Smart Agricultural Technology 8 (2024) 100447

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

Enhancing culling decisions in Swiss dairy farming: Introducing a tool for improved replacement choices

S. Schlebusch [a,d,*], D. Hoop [a], P. von Rohr [b], H. Pausch [c], C. Gazzarin [a]

[a] Agroscope, Tänikon 1, 8356 Ettenhausen, Switzerland
[b] Qualitas AG, Chamerstrasse 56, 6300 Zug, Switzerland
[c] ETH Zürich, Universitätsstrasse 2, 8092 Zürich, Switzerland
[d] Braunvieh Schweiz, Chamerstrasse 56, 6300 Zug, Switzerland

ARTICLE INFO

Keywords:
Dairy cow
Replacement policy
Bio economic model

ABSTRACT

Making improved replacement decisions for dairy cattle is a complex and crucial task for farmers. Research suggests that the ideal economic productive lifespan of a cow is typically between 5 and 6 lactations, yet real-world practices fall short of this potential. Farmers often face suboptimal decisions owing to the intricate nature of the culling process, which involves numerous economic and non-economic factors that vary between farms. This complexity is compounded by a lack of comprehensive information on the economic implications of culling decisions. To address this challenge, we present an algorithm and tool designed for Swiss dairy farmers, aiming to simplify and optimize their culling decisions. This algorithm, inspired by previous models, leverages a Markov chain approach to calculate anticipated survival probabilities, considering factors such as pregnancy. Key aspects of this tool include assigning a monetary value, known as the ``cow value,'' to each cow based on expected survival and monthly revenue. The cow value allows farmers to rank all cows comprehensively, aiding in the identification of less productive cows that merit replacement. The algorithm considers the diverse production systems and breed variations in Swiss dairy farming. It factors in variables such as the cost of acquiring replacement heifers, milk prices, protein and fat contents, fertility, and health. This tool offers Swiss dairy farmers valuable insights, especially in larger herds, where culling decisions may be less evident. By providing economic implications of culling choices, the algorithm optimizes average herd life and enhances farmers' income.

Introduction

Determining the replacement policy for a dairy farm, including the decision when to cull and which cow to cull, is a complex decision-making process. Research in the field suggests that the optimal economic productive lifetime of a cow is typically between 5 and 6 lactations [14,17]. Moreover, a longer productive lifetime for cows not only yields economic benefits but also contributes to mitigating environmental impacts (2008; [14]). However, the observed average productive lifetime of cows is 2 to 3 lactations shorter than the optimal lifespan identified in research. This pattern holds true not only in Switzerland but also worldwide [1,8,16,18,20,21]. This would suggest that farmers often make suboptimal replacement decisions or research could also overvalue longevity. A major reason is the complexity surrounding the culling decision, which involves considering various economic and non-economic factors that likely differ between farms. Additionally, a lack of comprehensive information regarding the economic implications of culling decisions further complicates the process.

Several economic factors need to be considered when replacing a cow on a farm. The cost of acquiring a replacement heifer and the slaughter price of the cow being culled is a crucial consideration. Additionally, the milk price and the potential for extra payments based on protein content, fat content, and a low somatic cell count should be taken into account. Cows producing more milk with high fat and protein concentrations are generally more economically viable than those with lower parameters. Fertility and health are also very important factors in culling decisions, although they can vary significantly [7,13,22]. The decision to replace a cow is also influenced by factors such as the availability of replacement heifers and the farm's expansion or contraction plans. Although in a population under selection a heifer may

* Corresponding author.
E-mail address: simon.schlebusch@braunvieh.ch (S. Schlebusch).

https://doi.org/10.1016/j.atech.2024.100447
Received 15 January 2024; Received in revised form 28 March 2024; Accepted 30 March 2024
Available online 1 April 2024

be genetically superior to a culled cow, older cows may still have the potential to reach their maximum milk production [5]. A high production potential of old cows should be considered before making the culling decision. Keeping old cows on the farm can delay genetic improvement but achieve higher milk production [12]. Animal welfare and environmental considerations also play a significant role in the replacement decision process. Direct payments or social and public incentives may be associated with certain animal welfare and environmental practices [19]. Moreover, different farms may have distinct optimal productive lifetimes owing to profound differences in their production systems (e.g., breed selection, feeding practices, environmental conditions, and management strategies). Therefore, it is essential to consider these aspects in the decision to replace a cow.

Swiss dairy farming exhibits significant diversity, characterized by various factors that influence the optimal replacement policy for each farm. Key distinctions include the classification into 3 regions based on the suitability for silage corn and ryegrass (lowlands, hilly area, mountain zone 1) or non-ryegrass (mountain zones 2 to 4). Seasonal calving, low-input mountain farms, and silage-free operations for cheese production are among the system variations observed. High-yield farms emphasizing concentrate feeding and organic farming are also prevalent [24]. Variations in herd sizes and varying proportions of forage conservation further contribute to the heterogeneity of Swiss dairy farming [9]. In addition, breed variations ranging from Holstein, Brown Swiss, and Jersey to Fleckvieh, Original Brown, and Simmental are prevalent. All these variations impact the cost revenue structure of the farms. Therefore, considering the unique characteristics of each production system and breed variation is crucial when formulating strategies for replacement decisions in Swiss dairy farming.

In the USA, Cabrera [6] developed a user-friendly decision support system for the cow replacement problem, considering factors such as pregnancy and expected future production. He utilized a Markov chain algorithm to calculate expected profit of dairy cows and optimize replacement policies. In Ireland, Kelleher et al. [15] introduced the “cow own worth” index, which ranks dairy cows based on expected profit and complements the national breeding index. To develop the cow own worth index, a model based on expected lifetime of the cow and estimated performance of the cow based on breeding values was used. Both studies provided practical tools and insights for efficient culling in the US American and Irish contexts.

The goal of our study was to develop an algorithm on which in a future step a tool for practical applications can be designed for Swiss dairy farmers to facilitate making better culling decisions by considering a wide range of farm-specific characteristics. The algorithm presented here builds upon the foundations laid by Cabrera [6] and Kelleher et al. [15], leveraging a Markov chain model to calculate anticipated survival probabilities. However, this algorithm provides a heightened level of flexibility, capable of accommodating diverse production systems and unique farm attributes. For this purpose, we use the “cow value” in German “Kuhwert”. It assigns every cow in a herd a monetary value based on expected survival and monthly revenue compared with her replacement. As a result, the tool offers Swiss dairy farmers valuable insights by identifying less productive cows that merit replacement, thereby offering actionable recommendations for enhancement within the herd.

Materials and methods

Calculating the cow value

The model calculates the cow value CV as the difference between the average revenue per month of the cow $\varnothing MCV_{\text{cow}}$ and the average revenue per month of the replacement $\varnothing MCV_{\text{replacement}}$ (Eq. (1)).

$$CV = \varnothing MCV_{\text{cow}} - \varnothing MCV_{\text{replacement}} \tag{1}$$

The $\varnothing MCV$ is the sum of all the monthly revenues per cow MCV_t over the productive lifetime of a cow divided by the productive lifetime t of the cow (i.e., the average monthly revenue; Eq. (2)).

$$\varnothing MCV = \sum_{t_0}^{t} (MCV_t)/t \tag{2}$$

The calculation of the revenue per cow and month is based on all income I_t and cost C_t of the cow for that month (Eq. (3)).

$$MCV = \sum_{t_0}^{t=1} I_t - C_t \tag{3}$$

The model behind the decision support algorithm consists of 2 main components. The first calculates the life expectancy of a cow, and the second determines the monthly revenue per cow. In the following sections, the methods and materials used to calculate the cow value are described and partial results are presented.

Datasets

The data used in this work were based on 3 large population datasets and 1 farm-specific herd dataset. All data had been provided by the Association of Swiss Cattle Breeders, which is the umbrella organization of Swiss cattle breeding organizations. The first dataset contained the data from the monthly milk recording for every cow affiliated to a breeding organization for the years 2010 to 2018. This dataset was used to calculate transition probabilities and included the identity (ID) of the cow, the breed, the birthdate, the date of the milk recording, as well as the associated lactation number and most recent calving date (n = 1,016,428 cows).

The second dataset contained information about artificial inseminations recorded between 2010 and 2018 for all animals included in the first dataset. The second dataset was also used to calculate transition probabilities and contained the ID of the cow, the birthdate, the date of the insemination, the number of the insemination in the current lactation, and the lactation number (n = 1,282,749 cows).

The third dataset contained milk recordings from 2019 to 2022. This dataset formed the basis to calculate the lactation curves. The dataset contained the ID of the cow, the breed, the birthdate, the date of the milk recording, the calving date, the lactation number, the milk yield, the protein content, and the fat content (n = 813,455 cows).

The fourth dataset contained individual farm-level data independent from the other datasets. This dataset was used to calculate the cow value for each cow in a farmer’s herd. The dataset contained the ID of the cow, the breeding values (based on a 305-day standard lactation) for milk yield, protein content, fat content, somatic cell count, fertility, and productive lifetime, the birthdate, the lactation number, and the current month in milk (n = 20–200 cows).

All datasets underwent thorough plausibility checks, and any implausible records were excluded. Implausible data points were cows with lactation number greater than 15, as well as month in milk greater than 20 and month in pregnancy greater than 9. Also, animals that left out a lactation, month in milk, or month in pregnancy were excluded. Additionally, cows lacking information in both the first and second datasets were excluded from the analysis to ensure data consistency and reliability.

Calculating the life expectancy

Transition matrix

Using datasets 1 and 2, it was possible to split the lives of cows into different states. These states were defined by the lactation number (L), the month in milk or month after calving (M), and the month in pregnancy (P; a specific state will hereafter be abbreviated as L#:M#:P#) [6, 15]. From giving birth to the first calf until being culled, each cow could transition through a variety of states. All data processing is done in R, to speedup calculations they are outsourced to C++.

As an example shown in Fig. 1, a cow in the third lactation, in the fourth month in milk, and in the first month in pregnancy would be in state 3:4:1. This cow can stay pregnant resulting in state 3:5:2, or she may not be pregnant (owing to abort), which would correspond to state 3:5:0, or she might be culled, which is a special state in itself. From datasets 1 and 2, we calculated the probability for an average cow to make the transition from one specific state to potential future states.

The probability of every state constituted the transition (probability) matrix and was later used for a Markov chain analysis and calculation (Fig. 2). By using a Markov chain, it is possible to predict the future states of the system or estimate the likelihood of reaching specific states [11]. The method assumes that the transition probability only depends on the current state and is independent of past states. To generate the states from datasets 1 and 2, preparatory steps were necessary. While the lactation stage was given directly by the milk recording data, the month in milk had to be approximated by counting the number of milk recordings in a certain lactation stage. This might have introduced small biases because milk recordings were not always conducted on the same day of the month for a given farm. One month after the last milk recording, the cow was considered culled. Therefore, the culled state included culling as well as the departure of the cow to a non-breeding organization or farm. The month in pregnancy was retrospectively derived from the calving date to the month in milk were the cow got pregnant. Artificial insemination data were used to derive unsuccessful inseminations and aborts (influencing the transition probabilities). If an insemination had been recorded within 3 months after a given insemination, the previous one was considered unsuccessful. If an insemination had been recorded more than 3 months after a previous insemination, the previous insemination was considered successful, but the pregnancy had ended in an abortion.

The minimum and maximum allowed values per lactation were 1 to 15, for month in milk 1 to 20, and for month in pregnancy 0 to 9. All described calculations to derive the states of cows were done separately for the breeds Brown Swiss, Holstein, and Simmental/Swiss Fleckvieh, resulting in a separate transition matrix for every breed. These transition matrices implied a certain life expectancy for a cow (starting in the first lactation and the first month in milk).

To be able to model farms with higher or lower average cow life expectancy, additional transition matrices were calculated by changing the probability of the cows being culled. That is, in order to create a transition matrix with increased life expectancy, the probability to be culled was decreased slightly in each state. In turn, the probabilities of transitioning into other (survival) states were increased proportionally, such that the sum of transition probabilities coming from a specific state remained 100 % in total. This was done repeatedly to get a list of transition matrices resulting in different average cow life expectancies. In a later step, a matrix could be chosen that matched most closely the life expectancy of a given herd at hand.

State probability matrix

Based on the transition matrices, we calculated the state probability matrices, a steady state. That is, an iteration through the Markov chain, starting from state 1:1:0 until culling, was performed 5000 times which included on average 40 monthly steps. After 5000 iterations, the state transition probability did not change significantly anymore. The collected data allowed us to calculate the probability of a cow being in one specific state. The steady state has also been calculated for various life expectancies and starting states.

Calculation for the cow on the farm

To calculate the expected lifespan of a cow in a specific herd, the fourth dataset provided information on the lactation and the number of months in milk for each cow on the farm. When using the tool, the farmer would need to specify the month in pregnancy for each cow. Because this information was missing for the examples, we assumed that cows became pregnant 2 to 4 months after calving for the purpose of our calculations. The average herd lifespan for the farm would also need to be determined by the farmer. For this study, we determined the average herd lifespan by calculating the average lactation number of all cows on a farm (assuming that 1 lactation equals 1 year). To the resulting number, we added the average month in milk.

Based on the precalculated steady states (see above), the steady state was selected that best matched the life expectancy of the herd and had the correct initial state. As each future state corresponded to 1 month, the product of “number of months to live” and “average profit per month” resulted in the cumulative profit that was to be expected from

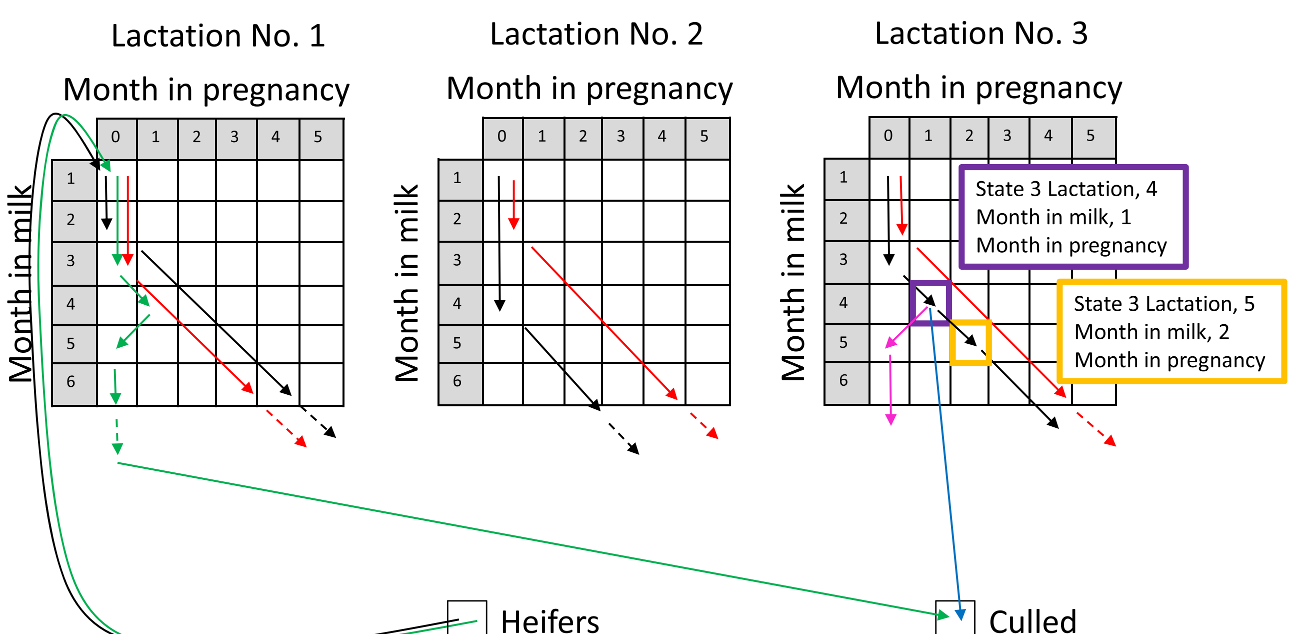

Fig. 1. An example of how cows transition through different states with an example cow starting in the third lactation, in the fourth month in milk, and in the first month in pregnancy. From this point forward the cow can follow the black path, stay pregnant, following the pink path the cow has an abortion and is not pregnant anymore, following the blue path the cow has an accident or issues why she is culled.

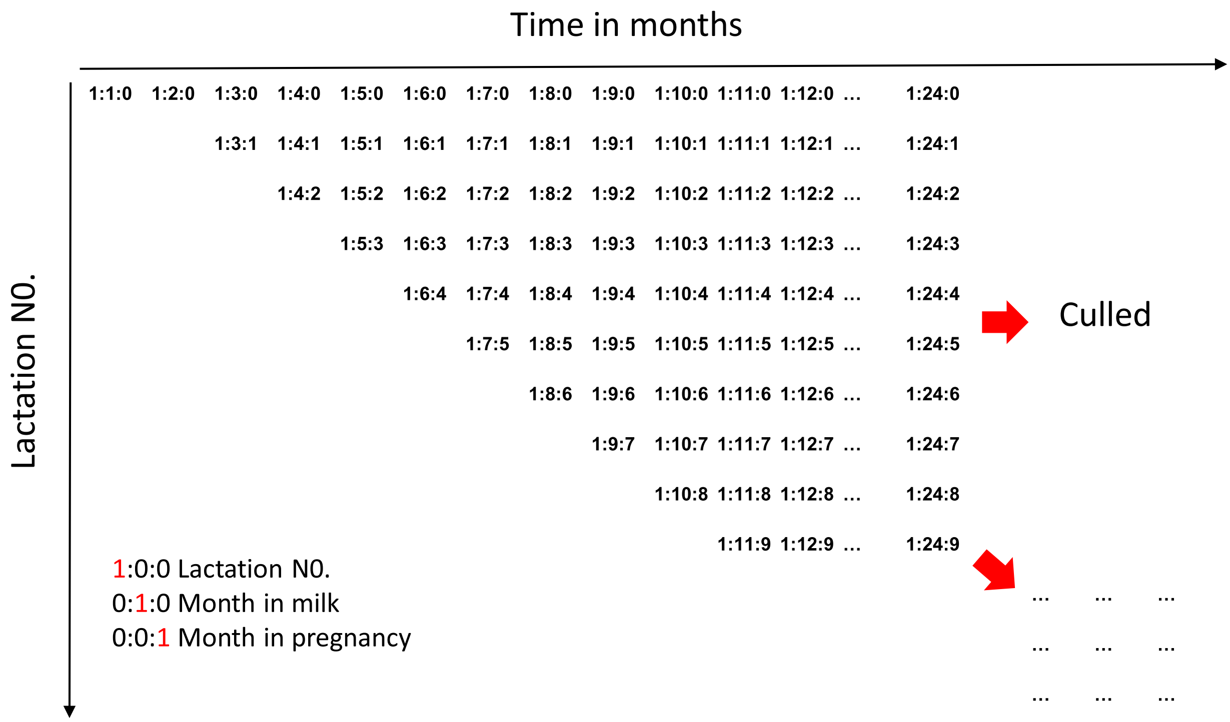

Fig. 2. Example of a Markov chain matrix, lactation N0 on the *y* axes, month in milk on the *x* axes and month in pregnancy on the diagonal.

one specific cow. This calculation avoided the need to perform thousands of iterations through the Markov chain for each cow, thereby considerably reducing the computational effort.

Preliminary calculations

Lactation curves

To be able to calculate the expected future profit for a specific herd or farm (in dataset 4), farm-specific lactation curves had to be assumed. The estimation was conducted using the Wood function [23]. Two different approaches were used to derive the lactation curve, depending on the size of the farm. For farms with less than 20 cows, the lactation curve was determined using data from the third dataset. For farms with more than 20 cows, the lactation curve was derived from the farm's own data, as described in the fourth dataset.

The lactation curves based on-farm data (dataset 4) were calculated for milk, protein, and fat yields in kilograms. The protein and fat yields were then converted to percentage values. The dataset provided information on the number of days in milk and the corresponding yield. For lactations 1 to 5, the lactation curve was estimated separately. Because the number of observations usually dropped considerably after the fifth lactation, the data of all subsequent lactations were combined and only one additional lactation curve was estimated that would be used for all subsequent months.

To account for different milk, protein, and fat yields in the third dataset, the data was split into 10 percentiles based on the results of a 305-day standard lactation. Lactation curves were then estimated for up to 12 lactations and up to 12 months in milk. To select the lactation curves that fit best to the farm to be analyzed, the specific percentile was chosen that matched most closely the milk yield, protein percentage, and fat percentage in the third lactation of the farm's herd.

Calculating lactation curves that cover up to 15 lactations and 25 months in milk with the available information posed a general challenge because the data typically only provided information for up to 8 lactations and 12 months in milk. To address the challenge of limited data for higher lactations and months in milk, we decided to utilize the last available input from the lactation curve as input for further calculations. This means that for parameters such as the 4th lactation and 15 months in milk, the milk yield information from the 4th lactation and the 12th month in milk would be used.

Calculation for the individual cow

To differentiate milk yield, protein content, and fat content among cows in the herd, the 305-day standard lactation from the last lactation from dataset 4 was utilized. For example, if a cow was currently in the fourth lactation, the information from the 305-day standard lactation of the third lactation was used. To bring all cows to a comparable level of milk yield, the fourth lactation was defined as the base level, and therefore the milk yield of cows with information on the first, second, and third lactations were multiped by specific factors to uplift the milk yield (Table 1; the multiplication factors were calculated from dataset 3 for Brown Swiss, Holstein, Simmental, and Swiss Fleckvieh). For protein and fat yields, the information from the 305-day standard lactation was used without further change to rank the cows because there was very little change between lactations 1 to 4 in our dataset 3.

Once all cows were brought to the same level of milk yield, we divided the herd in quintiles, which was done for milk yield as well as for protein and fat percentages. Depending on the quintile, the cow was expected to perform better or worse than the herd average. Cows in the fifth quintile were expected to perform 10 % better than the average, whereas cows in the first quintile were expected to perform 10 % worse than the herd average. Accordingly, a cow with a relative production level of 1.10 was considered a top performer, with 1.05 an above-average performer, with 1.00 an average performer, with 0.95 a below-average performer, and with 0.90 a bottom performer. The

Table 1
Multiplication factors for calculating comparable milk yield levels calculated from dataset 3.

Lactation	Brown Swiss	Holstein, Simmental and Swiss Fleckvieh
1	1.190	1.204
2	1.073	1.062
3	1.017	1.012
4 and higher	1	1

production levels for milk, protein, and fat were independent of each other. Therefore, a cow could be a top performer in one category and an average performer in another.

Cows that had not finished their first 305-day standard lactation as well as heifers were expected to perform at the herd average. By incorporating the information about the 305-day standard lactation from the first lactation and adjusting the milk yield and protein and fat contents based on the differences from the herd average, a reasonable estimation of an individual cow's milk production and milk composition could be achieved.

Feed cost calculation

The amount of feed needed for a cow—differentiating between concentrates and roughage—depended on the milk yield of the cow, her liveweight, age (therefore growth), and pregnancy status and was calculated by a function provided by Agroscope [4]. Frist the energy corrected milk yield is calculated by milk yield, fat and protein content, then maintenance requirement is added for cow live weight, then the energy requirement for pregnancy is added per day in pregnancy and if the cow is in first or second the energy requirements for growth is calculated by kg growth per day and added as well combining to the total energy requirement of the cow.

The cost of roughage production was estimated using the "PARK" farm model, which had been developed by Gazzarin et al. [10] and calculates the roughage price for 1 kg milk yield for the farm based on the summer feeding, the feed storage, the number of cows, the average herd milk yield, the milking system, and other mechanization.

Default costs and prices

Values for costs and prices as well as other important information were based on generic industry average values, which can be found in Table 2. As explained in Section 2.4.2, the assumed milk yield, protein content, and fat content were not only specific to the farm's herd, but specific to each cow. Also, based on the farm's characteristics and estimated cost of roughage production, the feed cost per cow and lactation month was calculated dynamically. The veterinary cost was given per month and cow. Insemination costs were incurred each month. Whenever there was a change in lactation, it was assumed that a calf was sold for fattening purposes at the age of 6 weeks. If a cow was replaced, the old cow was sold for the slaughter price. A new heifer was then introduced to the herd. If the heifer was purchased from the market, the market price was paid.

Table 2
All prices and costs as well as other important information [2,3].

Costs and prices	High performance	Cheese production	Full pasture	Unit
Milk price complex				
Milk price	0.6	0.73	0.6	CHF/kg
Baseline protein	3.3	3.3	3.3	%
Baseline fat	4	4	4	%
Content payment protein	0.05	0.05	0.05	CHF/0.01 %
Content payment fat	0.04	0.04	0.04	CHF/0.01 %
Costs				
Veterinarian	17	14	12.5	CHF/month
Insemination	60	60	53	CHF/insemination
Replacement heifer	3600	3000	2800	CHF/heifer
Concentrate price	0.85	0.85	0.85	kg
Share of concentrate	0.15	0.09	0	%
Replacement				
Liveweight cow	700	700	600	kg
Slaughter weight cow	315	322	288	kg
Liveweight calf at 6 weeks	75	75	75	kg
Other prices				
Slaughter price	8.4	8.4	9.3	CHF/kg
Price calf at 6 weeks	8.1	8.1	9.5	CHF/kg

Results

The cow value

Exemplary results of the cow value for 8 cows and 3 production systems (high-yielding Holstein herd, cheese-producing Brown Swiss herd, fully pasture-based Swiss Fleckvieh herd) are shown in Table 3. Columns 2 to 4 describe the initial state, defined by the lactation, the month in milk, and the month in pregnancy. Some selected cows are shown with both a pregnant and non-pregnant initial state to show the effect of pregnancy on life expectancy, revenue per month, and the cow value. The cow with number 0 is the average replacement cow and the counterbalance for the other cows resulting in the cow value. If the cow value is positive, it is economically rational to keep a cow in the herd, but if the cow value is negative, it is economically better to replace a cow. Older cows tended to have a short life expectancy, but a pregnancy increased life expectancy as well as the revenue and the cow value. The older cows also tended to have a lower revenue per month, but there were exceptions.

There were also differences between production systems with regard to revenue per month and cow value and differences in life expectancy

Table 3
Exemplary results of the cow value calculated for individual cows of various breeds and production systems, the Cow value is the difference between the Revenue per month of the cow and the monthly Revenue of its replacement.

Identity	Lactation	Month in milk	Month in pregnancy	Expected lifespan (years)	Revenue per month (CHF)	Cow value
High performance, Holstein						
HOL0	1	1	0	3.05	208	0
HOL1	6	8	0	0.7	125	−83
HOL2	5	8	6	1.91	304	96
HOL3	5	3	0	2.38	243	35
HOL3	5	3	1	2.38	262	54
HOL4	3	6	4	2.53	287	79
HOL5	2	10	8	2.51	268	60
HOL6	2	4	2	3	307	99
HOL7	1	8	0	1.16	138	−70
HOL8	1	3	0	2.66	255	47
HOL8	1	3	1	3.62	300	92
Cheese production, Brown Swiss						
BS0	1	1	0	3.29	188	0
BS1	6	3	0	1.76	197	9
BS1	6	3	1	2.29	230	42
BS2	4	9	7	2.23	235	47
BS3	4	2	0	2.48	205	17
BS4	3	6	4	2.7	168	−19
BS5	3	1	0	2.83	269	82
BS6	2	9	7	2.8	229	42
BS7	2	2	0	3.02	238	50
BS8	1	7	0	1.63	90	−98
BS8	1	7	5	3.4	206	19
Full pasture, Swiss Fleckvieh						
SFL0	1	1	0	4.01	65	0
SFL1	8	3	0	1.57	28	−37
SFL1	8	3	1	2.04	61	−4
SFL2	5	6	4	2.73	−7	−10
SFL3	6	7	5	2.33	−51	−19
SFL4	4	1	0	3.21	80	15
SFL5	3	7	5	3.34	−13	3
SFL6	3	8	6	3.23	−17	25
SFL7	3	1	0	3.57	82	17
SFL8	1	7	0	1.77	−33	−98
SFL8	1	7	5	4.18	68	4

for the initial state.

Within the context of the provided example as seen in the "cow value" column in Table 3, the tool's recommendations for replacement align as follows: For the high-performance Holstein herd, considering HOL1 and HOL7 for replacement would be prudent. For the cheese-production Brown Swiss herd, the candidates for culling are BS4 and BS8.

For the Swiss Fleckvieh herd on full pasture, the tool would suggest replacing SFL1, SFL2, SFL3 and SFL8. In the following sections, the cow value is decomposed, and its partial results are shown. In Figs. 3 and 4 the cow value over the initial state/ the expected lifespan is shown for the example divide by breed.

The transition matrix and life expectancy

An extract from the transition matrix for the Brown Swiss breed is shown in Table 4, which lists a sequence of probabilities with which a cow will transition from her current state to a future state. For example, starting from state 1:8:7, the cow has a probability of 0.579 (or 57.9 %) to transition to state 2:1:0. Column 2:1:0 indicates the probability of the cow calving and starting the second lactation. The last column shows the culled state and indicates the probability of a cow being culled. The sum of every row is 1. Depending on the initial state, the likelihood of transitioning to the next state is determined by the transition matrix. For instance, if a cow is currently in state 1:8:6, there is a 93.9 % chance of transitioning to state 1:9:7, a 0.054 % chance of progressing to the second lactation in state 2:1:0, and the remaining 0.8 % is distributed among states 1:9:0, 1:9:1, and the culled state. From one state to the next, this process is repeated until the cow is culled; the total number of states reached by the cow results in her expected lifespan. Please refer to Section 2.3.3 for a detailed description of the method.

Table 5 displays the average expected lifespan for various breeds, starting from state 1:1:0. According to the baseline transition matrix, the expected lifespan was 4.19 years for Brown Swiss, 3.61 years for Holstein, and 3.85 years for Simmental/Swiss Fleckvieh. To enhance the accuracy of the algorithm, the baseline transition matrix was adjusted to account for longer and shorter expected lifespans, with the longest expected lifespan being approximately 7 years and the shortest around 2 years. For further calculations, the transition matrix closest to the farm's average productive lifespan was chosen. Please refer to Section 2.3.1 for a detailed description of the method.

Results of the preliminary calculation for the individual herd

Using the farm-specific herd information from dataset 4, the results shown in Table 6 were calculated. The average productive life for the high-performance Holstein herd was estimated to be 3.05 years, for the cheese-production Brown Swiss herd 3.29 years, and for the full-pasture Swiss Fleckvieh herd 4.01 years. Every herd also had a different milk yield and different protein and fat contents. The most suitable transition matrix was chosen based on the average herd life and the breed of the herd.

In Fig. 5 the lactation curve for the first lactation of the high-performance Holstein herd is shown. This curve resembles the curves for higher lactations and the curves for other herds. The lactation curve gives the average milk, protein, and fat yields for the herd. To differentiate cows in the herd, this lactation curve would be offset by the relative production level of each cow (in a subsequent step).

Based on their last finished milk record, the cows were divided into relative production levels for milk, protein, and fat yields. The average production is indicated by a 1. Top performers have a relative production level of 1.1 indicating that they produce 10 % more than the herd average, and bottom performers have a relative production level of 0.9 indicating that they produce 90 % of the average cow in the herd. Animals that did not finish a lactation as well as the replacement heifer (indicated by ID 0) are expected to perform at the herd average.

In Table 7, the results for the feed calculation are shown. The high-performance Holstein herd had a roughage feed price of CHF 0.254 per kilogram milk produced, the cheese-production Brown Swiss herd a price of CHF 0.379, and the full-pasture Swiss Fleckvieh herd a price of CHF 0.320. The roughage prices reflected the differences in production systems and farm size. The full-pasture farm had low roughage costs through low input, whereas the high-yielding farm leveraged scale effects to achieve low roughage costs, and the more complex silage-free

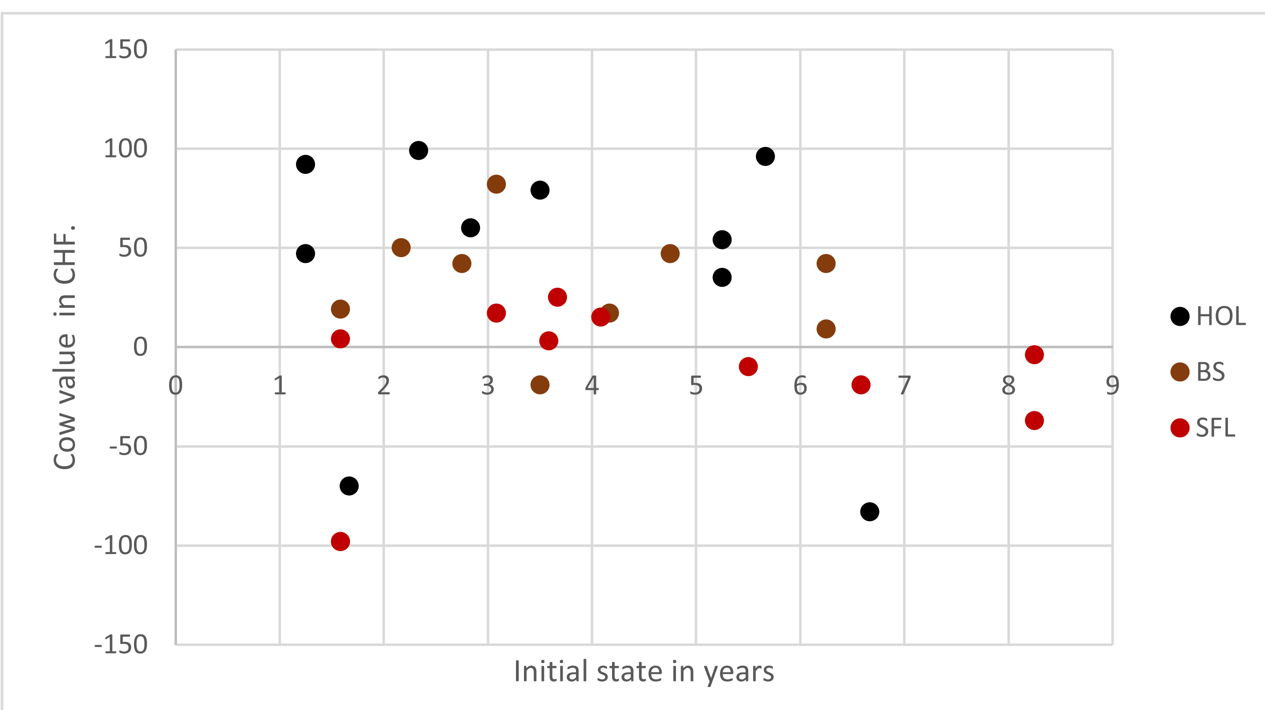

Fig. 3. The cow value in CHF. over the initial state in years split for the breeds Holstein (HOL), Brown Swiss (BS) and Swiss Fleckvieh (SFL).

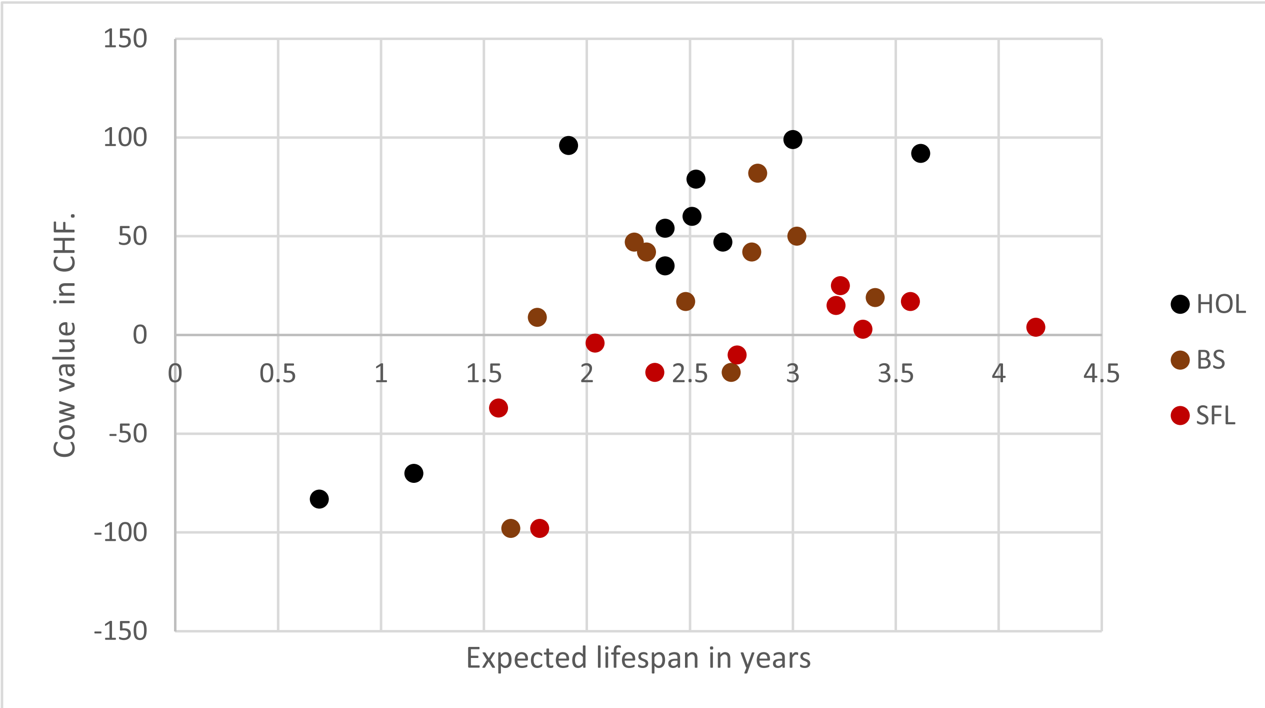

Fig. 4. The cow value in CHF. over the expected lifespan in years split for the breeds Holstein (HOL), Brown Swiss (BS) and Swiss Fleckvieh (SFL).

Table 4
An extract from the Markov chain for Brown Swiss cows (with the states coded as lactation:month in milk:pregnancy month); starting at state 1:8:4 all the probabilities to reach another state are calculated, Green highlights the live states, red highlights the culled state.

Initial state	1:9:0	1:9:1	1:9:2	1:9:3	1:9:4	1:9:5	1:9:6	1:9:7	1:9:8	1:10:0	1:10:1	2:1:0	Culled
1:8:4	1.2%	0.5%	0%	0%	0%	98.3%	0%	0%	0%	0%	0%	0.0%	0%
1:8:5	0.6%	0.2%	0%	0%	0%	0%	99.1%	0%	0%	0%	0%	0.0%	0%
1:8:6	0.6%	0.2%	0%	0%	0%	0%	0%	93.9%	0%	0%	0%	5.4%	0%
1:8:7	2.3%	0.4%	0%	0%	0%	0%	0%	0%	39.2%	0%	0%	57.9%	0.1%
1:9:0	0%	0%	0%	0%	0%	0%	0%	0%	0%	79.0%	7.0%	0%	14.0%

Table 5
The different average expected lifespans for different breeds starting from state 1:1:0, the baseline expected lifespan is 4.19 for Brown Swiss, 3.61 for Holstein and 3.85 for Simmental/Swiss Fleckvieh.

Average expected lifespan (years)		
Brown Swiss	Holstein	Simmental/Swiss Fleckvieh
7.23	6.39	7.18
6.61	5.87	6.46
6.02	5.45	5.95
5.64	5.03	5.55
4.99	4.44	4.93
4.49	3.94	4.4
4.19	3.61	3.85
3.69	3.32	3.51
3.47	3.25	3.4
3.31	2.99	3.34
2.92	2.46	2.92
2.8	2.42	2.56

Table 6
Herd and milk yield information, the chosen transition matrix for the herd, the average herd life, the average milk, protein and fat yield as well as the breed based on herd data.

Transition matrix (years)	Average herd life (years)	Breed	Milk yield (kg)	Protein (%)	Fat (%)
3.05	3.05	Holstein	11,873	3.24	3.98
3.29	3.29	Brown Swiss	6719	3.59	4.37
4.01	4.01	Swiss Fleckvieh	5890	3.28	4.28

production system led to higher roughage costs.

Discussion

The described algorithm and its underlying economic information can help in guiding the farmers' decision-making processes regarding the retention or culling of cows. By providing economic implications of

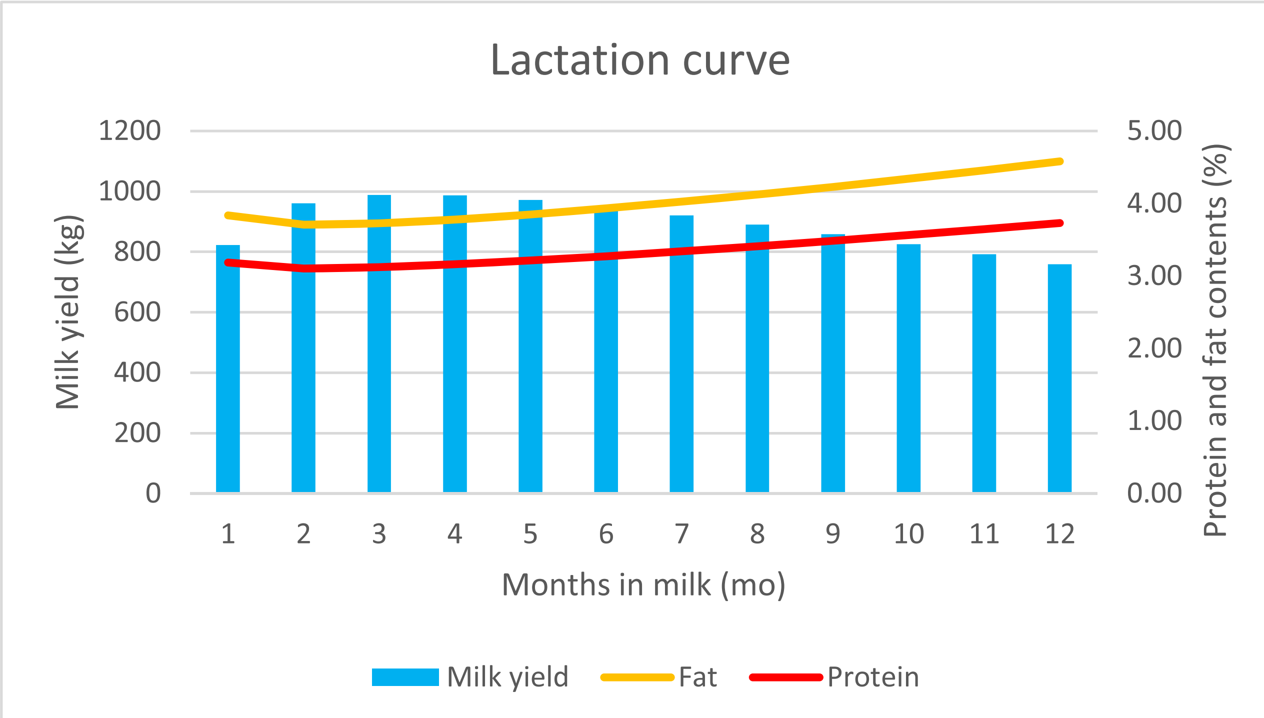

Fig. 5. An example of a lactation curve with milk, protein and fat yield used in the model (high-performance Holstein herd).

Table 7
Roughage price calculation based on summer feeding, feed storage, number of cows, milking robot, mechanization with the Park model by Gazzarin et al. [10].

Summer feeding	Roughage feed storage	Number of cows	Milk yield per cow (kg)	Milking robot	Mechanization	Roughage feed price (CHF)
Year-round silage	Silage	140	11,873	No	Medium to high	0.254
Pasture and barn feeding of freshly cut forages	Silage-free	51	6719	No	Medium to high	0.379
Full pasture	Silage	68	5890	No	Low	0.320

culling decisions, the algorithm has the potential to optimize the average herd life and farmers' income. By summarizing all costs and revenues of a cow into a single metric, the cow value offers Swiss dairy farmers an opportunity to make more comprehensive culling decisions. From the results of our analysis, a consistent pattern emerged wherein older animals would be recommended for replacement more frequently than currently practiced. This recommendation is based on the anticipated shorter lifespan of older cows. Yet, a noteworthy observation surfaced when accounting for pregnancy states, as this factor significantly influenced both the expected lifetime and the cow value. Consequently, differing replacement choices emerged based on pregnancy status for example for cows BS8 and SFL8. The inclusion of the cow value introduces an avenue for informed decisions regarding veterinary treatments. Furthermore, the utility of this tool is particularly pronounced in larger herds where the abundance of similar animals can make culling decisions less evident. In contrast, smaller herds may have more apparent candidates for culling, often involving only 1 or 2 animals.

To perform the exemplary calculations described in this paper, we used a mix of data sources. We collected cow and herd data from breeding organizations accessible to Swiss farmers who are part of these organizations. Additionally, we utilized industry data from sources such as [2,3] and incorporated data from the PARK model [10]. Based on these sources we modeled 3 different farm scenarios. These scenarios demonstrated how the algorithm can be applied using industry standard values and different farm data. When farmers use the algorithm, they themselves can provide all the necessary values, which ensures the highest level of accuracy in the results, or they can rely on default parameters.

The developed model is more complex than similar tools [6,15] because it considers various farm structures in Switzerland, aspiring to achieve accurate results across a wide range of farm types. The tool developed in Ireland by Kelleher et al. is fully based on herd information provided by the breeding organizations. Other production parameters such as prices are taken into account, though not on a farm level; hence, the farms are expected to be relatively similar [15]. The tool devolved in the USA by Cabrera calculates the replacement decisions based on a few key farm parameters given by the farmer [6]. Our developed algorithm uses the available herd information provided by the breeding organizations, as well as giving the farmers the option to individually set all the parameters relevant to the replacement decisions on their own. This procedure ensures that all available information is incorporated in the cow value, thus leading to better replacement decisions.

The introduction of a tool providing economic information on culling and replacement decisions could lead to increased attention being given to the replacement policy on farms, similar to the significance of breeding values. As breeding values have become integral to almost every breeding decision and widely available to all farms, a support tool for culling decisions and the associated replacement policy could significantly impact farmers' reconsideration of their replacement strategy, leading to a more economically stable state.

There are several areas where further improvements can be implemented. For instance, introducing an annual discount for future profits is possible. We decided to forgo this option due to the currently very low annual interest rates in Switzerland, as well as our focus on relatively short timespans ranging from 1 to 3 years. The model could be improved by considering payments paid for older cows according to the Swiss direct payment scheme from 2024 onwards. Enhancing the calculation of veterinarian costs is another aspect that could be improved. One approach could be linking veterinarian costs to the number of lactations, where costs increase with each subsequent lactation. Alternatively, farmers could assign a low, medium, or high veterinarian cost class to each cow in the herd, with corresponding costs associated with each class. These improvements would refine the accuracy and functionality of the algorithm.

We faced challenges when trying to determine the milk yield of individual cows. Initially, we attempted to use breeding values by comparing each cow to the herd's average. However, in tests, we found that the expected milk yield based on breeding values correlated little with the actual milk yield achieved. Generally, the issue with breeding values is that they are used to predict offspring performance; therefore, they are limited in assessing individual cow performance, because the only include genetic effects, not taking into account environmental effects, like feeding, altitude or weather. Alternatively, the use of a net merit index was impossible due to unavailability of economic value of breeding traits in Switzerland. We also considered the ranking of cows based on their first lactation performance. However, these methods turned out to be unreliable. The most reliable approach was to use the most recent data available for each cow and classify the cows based on that information. Though also not without its limitations, since 5 quantiles and a differential of -10 up to $+10$ may not correspond completely with reality, through this ranking it is possible to penalize a low producing cow compared to higher producing one. A further limitation of our model is that the history of health and fertility of a cow does not impact the future states of a cow even though this might be a reasonable expectation. However, this independency from previous states is a core attribute of the Markov chain methodology. It could have been addressed by adding a dimension like Somatic Cell Count, but we decided against it because adding another dimension would have further increased the complexity of the model and reduced the number of data points per state. Therefore, the farmer must personally consider the health and fertility information when making a sound replacement decision.

An additional extension could involve considering the environmental impact of the culling decision. This would entail calculating the emissions of carbon dioxide, methane, nitrous oxide, and nitrate based on factors such as culling age and milk yield. The resulting emissions output could be provided to the farmers as an additional variable, enabling them to incorporate environmental considerations into their decision-making process. Alternatively, the algorithm could incorporate a pricing mechanism for emissions, thereby directly including the cost of emissions in the calculation of the cow value. By including the cost of emissions, the algorithm would provide a more comprehensive assessment of the economic and environmental implications of different culling decisions.

The developed algorithm also holds considerable potential for simulation purposes within the farm itself or for policy makers. Farmers or advisors can simulate how different replacement policies or milk prices affect farm profitability, enabling them to suggest economically viable steady states. Furthermore, the tool can be utilized to assess the impact of direct payments, such as those for older cows starting in 2024 in Switzerland.

Conclusion

In summary, the developed algorithm provides invaluable insights into the economic aspects of replacement decisions on dairy farms, through the introduction of the cow value metric. This single monetary figure serves as a practical aid for farmers, assisting them in making more informed and optimized replacement choices. The algorithm has been designed to address the multifaceted complexities surrounding replacement decisions, taking into consideration the wide spectrum of dairy farming practices found in Switzerland. By accommodating the unique characteristics of individual farms, the algorithm leverages data provided by farmers themselves to offer tailored recommendations. This algorithm can also be helpful in designing a better replacement policy for a farm.

Funding

This work was funded as part of the project Ecobreed by the Association of Swiss Cattle Breeders ("Arbeitsgemeinschaft Schweizerischer Rinderzüchter", ASR).

Ethics statement

This manuscript does not include human or animal research.

CRediT authorship contribution statement

S. Schlebusch: Writing – review & editing, Writing – original draft, Validation, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **D. Hoop:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization. **P. von Rohr:** Writing – review & editing, Data curation, Conceptualization. **H. Pausch:** Writing – review & editing, Supervision. **C. Gazzarin:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

The authors do not have permission to share data.

References

[1] T. Ahlman, B. Berglund, L. Rydhmer, E. Strandberg, Culling reasons in organic and conventional dairy herds and genotype by environment interaction for longevity, J. Dairy Sci. 94 (3) (2011) 1568–1575, https://doi.org/10.3168/jds.2010-3483.

[2] AGRIDEA, 2022. REFLEX 2022 Betriebswirtschaftliche Datensammlung. AGRIDEA Lindau. Zugang:www.agridea.ch.

[3] AGRIDEA, 2023. Deckungsbeiträge 2023. AGRIDEA Lindau. Zugang: www.agridea.ch.

[4] Agroscope, 2021. Fütterungsempfehlungen für Wiederkäuer (Grünes Buch). Agroscope, Posieux. Zugang: www.agroscope.ch/gruenes-buch (Konsultationsdatum 12.09.2023).

[5] H. Bergeå, A. Roth, U. Emanuelson, S. Agenäs, Farmer awareness of cow longevity and implications for decision-making at farm level, Acta Agric. Scand. A Anim. Sci. 66 (1) (2016) 25–34, https://doi.org/10.1080/09064702.2016.1196726.

[6] V.E. Cabrera, A simple formulation and solution to the replacement problem: a practical tool to assess the economic cow value, the value of a new pregnancy, and the cost of a pregnancy loss, J. Dairy Sci. 95 (8) (2012) 4683–4698, https://doi.org/10.3168/jds.2011-5214.

[7] A. De Vries, Symposium review: why revisit dairy cattle productive lifespan? J. Dairy Sci. 103 (4) (2020) 3838–3845, https://doi.org/10.3168/jds.2019-17361.

[8] A. De Vries, M.I. Marcondes, Review: overview of factors affecting productive lifespan of dairy cows, Animal 14 (S1) (2020) s155–s164, https://doi.org/10.1017/S1751731119003264.

[9] C. Gazzarin, B. Häller, P. Hofstetter, Economic potential of milk production strategies with restrictive use of concentrated feed—An experiment on 36 family farms in the pre-alpine region, Grassl. Sci. 67 (4) (2021) 343–351, https://doi.org/10.1111/grs.12325.

[10] Gazzarin, C., & Schick, M. (2004). Milchproduktionssysteme für die Talregion: Vergleich von Wirtschaftlichkeit und Arbeitsbelastung. FAT.

[11] D. Gamerman, H.F. Lopes, Markov Chain Monte Carlo: Stochastic Simulation for Bayesian inference, second ed., Chapman & Hall/CRC, Boca Raton, FL, 2006.

[12] H. Groenendaal, D.T. Galligan, H.A. Mulder, An economic spreadsheet model to determine optimal breeding and replacement decisions for dairy cattle, J. Dairy

Sci. 87 (7) (2004) 2146–2157, https://doi.org/10.3168/jds.S0022-0302(04)70034-X.

[13] A.M. Heikkilä, J.I. Nousiainen, L. Jauhiainen, Optimal replacement policy and economic value of dairy cows with diverse health status and production capacity, J. Dairy Sci. 91 (6) (2008) 2342–2352, https://doi.org/10.3168/jds.2007-0736.

[14] M. Horn, W. Knaus, L. Kirner, A. Steinwidder, Economic evaluation of longevity in organic dairy cows, Org. Agric. 2 (2) (2012) 127–143, https://doi.org/10.1007/s13165-012-0027-6.

[15] M.M. Kelleher, P.R. Amer, L. Shalloo, R.D. Evans, T.J. Byrne, F. Buckley, D. P. Berry, Development of an index to rank dairy females on expected lifetime profit, J. Dairy Sci. 98 (6) (2015) 4225–4239, https://doi.org/10.3168/jds.2014-9073.

[16] J.I. Kerslake, P.R. Amer, P.L. O'Neill, S.L. Wong, J.R. Roche, C.V.C. Phyn, Economic costs of recorded reasons for cow mortality and culling in a pasture-based dairy industry, J. Dairy Sci. 101 (2) (2018) 1795–1803, https://doi.org/10.3168/jds.2017-13124.

[17] A. Kiefer, L. Sonntag, E. Bahrs, Ökonomische bewertung der nutzungsdauer von milchkühen im kontext erwarteter erkrankungen /Economic analysis of productive life of dairy cows in the context of expected disease occurrence, Austrian J. Agric. Econ. Rural Stud. 28 (5) (2020) 27–34, https://doi.org/10.15203/OEGA_28.5.

[18] N.M. Nor, W. Steeneveld, H. Hogeveen, The average culling rate of Dutch dairy herds over the years 2007 to 2010 and its association with herd reproduction, performance and health, J. Dairy Res. 81 (1) (2014) 1–8, https://doi.org/10.1017/S0022029913000460.

[19] B. Odermatt, N. Keil, M. Lips, Animal welfare payments and veterinary and insemination costs for dairy cows, Agriculture 9 (1) (2019) 3, https://doi.org/10.3390/agriculture9010003.

[20] M. Rödiger, R. Home, Systemic enablers and barriers to extending the productive life of dairy cows in Switzerland, J. Rural Stud. 100 (2023) 103031, https://doi.org/10.1016/j.jrurstud.2023.103031.

[21] J.C. Schuster, H.W. Barkema, A. De Vries, D.F. Kelton, K. Orsel, Invited review: academic and applied approach to evaluating longevity in dairy cows, J. Dairy Sci. 103 (12) (2020) 11008–11024, https://doi.org/10.3168/jds.2020-19043.

[22] J.A.M. Van Arendonk, A.A. Dijkhuizen, Studies on the replacement policies in dairy cattle. III. Influence of variation in reproduction and production, Livest. Prod. Sci. 13 (4) (1985) 333–349, https://doi.org/10.1016/0301-6226(85)90025-9.

[23] P.D.P. Wood, Algebraic model of the lactation curve in cattle, Nature 216 (5111) (1967) 164–165, https://doi.org/10.1038/216164a0.

[24] A. Zorn, F. Zimmert, Structural change in the dairy sector: exit from farming and farm type change, Agric. Food Econ. 10 (1) (2022) 7, https://doi.org/10.1186/s40100-022-00212-z.