed to gain more insight into the variability between variables, farms and years and its underlying causes. This should include research on techniques concerning the combination of information from an individual herd and overall averages. The knowledge obtained could be included in the DBMS to assist in determining the scenario for obtaining farm-specific input parameters of high quality. In this scenario, additional information about what happened on a certain farm (obtained interactively from the farmer and/or adviser) could also be used. Moreover, checks for consistency can help to improve the quality of the input parameters. If the herd size or structure has recently changed, relationships between parameters, such as replacement rate and average parity at culling, may not be consistent and may, therefore, not be representative for the long-term (i.e. steady state) situation.

In those cases, farm-specific input values may be combined to a more or lesser content with default input values, as illustrated by King and Dijkhuizen (1988). They integrated knowledge based software modules into the retrieval of farm-specific input parameters.

In all cases it will remain difficult to mimic a herd exactly in all its aspects. Prerequisite is that at least the input parameters of the model that determine the outcome of the calculations most are farm-specific. This may imply that a variable with not much variation between herds has to be farm-specific, while another with a large variation within herds does not have to be farm-specific. Furthermore, the farmer needs to be convinced that the outcome of calculations refers to the situation at the own farm. These two aspects might not always concur. Sensitivity analysis can be used to determine which input parameters are most decisive in model outcome. It can also be used to help convince the farmer that not all input parameters need to be farm-specific by showing the impact of modifying their values.

3.3 Model base subsystem

The model base can contain several kinds of models, some of which to be used for strategic planning, others for support of tactical and operational decisions (see Figure 1). The model base management system performs the same basic tasks as the DBMS. It is responsible for retrieving the appropriate model(s) needed for a specific purpose and then requesting the necessary input data for the model from the database management system and/or the user interface. The models should be available as modules that can stand alone or be used in conjunction with one another to form more expansive models. A module is a model capable of being used in some configuration with other modules in order to form a larger or more comprehensive model (Bonczek et al., 1983).

In this thesis, tactical models focusing on production, reproduction and replacement issues in dairy and swine were developed and could be included in the model base of an IDSS. A modular approach to model-development was applied. For instance, in case of the dairy models, several modules and models can be distinguished. Considering the basic modules, these include:

(1) *Performance module*, simulating milk production, feed intake, slaughter value, calf revenues and gross margins (if desired) in a deterministic way for individual animals for each month of lactation.

(2) *Dynamic programming module*, derived from Van Arendonk (1986) to determine the farm-specific optimum insemination and replacement

decisions for individual cows.

(3) *Herd dynamics module*, including three types of simulations:
   (a) the steady state of a herd
   (b) herd dynamics over time
   (c) single-month equilibrium herds (SME-herds; twelve steady state herds, each referring to a herd in which all heifers calve in one specific month)

   The module is combined with the performance module in order to obtain technical and economic results of a herd.

(4) *Simple steady state derivation module*, easily derives the technical and economic results of a steady state herd with any calving pattern, by weighing the results of the twelve different SME-herds, according to the proportion of heifer calvings in each month for that herd.

(5) *Linear programming module*, which uses the number of monthly heifer calvings as decision variables. The coefficients for the objective function and constraints are derived from the SME-herds. The contents of the objective function and constraints depend on the configuration of modules in which the module is used.

The performance module and the herd dynamics module, and indirectly the other modules, offer the possibility of carrying out aggregated as well as detailed simulations, by varying the number of state variables or the number of classes per state variable included (Chapter 2).

At the moment, five different configurations of modules can be constructed. The relationships between the basic modules and the models constructed are presented in Table 3.

The following models can be composed:

(A) *Determination of the optimum calving interval*. Based on the results calculated by the performance module, the optimum calving interval can be determined. Based on the actual age distribution of the herd and the distribution of calving intervals observed, the farm-specific economic loss of a sub-optimum calving interval at herd level can be calculated.

(B) *Steady state comparison of management strategies*. The effects of an increase in reproductive performances can be studied, as well as the application of different insemination and/or replacement strategies. The optimum insemination and replacement strategy determined by the dynamic programming module is one of the possible strategies (Chapter 4).

(C) *Steady state comparison of calving patterns*. After generating the results of the SME-herds using the herd dynamics module, the technical and economic results of steady state herds with any heifer or herd calving

Table 3. Overview of relationship between possible configurations of modules and the available basic modules. A module can be required (R), optional (O) or not be used (-) in a configuration.

Possible configuration		Available basic modules						
		1[a]	2	3a	3b	3c	4	5
A.	Determination optimum calving interval	R	-	-	-	-	-	-
B.	Steady state comparison of management strategies	R	O	R	-	-	-	-
C.	Steady state comparison of calving patterns	R	O	-	-	R	R	-
D.	Determination of optimum calving pattern	R	O	-	-	R	R	R
E.	Comparison of strategies to change calving pattern	R	O	R	R	-	-	R

[a] Available modules: (1) Performance module, (2) Dynamic programming module, (3a) Herd dynamics module - steady state of a herd, (3b) Herd dynamics module - herd over time, (3c) Herd dynamics module - SME-herds, (4) Simple steady state derivation module, (5) Linear programming module.

pattern can be generated. The steady state herd for a herd which heifer calving pattern depends on a certain characteristic of the herd (e.g. equal to herd calving pattern) can be generated as well. By using the SME-herds, computer time is reduced considerably, because separate simulation of herd dynamics for the herd is no longer needed (Chapter 4).

(D) *Determination of the optimum calving pattern of the herd.* The objective function and constraints of the linear programming problem are defined by the user. The corresponding coefficients are obtained from the results of the SME-herds. The derived optimal heifer calving pattern is used by the simple steady state derivation module to generate the technical and economic results for the herd with the optimum calving pattern (Chapter 6).

(E) *Comparison of strategies in order to change a herd's calving pattern.* At first, the results for the steady states concerning to the starting herd and the desired herd are generated. The herd dynamics module is used to follow the herd over time, when going from the steady state starting herd to the steady state desired herd. The strategies to change calving pattern focus on the intake of young stock and/or on the insemination and/or replacement of dairy cows. The linear programming module is used to tune the intake of available replacement heifers on the desired intake (Chapter 5)

The developed modules are not able to support all possible decisions at the tactical planning level, but make a good start for a further extension of the model base. Even if all processes were simulated, however the question remains, how to value intermediate products such as home-raised replacement heifers and roughage production. Linear programming has long been recognized as an appropriate technique to provide these values, taking into account the availability of and restrictions on land, labour and capital (Renkema, 1970). A further and farm-specific integration of computer simulation and optimization, as illustrated in Chapter 6 for the herd's calving pattern, is worth considering. Besides such an integration, the simulation models can be used to carry out sensitivity analyses, in order to show the impact of different values for intermediate products on the economic outcome and ranking of the management strategies under consideration.

3.4 Decision maker

Suggestions for the models developed in this thesis were generated from the so-called information models (Verheijden et al., 1985; Brand et al., 1986) and from interviews with farmers (De Hoop et al., 1988). So far the development of the models has mainly focused on the technique for simulating herd dynamics and on the illustration of its possibilities. Now the time seems ripe for the next step: making the prototypes available for on-farm use while involving the potential users and decision makers. Discussions have been started between user groups, research and extension organizations and private software companies about the implementation of the models for on-farm use. Issues such as which models should be started with, how should they be used and who is responsible for further adjustments and maintenance of the models, the integration with data bases, and the distribution are being discussed. Having prototypes available in these discussions is a great advantage. It helps structure the ideas on both potential applications and necessary adjustments of the models. In this part of the discussion chapter, attention will be paid to how the models could be used by the decision maker.

Different possible usage patterns of the models can be distinguished, such as terminal mode, clerk mode and intermediary mode (Alter, 1980). Since the developed models concern support of decisions at tactical level, individual farmers may use a certain model only once or twice per year. Due to this low frequency, they will not gain (enough) experience and therefore it is likely that farmers will use the models with the help of an adviser, for example an extension worker or a veterinarian. In that, the decision maker, being the farmer, may use the models directly or indirectly. As a start, the models are likely to become available for a central computer, which can be reached by individual users. In case of indirect use, the adviser performs the model calculations and interprets and reports the results to the farmer (i.e. intermediary mode). In case of direct use, the decision maker and the adviser may use the model on-line (i.e. terminal mode), or off-line (i.e. clerk mode) by preparing and submitting input to the central computer. There may also be farmers who prefer to use the models without the assistance of an adviser, especially when they have gained some experience in using those models. It should, therefore, also be possible for a farmer to have the models available on the personal computer.

In order to assure successful on-farm use of the models as part of an IDSS, particular attention needs to be paid to the design of the user interface. The user interface takes care of the communication between the user and the data base and model base. The user interface includes the hardware and software, but also factors that deal with ease of use, accessibility, and human-machine interactions (Turban, 1990). Noell (1992) stated that the acceptance of a system and its results by farmers is directly connected to the ease-of-use and transparency of the user interface, since farmers were usually not interested in the underlying theories and methodologies. Therefore, the tasks of the user, users' cognitive preferences and abilities, and ways of arriving at decisions should be taken into account in further developing the system (Sprague and Watson, 1983). For that reason, different dialogue styles may be included in the interface, each suited for a different type of user (e.g. farmer or adviser, experienced or novice user).

In case several models are available in the model base, the user interface should optimize the use of the system by the user. For that reason, expert systems and other artificial intelligence tools might be integrated in the user interface (Huirne, 1990). An expert system could assist the decision maker in deciding which model configuration is most appropriate for the problem, make suggestions regarding possible alternatives to evaluate and help interpret model outcomes. In choosing the most appropriate configuration, the IDSS might include available expert systems that carry out individual farm analysis to detect the strong and weak elements in the farm's performance (Huirne et al., 1992; Hennen and De Hoop, 1992). Outcome of the simulations can serve as a set of standards for comparison in individual farm analysis, while the outcome of individual farm analysis can serve as a starting point for simulations. In this way an interesting interaction is possible, with the overall goal improving the farmer's management and income.

4 Main conclusions from the study

- The probabilistic modelling approach using transition probabilities (Markov chain approach) has shown to be very powerful in simulating herd dynamics, both in dairy cattle and swine. The method can be used to derive directly the steady state of the herd and corresponding technical and economic results. Steady state results reflect the long-term results of the herd and offer a basis for a sound comparison of different management strategies. When insight into the short-term results of a management strategy is preferred, then the herd can be followed over time while approaching the (new) steady state.
- The modelling approach includes probability distributions to account for uncertainty, without the need for replicated simulations as is the case when using probabilistic modelling involving random number generators. The fact that results can be obtained from a single run of the model, reduces the computing time needed and increases the opportunity for alternatives to be analyzed. Sensitivity analyses, therefore, can easily be carried out, which will improve the acceptance of the results by a potential user.
- The models offer the possibility of carrying out detailed as well as aggregated simulations, because they allow for variation in the number of states to be used for representing animals. The choice between detailed or aggregated simulations depends on the objective of the simulation.
- The models could serve as a useful extension of the current management information systems. They allow for the input of herd-specific parameters, resulting in herd-specific consequences of different management strategies on overall performance. The current prototypes are a good basis for user involvement to finalize the models for on-farm use.
- There seem to be more possibilities of improving income by management strategies at tactical level on production, reproduction and replacement in dairy than in swine, as a result of the higher repeatability in production and the seasonal variation in performance and prices in case of dairy.
- To evaluate consequences of alternative calving patterns of a dairy herd, a static comparison of the steady state herd of each alternative is not sufficient. The static comparison results in the maximum possible benefits of a change. The period between the starting calving pattern and the arrival at the desired calving pattern should also be taken into account. The management strategy applied in order to actually change the calving pattern determines the final profit that can be realised to a large extent.

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Summary

1 INTRODUCTION

Improving management is an important option for farmers to reduce costs of production. This option has become increasingly important over the last few years, because of restrictions on other options to improve farm income (e.g. milk quotas and manure legislation). Management information systems can play an important role in improving management. Current management information systems in (Dutch) livestock farming are not suited yet for this task. Management information systems mainly concentrate on the recording of data. They need to be extended with tools that allow for the evaluation of technical and economic consequences of alternative decisions and management strategies. The latter will provide the farmer with information about the potential impact of decisions on farm results in the future. Simulation models could serve as the desired tools. These models will most likely have the largest impact when they can use farm-specific input and when they are available for on-farm use. In this thesis, simulation models were developed for the support of tactical planning related to production, reproduction and replacement in dairy cattle and sow herds. This research was part of the project TACT-Systems in which several institutes collaborated in developing models for on-farm support of tactical planning.

In Chapter 1, a general outline of the framework was given in which simulation models could be used in on-farm decision support. Models available in the literature, primarily focused on production, reproduction and replacement in dairy cattle and swine, were studied to examine the extent to which they are suitable for use in on-farm decision support. The structure of each single model and the differences/similarities between main characteristics of the models were described. An enormous variation in structure was observed between available models. For on-farm use it was considered best to build new models using the available knowledge from existing models, rather than to adjust and combine existing ones.

the economic culling index, including age and productive history of individual sows, were found to be the best. In the basic situation the annual culling rate was 47.4% and gross margin per sow per year Dfl. 1086. Economic differences between strategies depended mainly on realised differences in culling rate. Strategies that referred to guidelines given by extension service were stricter and led to an increase in culling rate (plus 5-6%) and a decrease in gross margin per sow per year (minus Dfl. 15). The strictest strategy (no reinseminations allowed) achieved the highest culling rate (+24.5%) and the largest reduction in gross margin per sow per year (minus Dfl. 62). A very liberal strategy, allowing 4 inseminations in all cases, showed almost the same results as the use of the economic culling index. In case of low farrowing rates, low slaughter values or high prices of replacement gilts, differences between use of the economic culling index and the more stricter strategies increased considerably. The strategies studied did not influence the number of pigs sold per sow per year, implying that this parameter has limited potential as an economic indicator in comparing strategies on production, reproduction and replacement.

4 DAIRY MODELS

The dynamic probabilistic model developed for dairy cattle was described in Chapter 4. Compared with the swine model, a new feature was included, namely the seasonal influence on herd dynamics and performance, which had a great impact on the model characteristics. The model was used to compare different calving patterns of the herd under different circumstances. Results for Dutch conditions showed that when considering gross margin per cow per year, it is most profitable to have calvings concentrated in autumn.

In Chapter 5, the dynamic probabilistic simulation model was further extended with the simulation of young stock from birth to first calving and used for a comparison of different strategies in order to change the calving pattern of a herd. Strategies to change the calving pattern focusing on the farm's intake of replacement heifers, allowing a certain variation in age at first calving, were compared. A method was developed which allows the tuning of the available replacement heifers to the desired heifer calving pattern, using linear programming. In the basic analysis a spring calving herd was changed into an autumn calving herd. The difference in gross margin per cow per year between the starting and the desired situation was Dfl. 115 in favour of the autumn calving herd. The strategy that allowed the largest variation in age at first calving resulted in the fastest change of the calving pattern. It took 9 years to realise the desired herd calving pattern, while the desired heifer calving pattern was already reached after 2 years. This strategy turned out to be the most profitable one. When considering a period of 10 years, this strategy on average yielded an additional income of Dfl. 105 per cow per year. In case of a strategy that did not allow changes in the initial age at calving, the increase was only Dfl. 6 per cow per year when considered over a period of 10 years. When after the start of the latter strategy a shorter period of time was considered, the costs of changing even exceeded the benefits. An additional measure which did not allow cows to be inseminated in certain months during the first few years, did not show to be economically attractive. The modelling approach can be used to determine the consequences of different price scenarios on the profitability of different calving patterns and of actually changing the calving pattern of the herd. If seasonal variation in prices of milk, calves, heifers and culled cows disappeared completely after a few years, the maximum profit to be realised would be Dfl. 50 per cow per year, indicating that it is still profitable to change the calving pattern to an autumn calving herd.

In Chapter 6, a method was developed that determined the farm-specific optimum herd calving pattern taking into account several restrictions at herd level, by integrating the dynamic probabilistic simulation model with a linear programming model. The objective function and the constraints of the linear programming problem were formulated in such a way that they could be related to the number of heifers calving per month. The required coefficients were obtained from the results of the so-called single-month equilibrium herds, calculated by the simulation model. The approach was flexible enough to include all kinds of constraints, of which a few were illustrated. Gross margin of the herd was maximized, given a certain milk quota. With only that constraint all heifers calved in August. In case only home-raised replacement heifers were used, as an additional constraint, heifer calvings took place from July to October. Gross margin was reduced by no more than Dfl. 0.13 per 100 kg of milk. The optimum herd calving pattern was also determined for situations in which the reproductive performance was lower and for the situation in which seasonal variation in prices was omitted.

5 FROM PROTOTYPES TO ON-FARM USE

The models described in this thesis were designed for use in on-farm decision support. The description of the models in Chapter 2 through 6 was focused on the technique for simulating herd dynamics and on possible applications. In the discussion chapter, attention was focused on how to proceed from the current prototypes towards a successful implementation in the field as part of an integrated decision support system (IDSS). Further research is needed to determine the best approach of obtaining farm-specific input parameters for the models from the data base. User involvement is required in the implementation of the current models in on-farm decision support. It is an advantage to have prototypes available in the discussion about how to use models in on-farm decision support. It will help the participants in the discussion (e.g. user groups, research and extension organizations) structure their ideas about the implementation of the models in the field.

6 MAIN CONCLUSIONS FROM THE STUDY

- The probabilistic modelling approach using transition probabilities (Markov chain approach) has shown to be very powerful in simulating herd dynamics, both in dairy cattle and swine. The method can be used to derive directly the steady state of the herd and corresponding technical and economic results. Steady state results reflect the long-term results of the herd and offer a basis for a sound comparison of different management strategies. When insight into the short-term results of a management strategy is preferred, then the herd can be followed over time while approaching the (new) steady state.
- The modelling approach includes probability distributions to account for uncertainty, without the need for replicated simulations as is the case when using probabilistic modelling involving random number generators. The fact that results can be obtained from a single run of the model, reduces the computing time needed and increases the opportunity for alternatives to be analyzed. Sensitivity analyses, therefore, can easily be carried out, which will improve the acceptance of the results by a potential user.
- The models offer the possibility of carrying out detailed as well as aggregated simulations, because they allow for variation in the number of states to be used for representing animals. The choice between detailed or aggregated simulations depends on the objective of the simulation.
- The models could serve as a useful extension of the current management information systems. They allow for the input of herd-specific parameters, resulting in herd-specific consequences of different management strategies on overall performance. The current prototypes are a good basis for user involvement to finalize the models for on-farm use.

- There seem to be more possibilities of improving income by management strategies on production, reproduction and replacement at tactical level in dairy than in swine, as a result of the higher repeatability in production and the seasonal variation in performance and prices in case of dairy.
- To evaluate consequences of alternative calving patterns of a dairy herd, a static comparison of the steady state herd of each alternative is not sufficient. The static comparison results in the maximum possible benefits of a change. The period between the starting calving pattern and the arrival at the desired calving pattern should also be taken into account. The management strategy applied in order to actually change the calving pattern determines the final profit that can be realised to a large extent.

Samenvatting

1 INLEIDING

Een verbetering van het management is voor veehouders een belangrijke optie om de kosten van hun produktie terug te dringen. Deze optie is de laatste jaren steeds belangrijker geworden. Door opgelegde beperkingen, zoals superheffing en mestwetgeving, zijn er namelijk minder andere mogelijkheden om het inkomen te verhogen. Bij een verbetering van het management kunnen management-informatiesystemen een belangrijke rol spelen. Daarvoor is het wenselijk de huidige (commerciële) systemen in de Nederlandse veehouderij, die zich nog voornamelijk beperken tot het vastleggen en analyseren van gegevens, uit te breiden met simulatiemodellen om de technische en economische consequenties van alternatieve beslissingen op voorhand door te kunnen rekenen. De veehouder kan dan bij het overwegen van beslissingen beschikken over inzicht in de potentiële invloed ervan op de toekomstige resultaten van het eigen bedrijf. In dit proefschrift zijn simulatiemodellen ontwikkeld ter ondersteuning van het management rond produktie, vruchtbaarheid en vervanging op melkvee- en zeugenbedrijven. Het onderzoek maakt deel uit van het project TACT-Systemen. Daarin werken verschillende instanties tezamen aan de ontwikkeling van modellen voor beslissingsondersteuning ten behoeve van de tactische planning.

In Hoofdstuk 1 is een algemeen overzicht gegeven van het raamwerk waarbinnen simulatiemodellen bij beslissingsondersteuning op het bedrijf gebruikt zouden kunnen worden. Bestaande modellen die zich met name richten op produktie, vruchtbaarheid en vervanging bij melkvee en zeugen, zijn bestudeerd aan de hand van de literatuur om te onderzoeken in hoeverre ze voor een dergelijk gebruik geschikt zijn. De structuur van elk model en de verschillen/overeenkomsten tussen de belangrijkste kenmerken van de modellen zijn beschreven. Tussen de bestudeerde modellen is een enorme variatie in structuur waargenomen. Voor gebruik bij beslissingsondersteuning op het bedrijf, wordt dan ook de voorkeur gegeven aan de ontwikkeling van nieuwe modellen boven het aanpassen en combineren van bestaande modellen. Daarbij is het wel mogelijk gebruik te maken van de beschikbare kennis uit de bestaande modellen.

2 SIMULATIE VAN DE DIERSTROOM

Bij het bepalen van de technische en economische consequenties van alternatieve beslissingen op het gebied van produktie, vruchtbaarheid en vervanging bij melkvee en zeugen, speelt de simulatie van de dierstroom een centrale rol. De benadering die in dit proefschrift is gebruikt om de dierstroom na te bootsen wijkt af van de daarvoor gebruikelijke aanpak, zoals die ook is gebruikt in de modellen die zijn beschreven in Hoofdstuk 1 (i.e. stochastische modellen met gebruik random getallen). In de in dit proefschrift ontwikkelde modellen is het principe van een Markov keten toegepast om de dierstroom te simuleren (i.e. probabilistisch modelleren met kansverdelingen). De veestapel wordt beschreven in termen van toestanden waarin dieren kunnen verkeren en de overgangen die mogelijk zijn tussen de toestanden. De corresponderende overgangskansen worden afgeleid uit invoerwaarden die betrekking hebben op biologische variabelen enerzijds en managementtactieken anderzijds. De modellen hebben de eigenschap dat ze op een directe en efficiënte wijze de veestapel kunnen bepalen die in een zogenaamde stabiele toestand (i.e. steady state of evenwichtssituatie) verkeert. Verschillende sets van invoerwaarden kunnen worden geëvalueerd door de technische en economische resultaten van de corresponderende steady state veestapels te vergelijken. De dierstroom kan ook worden bestudeerd door de veestapel te volgen in de tijd, om zo inzicht te verkrijgen in hoe de veestapel de (nieuwe) steady state bereikt.

De in dit proefschrift toegepaste probabilistische modelaanpak gebruikt kansverdelingen om rekening te houden met onzekerheid ten aanzien van toekomstige prestaties van dieren. Daarbij wordt de noodzaak om herhaalde berekeningen uit te voeren vermeden, omdat één enkele berekening de verwachte waarde (i.e. gewogen gemiddelde) van de resultaten oplevert. De voor- en nadelen van deze benadering zijn uitgebreid beschreven in het discussie hoofdstuk.

Het aantal toestanden dat in de modellen wordt onderscheiden is variabel. Dit schept de mogelijkheid om zowel gedetailleerde als geaggregeerde simulaties uit te voeren. Laatstgenoemde vorm biedt de mogelijkheid cq. ruimte om meerdere (deel)modellen te koppelen om zo te komen tot een simulatie van het bedrijf als geheel. Verder kunnen de invoergegevens eenvoudig worden aangepast. Problemen die gerelateerd zijn aan het verkrijgen van bedrijfsspecifieke invoergegevens voor de modellen zijn besproken in het discussie hoofdstuk.

3 ZEUGENMODELLEN

De dynamisch probabilistische modelaanpak gericht op zeugenbedrijven is beschreven in Hoofdstuk 2. Het gedrag van het model is bestudeerd door een typisch Nederlands bedrijf te evalueren. Een gevoeligheidsanalyse is uitgevoerd om inzicht te verkrijgen in de invloed van variatie in verschillende invoerwaarden op de technische en economische resultaten van het bedrijf.

In Hoofdstuk 3 is het model gebruikt om zes managementtactieken op het gebied van produktie, vruchtbaarheid en vervanging te vergelijken. Het gebruik van het kengetal gebruikswaarde, recent ontwikkeld om inseminatie- en vervangingsbeslissingen van individuele zeugen economisch te optimaliseren, is vergeleken met meer algemene vuistregels. Onder de bestudeerde omstandigheden leverden de tactieken op basis van het kengetal gebruikswaarde (o.a. rekening houdend met leeftijd en produktiegeschiedenis van de zeug) de beste resultaten. In de basissituatie bedroeg het jaarlijkse uitvalspercentage 47,4% en het saldo per zeug per jaar *f*1086. Economische verschillen tussen de tactieken hingen voornamelijk af van gerealiseerde verschillen in uitvalspercentage. Tactieken die betrekking hebben op het gebruik van richtlijnen gegeven door het IKC-Varkenshouderij waren strikter en leidden derhalve tot een toename in het uitvalspercentage (plus 5-6%) en een daling in het saldo per zeug per jaar (min *f*15). De meest strikte tactiek, geen herinseminaties toegestaan, realiseerde het hoogste uitvalspercentage (+24,5%) en de grootste reductie in saldo per zeug per jaar (minus *f*62). Een zeer tolerante tactiek, in alle gevallen 4 inseminaties toegestaan, resulteerde in bijna dezelfde resultaten als het gebruik van het kengetal gebruikswaarde. In het geval van een slechte vruchtbaarheidssituatie op het bedrijf, lage slachtwaarde of hoge prijzen van opfokzeugen, namen de verschillen tussen de tactieken gebruikmakend van gebruikswaarde en de striktere tactieken aanzienlijk toe. De bestudeerde tactieken beïnvloedden het aantal grootgebrachte biggen per zeug per jaar niet of nauwelijks, hetgeen impliceerde dat deze parameter geen goede economische indicator is bij het vergelijken van tactieken op het gebied van produktie, vruchtbaarheid en vervanging.

4 MELKVEEMODELLEN

De dynamische probabilistische modelaanpak ontwikkeld voor melkvee is beschreven in Hoofdstuk 4. Het model is ten opzichte van het zeugenmodel uitgebreid met de invloed van seizoen op dierstroom, dierprestaties en prijzen. Dit had een grote invloed op de structuur van het model. Het model is gebruikt om verschillende afkalfpatronen van veestapels te vergelijken onder verschillende omstandigheden. Resultaten laten zien dat onder Nederlandse omstandigheden een concentratie van alle afkalvingen in het najaar economisch gezien het meest aantrekkelijk is.

In Hoofdstuk 5 is het model verder uitgebreid met de simulatie van jongvee van geboorte tot eerste keer afkalven. Het model kon daardoor worden gebruikt om verschillende tactieken te vergelijken waarmee het afkalfpatroon van een veestapel daadwerkelijk kan worden verschoven. De tactieken die zijn vergeleken richten zich op de instroom van vervangende vaarzen in de veestapel, en wel in het bijzonder op de variatie die wordt aangebracht in de lengte van de opfokperiode van vaarzen. Er is een methode ontwikkeld waarbij de beschikbaar komende vaarzen worden afgestemd op de gewenste instroom in de veestapel, gebruikmakend van lineaire programmering. In de analyse is als voorbeeld een voorjaarsafkalvende veestapel gewijzigd in een voornamelijk in het najaar afkalvende veestapel. Het saldo per koe per jaar lag bij het gewenste afkalfpatroon (najaar) *f*115 hoger dan in de startsituatie (voorjaar). De tactiek die de grootste variatie in leeftijd bij eerste keer afkalven toestond (22-29 maanden), resulteerde in de snelste verschuiving naar het gewenste afkalfpatroon. Het duurde dan niettemin nog 9 jaar voordat het gewenste afkalfpatroon van de veestapel was bereikt. Het gewenste afkalfpatroon van de vaarzen werd al na 2 jaar bereikt. Deze tactiek was economisch gezien ook de meest aantrekkelijke. Bekeken over een periode van 10 jaar leverde de tactiek gemiddeld een additioneel inkomen op van *f*105 per koe per jaar. In het geval van een tactiek die geen bewuste aanpassing van de lengte van de opfokperiode toeliet, bedroeg de toename over 10 jaar bezien slechts *f*6 per koe per jaar. Werd in het geval van de laatste tactiek een kortere periode dan 10 jaar bekeken, dan overtroffen de kosten van het verschuiven de voordelen. Een aanvullende maatregel, het in de eerste jaren niet insemineren van koeien in bepaalde maanden, bleek bij geen van de onderscheiden tactieken economisch gezien aantrekkelijk te zijn. De modelaanpak kan worden gebruikt om de consequenties van verschillende prijsscenario's op de winstgevendheid van verschillende afkalfpatronen en het daadwerkelijk verschuiven van het afkalfpatroon te bepalen. Wanneer seizoensvariatie in de prijzen van melk, kalveren, vaarzen en afgevoerde koeien na enkele jaren zou verdwijnen, bedroeg de maximale winst die kan worden gerealiseerd nog altijd *f*50 per koe per jaar. In dat geval is het dus nog steeds voordelig om het afkalfpatroon van de veestapel te verschuiven naar het najaar.

In Hoofdstuk 6 is een methode ontwikkeld die het bedrijfsspecifieke optimale afkalfpatroon bepaalt, rekening houdend met verschillende beperkingen op bedrijfsniveau. In deze methode is het dynamische probabilistische model geïntegreerd met een lineair programmeringsmodel. De doelfunctie en beperkingen van de lineaire programmering zijn zodanig geformuleerd dat ze gerelateerd kunnen worden aan het aantal vaarzen dat per maand afkalft. De benodigde coëfficiënten worden verkregen uit de technische en economische resultaten van de twaalf zogenaamde basisveestapels die zijn berekend met het simulatiemodel. In deze basisveestapels kalven alle vaarzen steeds in één van de kalendermaanden af. De benadering is zo flexibel dat allerlei beperkingen zijn op te nemen, waarvan er een paar zijn geïllustreerd in Hoofdstuk 6. Als voorbeeld is het saldo van de veestapel gemaximaliseerd gegeven het beschikbare melkquotum. Met alleen deze beperking kalfden alle vaarzen af in augustus. In het geval van een additionele beperking waarin uitsluitend eigen gefokte vaarzen de veestapel mochten instromen, vonden de afkalvingen van vaarzen plaats van juli tot oktober. Het saldo per kg melk was dan slechts weinig lager. Het optimale afkalfpatroon is ook bepaald voor de situatie waarin de vruchtbaarheidssituatie op het bedrijf slechter is en voor de situatie waarin seizoensvariatie in prijzen is weggelaten.

5 VAN PROTOTYPES NAAR GEBRUIK IN DE PRAKTIJK

De modellen die zijn beschreven in dit proefschrift zijn ontwikkeld voor gebruik bij beslissingsondersteuning op individuele bedrijven. De beschrijving van de modellen in Hoofdstuk 2 tot en met Hoofdstuk 6 is met name gericht op de techniek die is gebruikt voor het simuleren van de dierstroom en op de mogelijke toepassingen. In het discussie hoofdstuk is aandacht besteed aan het te bewandelen pad om te komen van de huidige prototypes naar een succesvolle implementatie in de praktijk als onderdeel van een geïntegreerd beslissingsondersteunend systeem. Een belangrijk punt voor nader onderzoek daarbij is te komen tot de beste aanpak voor het verkrijgen van bedrijfsspecifieke invoerwaarden voor de modellen uit de database. Het betrekken van gebruikers bij de verdere aanpassing en implementatie van de huidige modellen is vereist. Het hierbij beschikbaar hebben van prototypes wordt als een groot voordeel gezien. Het helpt de deelnemers aan de discussie (gebruikersgroepen, onderzoek en voorlichting) bij het structureren van hun ideeën over wat nodig is voor het praktijkklaar maken van de modellen.

6 BELANGRIJKSTE CONCLUSIES VAN HET ONDERZOEK

- De probabilistische modelaanpak gebruikmakend van kansverdelingen (Markov keten benadering) heeft laten zien zeer krachtig te zijn in het simuleren van de dierstroom. De methode kan worden gebruikt om snel en direct de steady state van een veestapel en de corresponderende technische en economische resultaten af te leiden. De steady state resultaten geven de lange termijn resultaten van de veestapel weer, en vormen de basis voor een eerlijke vergelijking van verschillende managementtactieken. Indien inzicht in de korte termijn resultaten wordt geprefereerd, kan de veestapel worden gevolgd in de tijd terwijl de (nieuwe) steady state veestapel wordt benaderd.
- De modelaanpak maakt gebruik van kansverdelingen om rekening te houden met onzekerheid, zonder dat er herhaalde berekeningen nodig zijn zoals het geval is bij de probabilistische aanpak die gebruik maakt van random getallen. Het feit dat resultaten kunnen worden verkregen met één enkele berekening van het model, reduceert de benodigde rekentijd en verhoogt de mogelijkheid om verschillende alternatieven te analyseren. Derhalve kunnen gevoeligheidsanalyses eenvoudig worden uitgevoerd, hetgeen de acceptatie van de resultaten door een potentiële gebruiker mogelijk verbetert.
- De modellen bieden de mogelijkheid om zowel gedetailleerde als geaggregeerde simulaties uit te voeren, omdat het aantal toestanden waarin dieren kunnen verkeren kan worden gevarieerd. De keuze tussen gedetailleerde of geaggregeerde simulaties is afhankelijk van het doel van de berekeningen.
- De modellen zouden kunnen fungeren als een zinvolle uitbreiding van de huidige management-informatiesystemen. Ze staan de invoer van bedrijfsspecifieke parameters toe, resulterend in bedrijfsspecifieke consequenties van verschillende managementtactieken. De huidige prototypes vormen een goede basis voor betrokkenheid van de gebruiker bij het gereedmaken van de modellen voor beslissingsondersteuning op het bedrijf.
- Bij melkvee lijken er meer mogelijkheden te zijn om het inkomen te verhogen middels managementtactieken op het gebied van produktie, vruchtbaarheid en vervanging dan bij zeugen. Dit is mogelijk een gevolg van de hogere correlaties in produktie en de seizoensvariatie in prestatie en prijzen bij melkvee.
- Bij het evalueren van alternatieve afkalfpatronen van een veestapel is een statische vergelijking van de steady state veestapels, zoals tot nu toe gebruikelijk in onderzoek en voorlichting, niet voldoende. De statische vergelijking resulteert namelijk in de maximaal mogelijke winst die bij een verschuiving kan worden behaald. De periode tussen uitgangsafkalfpatroon en gewenst afkalfpatroon moet ook worden meegenomen in de vergelijking. De tactiek waarmee het afkalfpatroon daadwerkelijk wordt verschoven, bepaalt in grote mate de uiteindelijke winst die kan worden behaald.

Related publications

1989

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Curriculum vitae

Aaltje Willemina Jalvingh (Alien) werd op 13 augustus 1965 geboren in Ruinerwold (Drenthe). In 1983 behaalde zij aan de toenmalige Rijksscholengemeenschap te Meppel het diploma ongedeeld VWO. In september 1983 werd een start gemaakt met de studie Zoötechniek aan de toenmalige Landbouwhogeschool Wageningen. In september 1988 sloot zij de studie Zoötechniek (afstudeervakken Veefokkerij en Agrarische Bedrijfseconomie) met lof af. De voor beide afstudeervakken gekombineerde scriptie getiteld "Computermatige ondersteuning van inseminatiebeslissing, afvoerstrategie en kwotumbeleid" werd in 1989 onderscheiden met een scriptieprijs van de Stichting Wageningenfonds.

Na haar afstuderen was zij tot september 1992 werkzaam als Assistent-in-Opleiding (AIO) bij de vakgroepen Agrarische Bedrijfseconomie en Veefokkerij van de Landbouwuniversiteit Wageningen. De aanstelling vond plaats in het kader van het project TACT-Systemen en heeft geleid tot dit proefschrift. Sinds september 1992 is zij binnen hetzelfde project werkzaam als toegevoegd onderzoeker. Vanaf september 1993 werkt ze als toegevoegd onderzoeker bij de vakgroep Agrarische Bedrijfseconomie. Dit in het kader van een EG-project dat zich richt op de ontwikkeling van een beslissingsondersteunend systeem ter bepaling van de optimale bestrijdingsaanpak bij een uitbraak van Mond- en Klauwzeer.