Dairy cattle replacement under changing agri-environmental policies

Pranav S. Kulkarni

Propositions

1. The rules of thumb used by Dutch dairy farmers to make replacement decisions are conservative.
   (This thesis)

2. The definitions of biological and economic culling are too rigorous and unnuanced to be used effectively in dairy herd research.
   (This thesis)

3. Using only epidemiological studies as basis for public health policy leads to erosion of confidence in scientific research.

4. Pressure to publish scientific literature has transformed science into scientific journalism.

5. Early adoption of disruptive General Purpose Technologies (GPT) into society is always net negative in short-term.

6. Ethical use of artificial intelligence is the individual responsibility of every member of society.

Propositions belong to the thesis entitled,

Dairy cattle replacement under changing agri-environmental policies

Pranav S. Kulkarni

Wageningen, 19 January 2024

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Pranav S. Kulkarni

Thesis committee

Promotors
Prof. Dr. H. Hogeveen
Personal chair, Business Economics Group
Wageningen University & Research

Prof. Dr. M. Nielen
Professor, Faculty of Veterinary Medicine
Utrecht University

Co-promotors

Dr M.C.M. Mourits
Associate Professor, Business Economics Group
Wageningen University & Research

Dr W. Steeneveld
Assistant Professor, Faculty of Veterinary Medicine
Utrecht University

Other members

Prof. Dr S.L.J.M. de Leeuw, Wageningen University & Research
Prof. Dr J. Niemi, Natural Resources Institute Finland
Dr A.T.M. van Knegsel, Wageningen University & Research
Dr T. van Werven, Utrecht University

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Pranav S. Kulkarni
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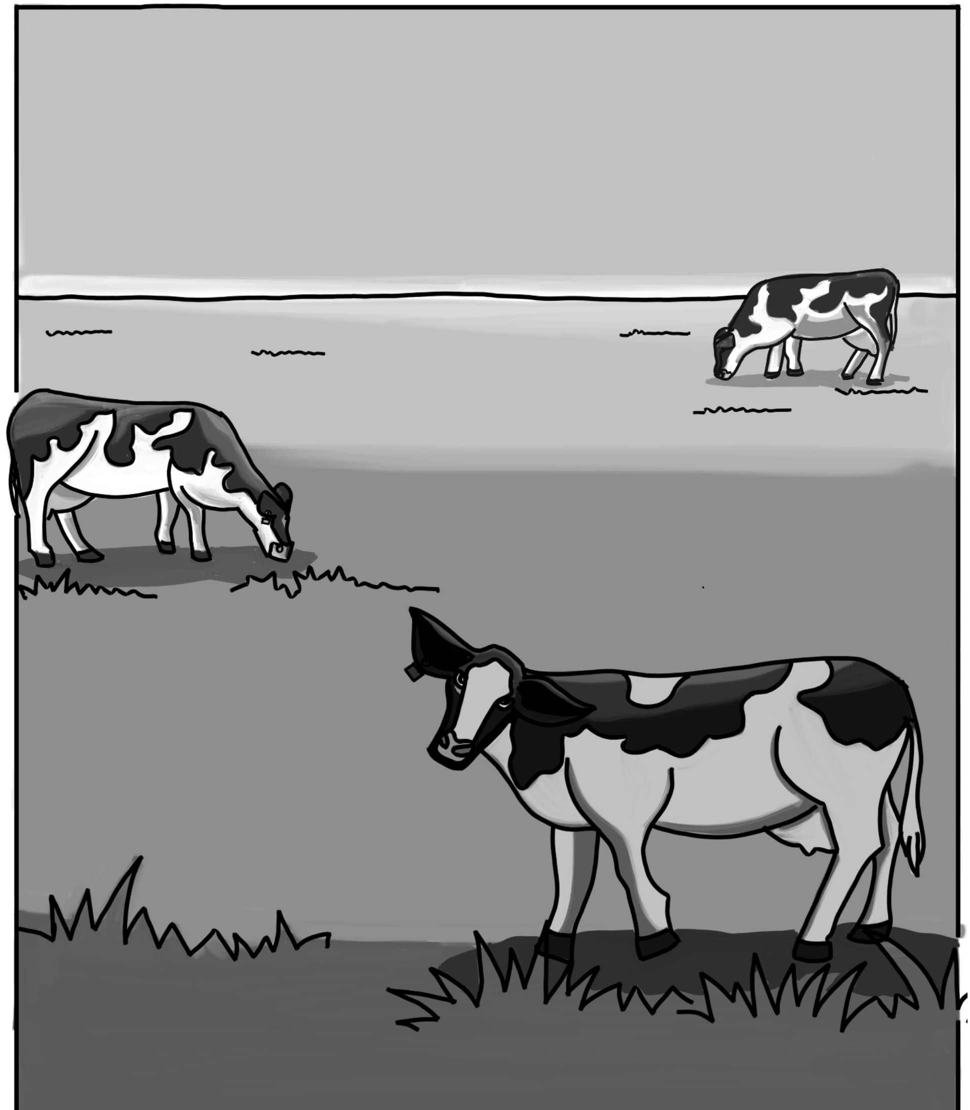
CHAPTER 1



General Introduction

1.1 Background

From 2000 onwards, the global market conditions for dairy improved and global demand for milk and milk products increased (Groeneveld et al., 2016). The global dairy sector found new markets in Asia, especially China. Due to technological development and industrialization of agriculture, milk production has increased tremendously worldwide to meet this demand. According to the USDA (Foreign Agricultural Service, 2022) the global milk production increased from 497 billion kg in 2015 to 544 billion kg by the end of 2022. The biggest contributor to the global milk production was the European Union (EU) at 145 billion kg of milk produced annually followed by USA and India producing 103 and 97 billion kg respectively (USDA Foreign Agricultural Service, 2022). The main contributors to the milk production in the EU are Germany, France, Poland, the Netherlands, and Italy. The dairy sector in these countries is defined by adoption of new technologies which increase the intensity and productivity of the farms. However, this increase in production intensity has resulted in negative environmental externalities, such as the pollution of soil and water and increased GHG emissions (Hensen et al., 2005; Oenema and Roest, 1998). Over time, new regulations and policy changes have been implemented to mitigate these environmental impacts.

1.1.1 Effect of agricultural policy on dairy sector of the Netherlands

The Netherlands is one of the world's leaders in commercial dairy production, accounting for 4.5% - 5% of total global milk trade from 2015-2020 (ZuivelNL, 2022). The total export revenue from Dutch dairy industry amounts to €7.7 billion annually contributing 1% to the GDP. In 2021-22, the Dutch dairy sector produced 14 billion kg milk from 1.6 million dairy cows distributed among approximately, 14,750 commercial dairy farms. In 2022, the Dutch dairy sector was worked by 46,000 full-time workers including farmers and contract labor thereby making it one of the major employing enterprise sectors in the Netherlands (ZuivelNL, 2022).

The Dutch dairy sector is regulated by the national agricultural policy within the framework of the EU Common Agricultural Policy (CAP). The combination of national agricultural policies in the framework of EU-CAP influences the structure and management of Dutch dairy farms. For instance, the milk quota that was implemented in 1984 until its abolishment in 2015, the total number of producing cows in the NL reduced from 2.5 million to 1.5 million heads (CBS, 2017). However, the number of active dairy farms also dropped considerably with a rate of 2.1% annually (Jongeneel and van Berkum, 2015). Over the three decades (1984-2015) of the milk quota, fewer dairy farms with larger, more intensive herds remained operational. During this period, the dairy farming sector was focused on application of new technology to reduce production costs, improving milk yield per cow, and reorganization in increasingly intensive operations with more cows per farm. Because of this, the milk production per cow was at 8,200 kg in 2014-15 which was almost double the amount produced in the 1960s (CBS, 2017). In anticipation of as well as a reaction to the abolishment of milk quota, dairy farms in the Netherlands expanded dramatically thereby maximizing their revenues by increasing the lactating herd sizes (CRV, 2019; Groeneveld et al., 2016). From 2014 to 2016, the average herd size increased from 108 to 115 and the number of active dairy farms reduced further by 3% annually (CBS, 2021).

This period of expansion, was however, short-lived. Considering the environmental implications, the government of the Netherlands imposed a new manure regulation policy (Dairy Act) pertaining to phosphates and nitrogen waste in 2015 (based on Dutch Nutrient Management Policy of 1991 and MINerals Accounting System – MINAS; Hanegraaf and den Den Boer, 2003). This Dairy Act of 2015 meant that expanding herd size would require extra land to process manure. The Netherlands has limited land under agricultural usage, and therefore purchasing land is expensive. The increase revenues from extra milk gained from expansion in post-milk quota era were lower than the costs of processing manure (Klootwijk et al., 2016).

Another example of policy change that affected the dairy farm structure and management was that of the Phosphate regulation policy which was enforced in 2017-18 (Rijksoverheid, 2018; Government of Netherlands, 2018). This policy granted limited rights to dairy farmers to produce manure. The number of phosphate rights granted to a dairy farmer was based on the number of cows kept in July 2015, subjected to a generic reduction of 8.3% (Rijksoverheid, 2018). As a result, many farmers were forced to immediately reduce their livestock numbers and halt expansion. The 2018 phosphate regulation policy had an EU-CAP approved tradable component (Fraters et al., 2020; Rijksoverheid, 2018). If the farmers produced below the rights granted to them, they were allowed to lease out their rights to farmers who expected to exceed them. As a result, there were financial incentives in reducing the phosphate production on the farm.

One way to do so, was to limit the animal stock on the farm. Farmers have to make choices between the non-producing youngstock (female calves and replacement heifers) and producing cows when deciding to limit their animal stock to be within the limits of the rules and regulations. According to RVO (2019) female calves (age 2 weeks to 1 year old) and young heifers (age 1-2 years old) produce 9.6 kg and 21.9 kg phosphate annually, respectively. On the other hand, each lactating cow, on average produces 42.5 kg of phosphate annually (although this number depends on annual milk production level). Grandl et al. (2019) showed that the environmental burden in terms of emissions from the dairy cows can be reduced by increasing the longevity of the dairy herd. Consistent with that, culling and replacement rate of the dairy herd need to be reduced to increase the longevity of the cows. So, dairy farmers might keep an extra milking cow for each 2.1 young non-producing animals being reared on the farm according to their phosphate production. However, reducing youngstock, limits the availability of heifers. Availability of heifers minimizes risk of sudden disposal in cows. Therefore, limited heifer availability can facilitate reduction in the future production potential of the herd. Any alterations in longevity and replacement need thus to be paired with efficient management practices and strategies (Schuster et al., 2020).

Nowadays, the Netherlands, like many other milk-producing countries, is increasingly considering environmental policies related to agriculture by introducing limits on nitrates, greenhouse gases (GHG) and other emissions. These policies will contribute towards reducing the impact of livestock agriculture on environment (Pachauri and Reisinger, 2007). Recently, increased tensions between dairy farmers and the Dutch government regarding the lofty goal of reducing nitrogen emissions by 50% until 2030 have surfaced in the media and zeitgeist. Looming possibility of such goals being implemented into national policies might require dairy farmers to drastically reduce their livestock numbers and size of their herds.

1.1.2 Culling and replacement of dairy cows

Culling and replacement of dairy cows is a routine but important aspect of dairy farm management. Culling is defined by removal of a cow from the herd for slaughter, salvage, disposal (due to death) or for dairy sale with intent to continue production (Fetrow et al., 2006). In theory, culled cows are replaced by younger, suitable heifers. In the Netherlands, the average annual replacement rate has been varying between 20% and 30% in the first two decades of the 21st century (CRV, 2019; Nor et al., 2014a). This means that dairy cattle longevity in the Netherlands of 5.8 years is far below the biological potential lifespan (Han et al., 2022).

These replacements can be either due to economic reasons (voluntary) or due to health considerations, hence involuntary (Van Arendonk, 1985). Fetrow et al. (2006) defined two types of culling namely, economic, and forced or biological. A large part of the replacements is due to economic reasons with the intent of improving production, reproduction, and the health of the producing herd. On the other hand, and in minority, biological or forced culling occurs when cows are incurable, permanently unable to produce, reproduce or recover or when cows die suddenly or are euthanized. Since most replacements of dairy cows are economic in nature and due to decisions made by farmers, it is pertinent to understand the drivers and risk factors for such culling decisions. Broadly, the culling and replacement has been shown to be influenced by individual cow performance, the farm or herd performance. It is also possible that external factors such as socio-economic changes and the policy induced perturbations affect culling and replacement.

In the Netherlands, the most frequent reasons for culling cows have been reproductive fitness, udder health and mastitis, lameness/other hoof disorders (Boer et al., 2013). Globally, on individual cow level, culling has been shown to be driven by parity, production, reproduction, and health performance (Bascom and Young, 1998; Gussmann et al., 2019; Pinedo et al., 2010; Rilanto et al., 2020; Schukken et al., 2003). Often, dairy cows are culled due to multiple reasons, while only the primary reason gets recorded in the database (De Vries and Marcondes, 2020; Pinedo et al., 2010). Culling reasons on herd level are different and more related to managemental aspects such as strategies of farmers, herd average milk production, structure of herd, style, and behaviour of farmers (Beaudeau et al., 1996; Han et al., 2022; Nor et al., 2014a; Vredenberg et al., 2021). Moreover, it has been shown that culling reasons differ between primiparous (1st parity cows) and multiparous (> 1 parities) cows (Gussmann et al., 2019). Since primiparous cows constitute the future economic potential for the dairy farm, their culling and replacement is particularly relevant to the study of dairy management (Archer et al., 2013).

Another important aspect of replacement is the supply of replacement heifers. Most farms in the Netherlands are closed, meaning they breed and rear their own replacement heifers which has substantial consequences on the dairy farm economics. Each replacement heifer reared successfully requires around €1500 (Mohd Nor et al., 2012). Mohd Nor et al. (2015) showed that 73% of all female calves above the age of 2 weeks need to be kept and reared in order to match the average culling rates on dairy farms. However, farmers tend to keep more youngstock than absolutely necessary, as a risk management tool to account for sudden or forced culling. Considering that the average age of first calving in the Netherlands is 26 months (Mohd Nor et al., 2013), there is a prolonged lag between input (rearing) and output (successful replacement) in replacement management from point of view of heifer supply. This makes it difficult for farmers to account for the costs of rearing while balancing the revenue gained from making replacement decisions. Therefore, culling and replacement management of dairy cows is a complex and multi-factorial subject.

1.1.3 Optimal culling and replacement of dairy cows

Management decisions made by dairy farmers fall under different levels of planning, namely, strategic (long-term), tactical (intermediate term) and operational (short term). Since most dairy farms in high milk producing countries (e.g., the Netherlands), are run and owned by families or single farmers, all three planning hierarchies depend on the management styles and attitudes of the dairy farmers and their families. Culling and replacement of dairy cows is an important aspect of dairy farm management that is relevant on all three levels of management planning hierarchy. A long-term cattle replacement strategy involving aspects such as herd size and rearing of replacement heifers, that drives the maximization of economic gains from milk production signify the strategic aspect of replacement decisions (Lehenbauer and Oltjen, 1998). Decision support tools that predict and compare short-term future profitability of the producing cow and replacement heifers when making a replacement decision show the tactical side of replacement decision (Langford and Stott, 2012). Deciding the optimal time for replacing a particular dairy cow in a herd is the operational aspect of the replacement decision (Ben-Ari et al., 1983; Kristensen, 1988).

In the past, many studies have attempted to investigate and subsequently optimize the replacement decisions of individual cows for better economic gains (reviews by De Vries and Marcondes, 2020; Lehenbauer and Oltjen, 1998; Nielsen and Kristensen, 2015). Van Arendonk (1984) identified two approaches in 1960s and 1970s to optimize replacement decisions mathematically, namely, Marginal Net Revenue (MNR) approach and Dynamic Programming (DP) approach. These methods were inspired by the asset replacement theories that were developed contemporarily (Perrin, 1972). Later, mathematical models such as those constructed by Van Arendonk (1985) involving stochastic dynamic programming and Kristensen (1987) involving Markov decision processes attempted to derive an optimal replacement policy for dairy farmers.

More complex models using hierarchical framework or alternate methodologies have since been developed to improve the dairy cow replacement (Cabrera, 2010; Cha et al., 2014a; Demeter et al., 2011; Houben et al., 1994). Most of these models and tools focus on individual cow replacements, while ignoring availability of heifers and inter-cow dependencies within herds. On the flipside, there have been studies to optimize heifer rearing strategies such that the rearing costs are minimized while maximizing the heifer's future profitability (Mourits et al., 1999). Given the lag of more than 2 years (26 months) between the decision to keep and rear female calves to heifers and the decision to replace a cow, it has been difficult to combine objectives and form coherent optimal strategies for replacement problem on a herd level.

Some of the models developed were intended to be decision support tools while others were intended for research to address knowledge gaps. For example, models by Van Arendonk (1985), DeLorenzo et al. (1992), and Cabrera (2010) were developed as tools for making optimal replacement decisions, whereas replacement decision models by Bar et al. (2008), and Demeter et al. (2011) were developed to study the cost of clinical mastitis and economic impact of breeding policies on dairy farms respectively. Nielsen and Kristensen (2015) gave detailed comments on the two applications of the decision optimizers as decision support tools and as research models.

Some studies also attempted to evaluate and rank cows for their future profitability to prioritize or delay replacement decisions (Van Arendonk, 1984; van Van Arendonk, 1991; De Vries, 2004). Attempts were also made to optimize replacement decisions on herd level to boost herd profitability while accounting for inter-dependencies between cows of the same herd (Ben-Ari and Gal, 1986; Kristensen, 1992; de De Vries, 2005). Despite these developments, most of these models and tools remained theoretical and were seldom applied on actual dairy farms (Groenendaal et al., 2004).

Instead, dairy farmers tend to make replacement decisions based on their intuition and heuristics while relying on experience and traditional know-how. Farmers might employ rules of thumb or guidelines that are not always adapted to the changes in agri-environmental policies. Therefore, factors that influence culling and replacement of dairy cows need to be understood, including farmers' perspectives and strategies behind culling decisions. Given that future farm goals must include a reduction in environmental burden while maintaining economic viability, a revisit of optimal replacement and heifer rearing strategies is sorely needed.

1.2 Aim of the thesis

The aim of this thesis is twofold:

1. Gain insights in the factors and reasons for culling and replacement of Dutch dairy cows under changing agri-environmental policies
2. Use these insights to explore the consequences of policy constraints on replacement strategies.

To achieve this aim, five sub-objectives were formulated:

1. To analyze the relevancy of cow-level risk factors for lifetime survival of Dutch dairy cows representing production, reproduction, and health performances under perturbations due to national policy changes related to the milk quota abolishment of 2015 and the phosphate regulations since 2017.
2. To gain insights into the cross-sectional associations between annual performance indicators of Dutch dairy farms and their corresponding magnitudes of (i) overall culling and (ii) primiparous cow culling after the introduction of the herd size restricting phosphate regulation in the Netherlands.
3. To (i) determine the reasons behind the culling of cattle on Dutch dairy farms, (ii) to determine whether Dutch dairy farmers follow specific culling strategies (plan) and (iii) if so, to evaluate whether they intend to change their strategies in the near future.
4. To study on herd level the economic impact of suboptimal replacement decisions due to a constrained replacement heifer supply while accounting for the interdependency among dairy cows within the herd.
5. To gain insights in the economic consequences of different heifer rearing strategies under the current Dutch phosphate rights policy.

1.3 Outline of the thesis

The outline of the thesis is visualized in Figure 1.1. The Chapters 2 to 6 of this thesis are divided in two distinct but inter-related sections namely, (1) exploratory analyses and (2) mathematical models.

Chapter 2 describes a survival study on the individual cow-level risk factors for lifetime survival of Dutch dairy cows under the perturbations of policy changes resulting from the abolishment of milk quota (2014-15) and the introduction of Phosphate rights regulation (2017-18). A parametric survival model was fit on longitudinal, national-level milk production data from the Netherlands between years 2009 and 2019. In Chapter 3 the associations between dairy farm performance indicators (in production, reproduction, health and longevity dimensions) and their culling proportions were explored by means of a cross-sectional study. Annual production data of Dutch dairy farms in the year 2018 was used to develop rank-correlation matrices and weighted logistic regression models. The studies described in Chapter 2 and Chapter 3 were both data-driven in nature. Chapter 4 describes the results of a national level online survey on perspectives of Dutch dairy farmers regarding their culling and replacement policies. Responses to questions regarding culling reasons, specific culling strategies and intentions to change these strategies were recorded and analyzed using descriptive methods.

To evaluate the economic impact of suboptimal replacement decisions due to constraints on heifer supply (Chapter 5), a modelling framework was developed, consisting of an individual cow-level optimization model integrated in a herd-level simulation model. In Chapter 6, the modelling framework from Chapter 5 was employed to study the consequences of different heifer rearing strategies taking into account the trade-off between economic and environmental effects, by assessing the related differences in phosphate production at farm level.

Chapter 7 comprises of the general discussion of this thesis including its synthesis of results, data and methodological approaches, the future implications and, main conclusions drawn from the thesis.

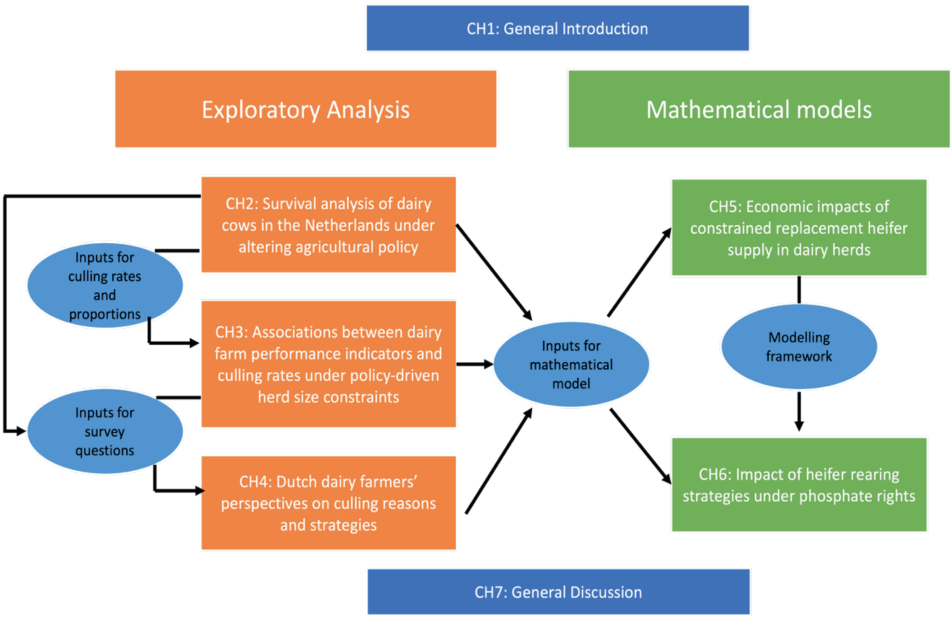
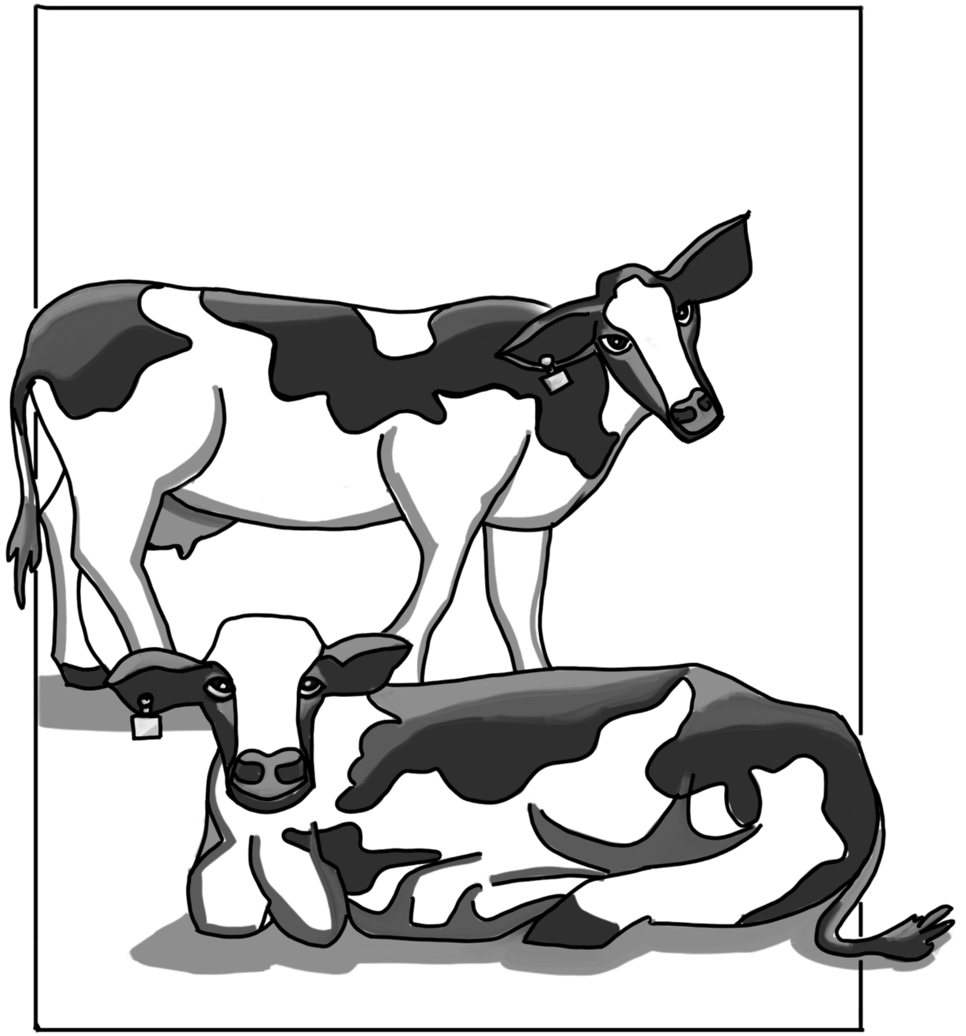


Figure 1.1. Overview of framework of the thesis illustrating five objectives and their relationship. (Note: The arrows represent the direction of inputs)

CHAPTER 2



Survival analysis of dairy cows in the Netherlands under altering agricultural policy.

Kulkarni P. S., Mourits M. C. M., Nielen M., van den Broek J., Steeneveld W.

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Abstract

Culling of underperforming dairy cows by replacement heifers is a fundamental part of Dutch dairy farm management. Changes in national agricultural policies can influence farmers' culling decisions. The objective of this study was to analyse the relevancy of cow-level risk factors for survival of Dutch dairy cows under perturbations due to national policy changes related to the -milk quota abolishment of 2015 and the phosphate regulations since 2017. For this purpose, an accelerated failure time model was fitted on-longitudinal dairy cows' data at national level covering the period 2009−2019. The associated cow-level risk factors for culling such as lactation value (relative production level), parity number, rolling average of inseminations over all parities, very high fat-protein ratio (highFPR) and very low fat-protein ratio (lowFPR) in early lactation, test-day somatic cell count, were fitted in the model. Along with these, a factor representing three target policy periods, namely Milk Quota period (MQ), Post-Milk Quota period (PMQ) and Phosphate regulation period (PH) were fitted. The mean survival age for all producing cows was 441 weeks overall. The predicted median survival time for the policy periods MQ, PMQ and PH were 273 weeks, 271 weeks, and 256 weeks, respectively. Risk factors such as lactation value, parity and highFPR, rolling average of inseminations over all parities were positively associated with survival time in all three policy periods. Risk factors such as test-day somatic cell count and lowFPR were negatively associated with survival time in all three policy periods. In conclusion, this study demonstrated the differences in survival of Dutch dairy cows in response to changing agricultural policy. The association of cow-level risk factors for culling was consistent across the three evaluated policy periods.

Keywords

Survival, Dairy culling, Milk-quota, Phosphate regulation, Risk factors

2.1 Introduction

Replacement of dairy cows is a fundamental part of dairy farm management. The replacement decisions involve removal of underperforming dairy cows and subsequent replacement by suitable heifers. On average, 25–30 % of Dutch dairy cows are replaced annually (CRV, 2018; Nor et al., 2014a) indicating a cow-longevity of 6–7 years (Nor et al., 2014a) which is much lower than the natural biological longevity. A large part of cow replacements involves voluntary culling of producing cows for slaughter/ salvage, which is defined as exit of producing dairy cows from the herd as a consequence of farmers' decision (Fetrow et al., 2006). This culling for slaughter on individual cow level was shown to be associated with older parity/ age, older age at first calving, calving complications and longer calving intervals, lower relative production level, and health indicators like high somatic cell count in milk, very high or very low fat-protein ratios in early lactation, etc. (Gussmann et al., 2019; Huijps et al., 2008; Nielsen et al., 2010; Pritchard et al., 2013; Rilanto et al., 2020; Schukken et al., 2003). These factors can be termed as associated risk factors for slaughter at cow level.

Changes in national agricultural policies can influence farmers' culling decisions. Dairy farmers might change their strategy either in anticipation or to mitigate the effects of changes in the country's agricultural policies. For example, the implementation of the EU milk quota regulation in 1984 initially caused a dramatic decrease in herd size and average herd age indicating higher replacement rates in EU nations such as the Netherlands (van Arendonk and Liinamo, 2003), whereas the abolishment of the same quota system in 2015 lifted this serious production limitation, resulting in increased herd sizes (CRV, 2018). Also, since 2017, a legal constraint has been set in the Netherlands on the amount of phosphate produced per farm (EU, 2017) which incentivised a reduction in the dairy herd sizes, increasing the importance of high production levels among cows and their potential replacements (Jongeneel et al., 2017; McCullough, 2018). Failure to respond to such policy changes might negatively affect the future profitability of the dairy farms (McDonald et al., 2013).

So, in combination with the changing policy climate, the culling strategy of dairy farms operates in a dynamic environment where the relevance of cow-level associated risk factors and replacement criteria might change periodically. Literature on risk factors influencing culling decisions and their trade-offs representing the changed Dutch farming policy climate is, however, lacking. Most studies conducted to analyse relevant risk factors in the Netherlands were, for instance, performed during the milk quota system (Nor et al., 2014a; Sol et al., 1984). There is a need for a study on the effects of policy and associated risk factors related to the slaughter (voluntary culling) of dairy cows. The objective of this study was to analyse the relevancy of cow-level risk factors for lifetime survival of Dutch dairy cows representing production, reproduction, and health performances under perturbations due to national policy changes related to the -milk quota abolishment of 2015 and the phosphate regulations since 2017. For this purpose, a parametric survival model at national level was fitted on-longitudinal dairy cow data covering the period 2009−2019.

2.2 Materials and Methods

2.2.1 Data

Anonymized production data on individual Dutch dairy cow-level were obtained from the Cattle Improvement Cooperative- CRV (CRV Holding BV, the Netherlands). This data comprised of 4 subsets, containing (1) Milk Production Registration (MPR) test records, (2) cow removal/exit records, (3) lactation records and (4) insemination records (see Table 2.1 for details). The data spanned the years 2009–2019 and included information on approximately 80 % of all the milk-producing cows in the Netherlands. The raw data files included repeated measures of 6,033,922 dairy cows from 19,885 farms.

Only data from commercial farms were selected. A commercial Dutch dairy farm was defined as a farm having (a) records (being active) for at least 5 years between 2009 and 2019, (b) an average of at least 30 producing cows (with a minimum of 25 in any given year) and (c) an average of 4 test-day observations per year for all cows (with a minimum of 3 observations in any given year) (Table 2.2). Furthermore, for farms that ended their farming operation, the records from the year of closure were omitted. Cow-level records containing missing birth dates, missing test-day records on selected variables as well as records containing unrealistic and misprint values were omitted.

Table 2.1. Summary of raw data in the study.

No.	Names of Data (sub)sets	Contents
1	Milk Production Registration (MPR data)	Records of producing cows on test-day milk, test-day fat%, test-day protein%, test-day somatic cell count, number of lactations, parity, etc.
2	Animal removal/ exit from herd records (Exit data)	Exit date of animals, code of exit (dead, alive/no exit, slaughter, export)

No.	Names of Data (sub)sets	Contents
3	Lactation records data (Lactation data)	Cow-level lactation summary of 305-milk, 305-fat, 305-protein, calving date, etc. (per parity)
4	Insemination records (Insemination data)	Records of insemination dates per parity, total inseminations, type of insemination, etc.

Records on cows that changed farms more than twice in their production lifetime were also excluded because it was analytically complicated to follow them throughout their life. This concerned only a small proportion of the total number of cow records (<0.1 %), as resale of producing cows is rare in the Dutch dairy sector. Cows which were exported to other countries were excluded from the data as information on their survival was not available. The four data (sub)sets were merged at cow level in a single final dataset, consisting of repeated records on 4,779,676 dairy cows from 13,936 commercial farms.

Table 2.2. Data editing steps with number of animals and number of farms retained in each step.

Editing step	Action	Number of animals	Number of farms
0	**Raw data from 2009−2019 as received**	6,033,922	19,885
1	**Select commercial farms** a. Farms active > 5 years between 2009−2019 b. Average number of producing animals per farm > 30 (with more than 25 in any year) **c.** Farms with more than 4 test-days on average per year	5,681,833	15,916
2	**Merge 4 data subsets (animals with observations in all four datasets retained)** **Cows which were exported to other countries were excluded from the data.**	5,289,957	14,618
3	**Filter/ select final data** a. Remove records of cows with missing data on selected variables and remove complete records of cows with missing birthdate	4,779,676	13,936

Editing step	Action	Number of animals	Number of farms
	b. Remove production records of cows with questionable (unrealistic) records (e.g., parity = 60)		
	c. Remove complete records of animals that were sold multiple times (animals on > 2 farms before exit)±		

± Excluded cows for this reason amounted to 0.1 % of total cows in the raw data (6,033,922).

2.2.2 Data transformation and variable selection

Based on the literature, variables reported as risk factors for culling were selected from the merged data. The final factors and their levels are presented in Table 2.3. Parity was categorised into 4 levels, Lactation value (LV), which denotes the relative milk production level of a cow in a herd was categorised in 3 levels. Details on how LV is calculated can be found at CRV (2020). Fat and protein percentages in the first 100 days of lactation were converted to fat-protein ratios (FPR). FPR < 1 has been considered as an indicator of Sub-Acute Rumen Acidosis (SARA) in early lactating cows (Enemark, 2008). However, based on expert opinion from the authors, a lower value of FPR < 0.9 was selected as lower threshold for normal ratio. Similarly, as FPR > 1.5 has been considered an indicator for subclinical ketosis (Čejna and Chládek, 2005; Duffield et al., 1997), it was selected as an upper threshold for normal ratio. The proportion of test-days with ratios above 1.5 and below 0.9 were determined in each parity per cow, representing very high and very low FPR, respectively. The two factors representing very high and very low FPR were split in two levels representing small proportion (less than 50 %) and large proportion (more than/ equal to 50 %) of low/high-FPR values in first 100 lactation days. Individual somatic cell count on test-day of more than 200,000 cells/ ml can be indicative of subclinical mastitis (De Vliegher et al., 2005). Individual somatic cell counts in test-day milk were classified in 4 levels with the first level (< 200,000 cells/mL) acting as reference. The 4 levels were created deliberately to check if the farmers distinguish between not just high SCC but also very high levels of SCC on individual cow level. Number of inseminations per parity were converted to rolling average of inseminations over all parities up to the current parity number. So, 1st parity cows had the rolling average equal to their absolute insemination number, whereas all the subsequent parities had rolling averages equal to the mean of all previous inseminations with the number of inseminations for that parity. The rolling average number of inseminations over all parities was classified in 3 levels. A factor for policy periods was generated based on calendar year representing three target policy periods, namely Milk Quota period (MQ), Post-Milk Quota period (PMQ) and Phosphate regulation period (PH).

The data were transformed into survival data in counting process format with start time, stop time and event variables (e.g., removal/exit) representing left-truncated (initial start time was the difference between the test date and birth date of the cows), and interval-censored repeated measures data (Figure 2.1) according to Klein and Moeschberger (2006). Each interval represented the time period between two test-days of MPR recording. Start and stop times for the intervals were represented in weeks of survival. Event “1″ represented removal of cows from MPR records as where the cow can be considered as “slaughtered” or “dairy sale” (sold alive to another herd) and the event of “0″ represented cows which were still producing, censored, or those which were involuntarily culled (euthanasia/ died naturally) during the period between 2009 and 2019. Factors were time-varying variables with observations for each survival interval between two subsequent test-dates of MPR recording. Test-date independent variables such as parity, Insem, Policy period were repeated for each test-date interval that had the same observation.

Table 2.3. Selected risk factors and their levels and numbers.

Factor	Abbrev.	Explanation	Levels	No. of test-day records
Lactation value	**LV**	Relative milk production level on test-day in comparison to the herd average of 100. Three levels represent less than 90, between 91 and 110, more than 110 L V.	below average	26,023,175
			average	65,532,040
			above average	22,950,930
Parity	–	Parity number of cows	1 st parity	34,517,660
			2nd parity	28,438,152
			3−4th parities	35,092,020
			> 4 parities	16,458,313
Very high-fat protein ratio	**highFPR**	Indicator for subclinical ketosis, reflected by the proportion of tests in first 100 days of lactation resulting in FPR > 1.5	< 50 %	112,705,286
			≥ 50 %	1,800,859
Very low-fat protein ratio	**lowFPR**	Indicator for Sub-acute Rumen Acidosis. reflected by the proportion of	< 50 %	114,436,777
			≥ 50 %	69,368

Factor	**Abbrev.**	**Explanation**	**Levels**	**No. of test-day records**
		tests in first 100 days of lactation resulting in FPR < 0.9		
Test-day somatic cell count (x 1000)	**SCC**	Somatic cell count in thousands per millilitre of milk on test-day	< 200	91,912,692
			≥ 200 and < 600	15,257,987
			≥ 600 and < 1000	3,202,567
			≥ 1000	4,132,899
Insemination	**Insem**	Rolling average of total number of inseminations over all parities	< 2	63,753,449
			≥2 and < 5	47,408,119
			≥ 5	3,344,577
Policy periods	**Period**	Time periods of test-day records MQ (Milk quota): 2009−2013, PMQ (post-milk quota): 2014−2016, PH (Phosphate regulation): 2017−2019	MQ	49,613,372
			PMQ	33,652,664
			PH	31,240,109

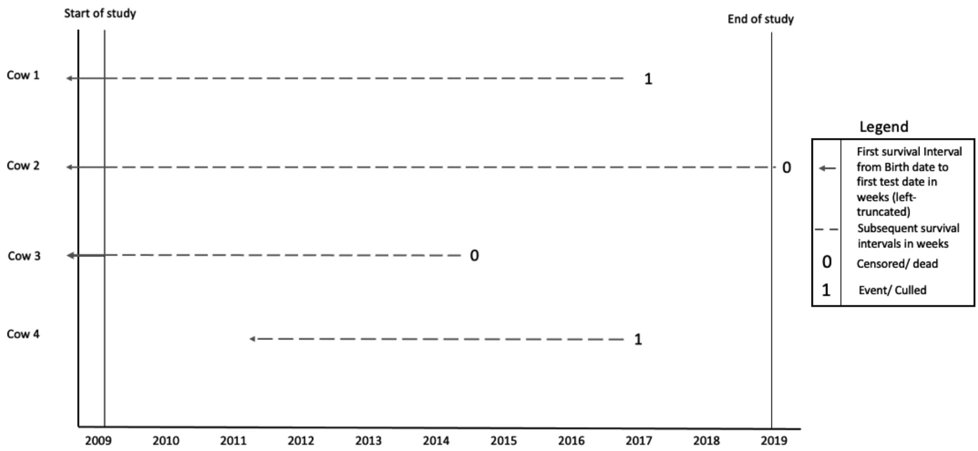


Figure 2.1. Explanation of survival analysis data ±

± Cow 1 represents a left-truncated cow (i.e., was already producing within the herd before the recording period) that has a culling event, Cow 2 represents a left-truncated cow that gets censored at end of study (e.g., no event registered during the recording period), Cow 3 represents a left-truncated cow that is censored before the study ends and Cow 4 represents a cow which starts producing within the study and has an event before the end of the study ends.

2.2.3 Statistical analysis

Time-varying effects or hazards of associated risk factors can be analysed with censored longitudinal survival data by appropriate parametric survival models (Klein and Moeschberger, 2006). Given the nature of the data, a parametric survival model with appropriate distribution for survival time was chosen. Parametric survival model assumes a specific distribution for time-to-event or survival time that is analysed linearly against covariates or in this case, factors with distinct levels. Interval censored data of cows can be utilized in such a model along with time-dependent factor levels (Klein and Moeschberger, 2006; Kleinbaum and Klein, 2010). Several parametric models with different underlying distributions for time-to-event (the dependent variable) were tested. Out of these tests, the lognormal Accelerated Failure Time (AFT) model was selected based on a visual conformation of the residuals and expected residual distribution as well as lowest Akaike-Information Criterion (AIC) as seen in Table A, Appendix 1. Logarithm of time-to-event was linearly regressed against these associated time-dependent factor-levels which were assumed to linearly increase or decrease time-to-event based on their effect.

Selected relevant factors (Table 2.3) were added to the model as fixed time-varying effects along with a random (shared variance) term to correct for effects within farms by clustering,

$$logT_{ij} = \beta X_{ij} + \varepsilon_{ij}$$

Where, T_{ij} represents the time-to-event in i^{th} cluster and j^{th} cow-level observation. β is a vector of time-ratio estimates, X_{ij} is a matrix of factor levels with i clusters and j observations of cow per cluster and ε_{ij} are random errors within cluster (not independent within cluster). This structure represents the correcting for cluster dependence by marginalizing the Time Ratio (TR) estimates similar to the method used in Fan and Datta (2011).

Since the objective of this study was to analyse the associated factors for lifetime survival of cows under policy perturbations, the model was structured in a way that it provided estimates on parity, lactation value, very low fat-protein ratio, very high fat-protein ratio, test-day somatic cell count and rolling average of inseminations over all parities, inside each level of the policy periods. This was achieved by fitting the main effects of all factors and subsequently by fitting interaction of policy period factor with other factors. Consequently, the model was refined by using the AIC-based stepwise backward selection protocol. The final model was defined as follow,

$$\begin{aligned} Y => \log(Ftime) \sim \mu + LV + Parity + SCC + lowFPR + highFPR + Insem + Period \\ + Period{:}LV + Period{:}Parity + Period{:}SCC + Period{:}highFPR \\ + Period{:}lowFPR + Period{:}Insem + cluster(farm) + \ e \end{aligned}$$

Where, $Ftime$ represents time-to-event, $LV,\ Parity,\ SCC,\ lowFPR,\ highFPR,\ Insem,\ Period$ represents the factors denoted in Table 1.1 and $cluster(farm)$ denote the cluster effects of the farms in which cows are producing and e represents the residual term. In the model, $Ftime$ is representative of survival intervals between previous and next test date in the MPR records. The interaction terms represent the proportion of effect of the factors under different policy periods ($Period$). Estimates of the factor levels were calculated 'inside' the levels of the $Period$ term with their standard errors.

To further explore the survival of the individual cows under different policy periods, the predicted survival times in weeks were drawn for all combinations of the factor levels. However, in order to analyse the culling in this survival time, the predicted log-survival times of only the 1st parity cows were retained as the survival of other parities is influenced by survival in previous parities making it difficult to interpret the predicted log-times. All analyses were done using R-studio v 3.6.3 (R Core Team, 2020) with packages ‘survival’, ‘data.table’, ‘dplyr’, ‘survminer’ and dependencies therein. Model diagnostics were analysed graphically using ‘AFTtools’ and ‘forestplot’ packages in R. ‘The computational capacity needed for such a big data analysis was achieved by utilizing the High-Performance Computing facility at Utrecht Bioinformatics Center (HPC, 2020).

2.3 Results

2.3.1 Descriptive statistics

The data spanned from year 2009–2019 with a maximum of 13,590 farms and minimum of 11,737 farms per year (Table 2.4). However, the majority of the selected farms (~78 %) continued production for the entire span of 11 years. Producing cows from the selected herds in the MPR data were tested on average 10 times per year.

Table 2.4. Recorded number of commercial farms and producing cows between 2009 and 2019.

Year	Cows	Farms
2009	1,308,083	13,375
2010	1,371,412	13,450
2011	1,405,444	13,531
2012	1,443,133	13,590
2013	1,492,813	13,453
2014	1,536,476	13,407
2015	1,600,403	13,355
2016	1,695,173	13,176
2017	1,634,629	12,732
2018	1,529,185	12,244
2019	1,388,810	11,737

Between 2010 and 2019, 337,754 new primiparous cows were introduced to the farms with a maximum of 396,909 cows in year 2016 and a minimum of 253,251 cows in year 2019 (Figure 2.2). Similarly, on average 268,206 cows had an event i.e., they were slaughtered or sold (dairy sale) with a maximum of 338,076 and a minimum of 230,002 cows in years 2017 and 2015, respectively (Figure 2.2). Based on this information and data on herd sizes, the average overall removal rates per year were calculated (Figure 2.3) per policy period. From Figure 2.3, it was clear that the year 2015 had the lowest removal rate (during PMQ), while year 2019 had the highest removal rate (during PH). Figure 2.4 shows the distribution of cows per parity over the years 2009−2019, indicating an initial increase in first parity animals during PMQ, followed by a gradual decrease during PH, indicating an increase in average herd age (e.g., a larger proportion of older animals).

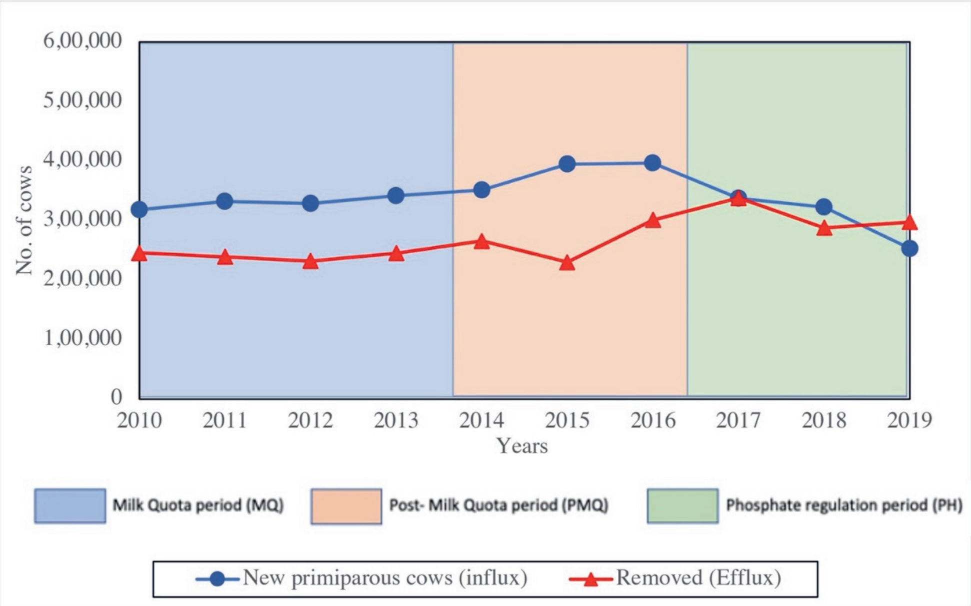


Figure 2.2. Recorded number of Influx and Efflux of cows from farms in years 2010 to 2019±.

± Note: influx-efflux figures for year 2009 are not displayed as they were biased due to left-truncation of cows that were already producing.

X- axis divided in 3 policy periods viz., Milk Quota (MQ, 2010–2013), Post-Milk Quota (PMQ, 2014−2016) and Phosphate regulation (PH, 2017−2019).

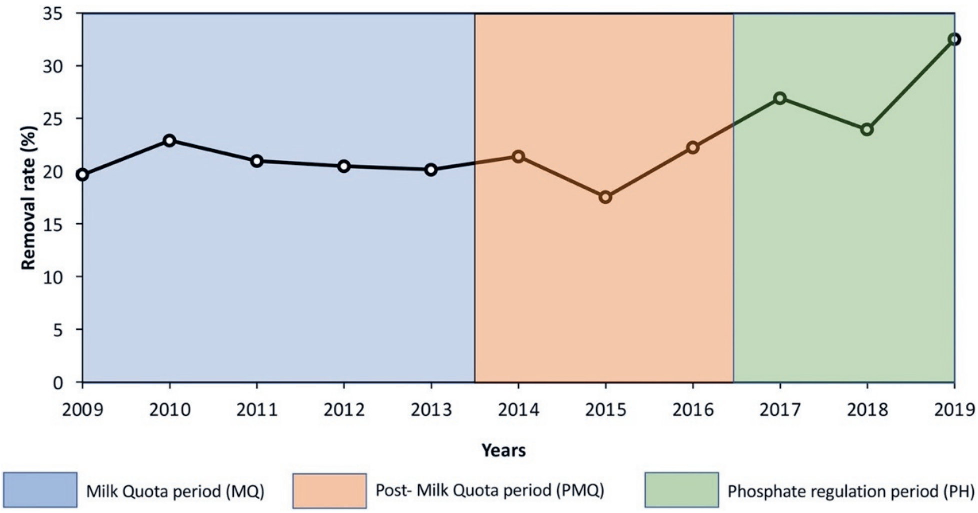


Figure 2.3. Average removal rate including slaughter and dairy sale of Dutch dairy cows between 2009 and 2019.

2.3.2 Survival Analysis using AFT model

Table 2.5 shows the effects of associated risk factors in the final model under the specified policy periods in terms of differences in survival time in weeks. All effects of the associated factors were based on 95 % confidence intervals. The output of estimates in TR can be seen in the Table B of Appendix 1.

In terms of differences between the policy period, the median survival of the cows decreased by 2.7 weeks and 15.3 weeks in PMQ and PH, respectively, compared to MQ (Table 2.5). Hence, the lowest median survival for cows under policy period was found in PH period. Based on the results of the lognormal AFT model (Table 2.5), it was shown that estimated survival increased with higher parities, above average LV, higher proportion of HighFPR and higher Insem of the cows and lower SCC and lower proportion of lowFPR within all three policy periods. The effect of Parity and inseminations over all parities (Insem) were directly related to age of the cows (see Discussion).

Figure 2.4. Distribution of Dutch dairy cows by parity in years 2009 to 2019.

The overall estimated mean survival for all producing cows in the data, based on the model, was 441 weeks (± 1 week). The predicted median survival time for the policy periods MQ, PMQ and PH were 273 weeks, 271 weeks, and 256 weeks, respectively. Focusing on 1st parity cows, in all three periods, the lowest predicted survival time was for a combination of below average LV, small proportion of highFPR values, high proportion of lowFPR values, high SCC and less than 2 Insem from the same model. Similarly, the highest predicted survival time for 1st parity cows was for a combination of factor levels such as above average LV, large proportion of highFPR values, small proportion of lowFPR values, low SCC (< 200,000 cells/mL) and more than 5 Insem (> 5) for all three policy periods.

2.4 Discussion

The objective of this study was to analyse the relevancy of cow-level risk factors for survival of Dutch dairy cows representing production, reproduction and health performances under perturbations due to national policy changes related to the -milk quota abolishment of 2015 and the phosphate regulations since 2017. In this study, large scale, national level data was utilized for the analysis. This enabled very precise estimations of associated effects of the relevant factors with small (95 %) confidence intervals. It was shown that there are some differences in the estimated survival of cows between the three policy periods Milk-Quota period, Post-Milk Quota period and Phosphate regulation period. Differences in estimated survival based on the associated risk factors were, however, limited between the policy periods. Consequently, there were no changes in the 'pattern' of estimated survival under the levels of associated risk factors within different policy periods. This showed that there were no differences in the relevancy of associated risk factors between the three policy periods. Based on this observation, it was theorized that the criteria used by farmers for culling decisions did not vary between policy changes but might have been more 'strictly' applied to select cows for culling.

Table 2.5. Estimated differences in survival time (in weeks) based on Time Ratios (TR) of lognormal model ±

Factor	Estimated survival in weeks
Intercept	246.7 (244.7–248.6)
Log(scale)	+0.3
Policy Periods	
MQ±	Ref
PMQ	−2.7
PH	−15.3

Factor	Levels	MQ	PMQ	PH
		Survival time in weeks§		
Policy Periods	**Reference (Ref)¶**	246.7	244	231.4
Parity	**1 st parity (Ref)**			

Factor	**Levels**	**MQ**	**PMQ**	**PH**
		Survival time in weeks§		
	2nd parity	+85.0	+83.3	+87.0
	3−4 parities	+217.4	+215.1	+222.1
	> 4 parities	+459.6	+441.5	+451.2
LV	**below average**	−29.8	−30.3	−29.5
	Average (Ref)			
	above average	+25.1	+25.2	+20.6
SCC (X 1000)	**< 200 (Ref)**			
	≥ 200 and < 600	−11.8	−9.7	−9.2
	≥ 600 and < 1000	−18.5	−14.8	−12.3
	≥ 1000	−32.4	−29.2	−24.4
highFPR	**< 50 % (Ref)**			
	≥ 50 %	+9.8	+9.6	+6.0
lowFPR	**< 50 % (Ref)**			
	≥ 50 %	−12.0	−10.9	−5.1
Insem	**< 2 (Ref)**			
	≥2 to 5	+18.9	+17.4	+15.3
	≥ 5	+29.2	+24.6	+24.6

± Abbreviations in the table: Ref (reference level of factor), MQ (milk quota), PMQ (post-milk quota), PH (phosphate regulation), LV (lactation value), SCC (test-day somatic cell count), highFPR (very high test-day fat-protein ratio), lowFPR (very low test-day fat-protein ratio), Insem (rolling average of inseminations over all parities).

§ Calculated as $e^{(\beta_0+\beta_{policy}+\beta_{TR})}$ where β_0 is the intercept, β_{policy} is the policy effect in time-to-event and β_{TR} is the time ratio of factor level to the reference.

§ 95 % confidence intervals for Parity, LV, SCC, low/ highFPR and Insem were small (< ±1 week) and are not displayed in the table.

¶ Baseline survival for each policy period. Calculated as $e^{(\beta_0+\beta_{policy})}$, where β_0 is the intercept,β_{policy} is the policy effect. All β-estimates can be found as Time ratios (TR) in Appendix 1, Table B.

2.4.1 Policy Periods

It was seen that the removal rate (which includes slaughter and dairy sale of cows) was stable prior to 2014 (Figure 2.4). Also, the influx of new cows (primiparous cows) in the producing herd was stable indicating a stable removal vs influx rate during the years 2009–2013 (Figure 3). From the AFT model (Table 2.3), the average estimated survival of cows in MQ was highest compared to PMQ and PH policy periods. This is in contrast to the expectation of having an increased survival after the abolishment of the milk quota (PMQ), due to an increase in herd size. During PMQ (2014−2016), the influx of new animals increased, whereas the removal rate decreased to its lowest value in 2015 (Figure 2.3, Figure 2.4). These changes in influx and efflux reflect the response of farmers to the abolishment of milk quota, which resulted in a herd expansion. However, the AFT model (Table 2.3) showed a slight decrease in estimated survival of the cows compared to MQ. Based on this finding, it is possible that farmers favored addition of new primiparous cows compared to decreasing the removal rate of already producing cows for herd expansion. This resulted in relative decrease in survival probability of already producing cows.

In the PH period (2017−2019), it was clearly seen that there was an increase in the average removal rate from ~ 20 % before 2017 to ~ 28 % (Figure 2.4). Also, the trendlines between influx of new animals and efflux/ removal of animals crossed between years 2017–2019 (Figure 3) indicating an attempt to radically decrease the herd sizes by reducing the influx rate and increasing the removal rate. From the AFT model (Table 2.3), there was a clear drop in the estimated survival during the PH period indicating the above changes. Based on the results of AFT model, it was also theorized that the adjustments made by the farmers in the context of changing policy climates may not have taken place strictly within the defined bounds of particular periods, except for PH where fast changes were ‘forced upon’ the farmers due to an unforeseen change in policy. Thus, it was theorized that the culling pattern in terms of relevant risk factors remained stable across the changing policy periods which was against the initial expectation. Hence, under changing policy climate the perturbations caused in culling patterns of the farms could be treated as a continuum rather than discrete changes per year or per period in future research.

2.4.2 Relevant risk factors and modelling strategy

In this analysis, each time interval in which the survival was estimated, was bounded by two subsequent test-dates of MPR records. This survival interval represents a decision interval for farmers in which they decide to retain or cull individual cows between two test-day performances. The assumption was such that ‘based on each testing interval, the decision to cull was updated’. Unlike existing literature such as Alvåsen et al. (2014), Gussmann et al. (2019), and Rilanto et al. (2020), each survival interval did not correspond to inter-calving intervals. This structuring of shorter time intervals also reduces the time lag between the time when the decision is made whether to cull or keep the cow, and the end of survival interval, giving more precise survival time estimates (test-date intervals << calving intervals).

This is a fundamental difference between survival per parity (Alvåsen et al., 2014; Rilanto et al., 2020) and lifetime survival (split in MPR test-date intervals). As a consequence, the time-varying variables have observations which vary per survival interval, except for the factors Parity and Insem.

The factors selected in this model encompassed production, reproduction and health performances based on the literature. The positive association of LV and negative association of SCC to the estimated survival from the models were in line with the findings of Bascom and Young, (1998), Gussmann et al. (2019), and Rilanto et al. (2020). In early lactation, FPR of very low (FPR < 0.9) or very high (FPR > 1.5) magnitude can be indicative of underlying subacute rumen acidosis-SARA (Danscher et al., 2015; Rojo-Gimeno et al., 2018)or subclinical ketosis (Duffield et al., 1997; Van Soest et al., 2019) respectively, which increases the risk of culling and replacement. However, use of FPR for indicating underlying SARA (lowFPR) for survival analysis as associated risk factors has not been reported in previous studies.

A higher proportion of lowFPR in early lactation was negatively associated with the survival of cows as seen in Table 2.5. It was theorized that, the negative association of lowFPR with survival might simply be due to the fact that cows had a lower production potential along with being indicative of SARA. However, based on the results in Table 2.5, it is seen that highFPR had a positive association. This might be explained by the fact that high magnitude of FPR might be associated with higher production potential of the cows and hence there is a potentially high correlation between test-day milk production and higher FPR values in early lactation. A similar result was explained by Shahid et al. (2015) due to preferential treatment of high producing cows with high FPR.

Moreover, it was found that a very small number of animals showed high proportions of highFPR and lowFPR during their first 100 days of lactation (≤ 2% of total observations per factor; see Table 2.3). The imbalance in numbers of observations in each factor level were expected due to biological reasons. However, in the analysis this imbalance did not visibly affect the standard errors of the estimated time ratios.

It was found that higher parities were associated with higher survival times which was not in line with findings of Miller et al. (2008), Rilanto et al. (2020), and Thomsen et al. (2004). In this study, survival was not analyzed per parity but over the entire life span (broken down into test-date intervals) under changing policy. Unfortunately, the side effect of this is that Parity factor is related to the age of the cow and hence survival estimates increase as parity increases. This can be explained by the fact that parity which serves as an indicator of age of the cow was related to the survival times. Hence, the interpretation of the parity factor estimates was not straightforward. Besides this, the event in this survival analysis was for slaughter and dairy sale, whereas natural death/ euthanasia served as censoring criteria. Since natural death or euthanasia (involuntary culling) are common for older age cows (Shahid et al., 2015; Thomsen et al., 2004), the effect of parity on the survival of cows could be counter indicative.

Similarly, it was found that a higher magnitude of Insem was associated with higher survival. However, according to the literature from Dijkhuizen et al. (1985), Sewalem et al. (2008), Van Arendonk and Dijkhuizen, (1985), higher numbers of inseminations required for conception were indicative of poor reproductive performance and, hence, increased culling risk. The deviation from existing literature can be explained by the fact that in this study, the number of inseminations were coded as a rolling average over all parities, which made this factor dependent on age and parity number. Consequently, the effect of this factor became dependent on survival time similar to parity number. One way to rectify this issue was to take insemination history (inseminations up to the last parity). However, the first parity cows which formed many of the culled cows were lacking this information. Moreover, Insem variable is used as a surrogate to “farmers’ confidence in the performance of the cow” since cows which show potential benefit may be inseminated more times by the farmer to retain them. Thus, Insem was reflective of the decision that farmer has already made to retain the cow for next lactation and did not reflect on the performance before the farmer’s decision. Thus, the results of this study indicated the associations of relevant risk factors of culling but did not provide insight into the actual culling decision processes and motivations of the farmers.

Besides this, other fertility indicators such as prolonged lactation, age of first calving, etc. were not analyzed in this study due to data constraints. Also, data on disease indicators for important production diseases such as clinical mastitis, lameness diseases, etc. were not available which are important risk factors for slaughter as well as involuntary culling (Bascom and Young, 1998; Gröhn et al., 2005; Olechnowicz and Jaskowski, 2011; Rajala-Schultz and Gröhn, 1999).

2.4.3 Conclusion

In conclusion, this study demonstrated the differences in survival of Dutch dairy cows in response to changing agricultural policy. It was also shown that the relevance of cow-level risk factors for culling did not change under changing agricultural policy.

Appendix 1: Outputs of Accelerated Failure Time (AFT) model

Model Selection and AIC scores

An Accelerated Failure Time (AFT) model assumes a specific distribution for time-to-event or survival time that is analysed linearly against covariates or in this case, factors with distinct levels. In order to test for the same model was fitted with different AFT variations of distributions for log-survival time such as Lognormal, Weibull, Loglogistic, Logistic and exponential. AIC scores were calculated based on the Log-Likelihood statistics for each model and are presented in Table B of this appendix. Based on these AIC-score, Lognormal distribution had the lowest AIC score which meant that the selected model had the least out-of-sample variance. Also, this finding further validates the underlying assumption of normality for the logarithm of dependent variable of this analysis along with the graphical error distribution seen in Figure 6 of Results section.

Table A. Comparison of different AFT models and their AIC score under different assumed distributions

Model distribution type	Degrees of Freedom	Akaike-Information Criterion (AIC)
Lognormal	**34**	**46881680**
LogLogistic	34	47397611
Weibull	34	47832641
Logistic	34	50139935
Exponential	33	57346377

Time Ratios (TR) of associated risk factors for survival of dairy cows

The output of estimated effects was in form of Time Ratios (TR) against the reference levels. TR can be interpreted as the logarithm of survival time increased or decreased in comparison to the reference level. For example, if Level A is the reference level and level B has a TR of 0.1 then it could be understood that observations under level B have an increased time-to-event/ survival of 10% derived by: $e^{0.1} \approx$ + 1.1-time units. In this literature, the TR were converted on observable scale of weeks to appreciate the estimated effects of factor levels as reported in Table 2.3 in the Results section.

Table B. Estimates of Time Ratios (TR) and their standard errors from the AFT model

Factor	Time Ratios [log(T)]	Std Err.
Intercept	5.508	0.002
Log (scale)	-1.310	0.002
Policy Periods		
MQ	Ref	
PMQ	-0.011	0.001
PH	-0.064	0.001

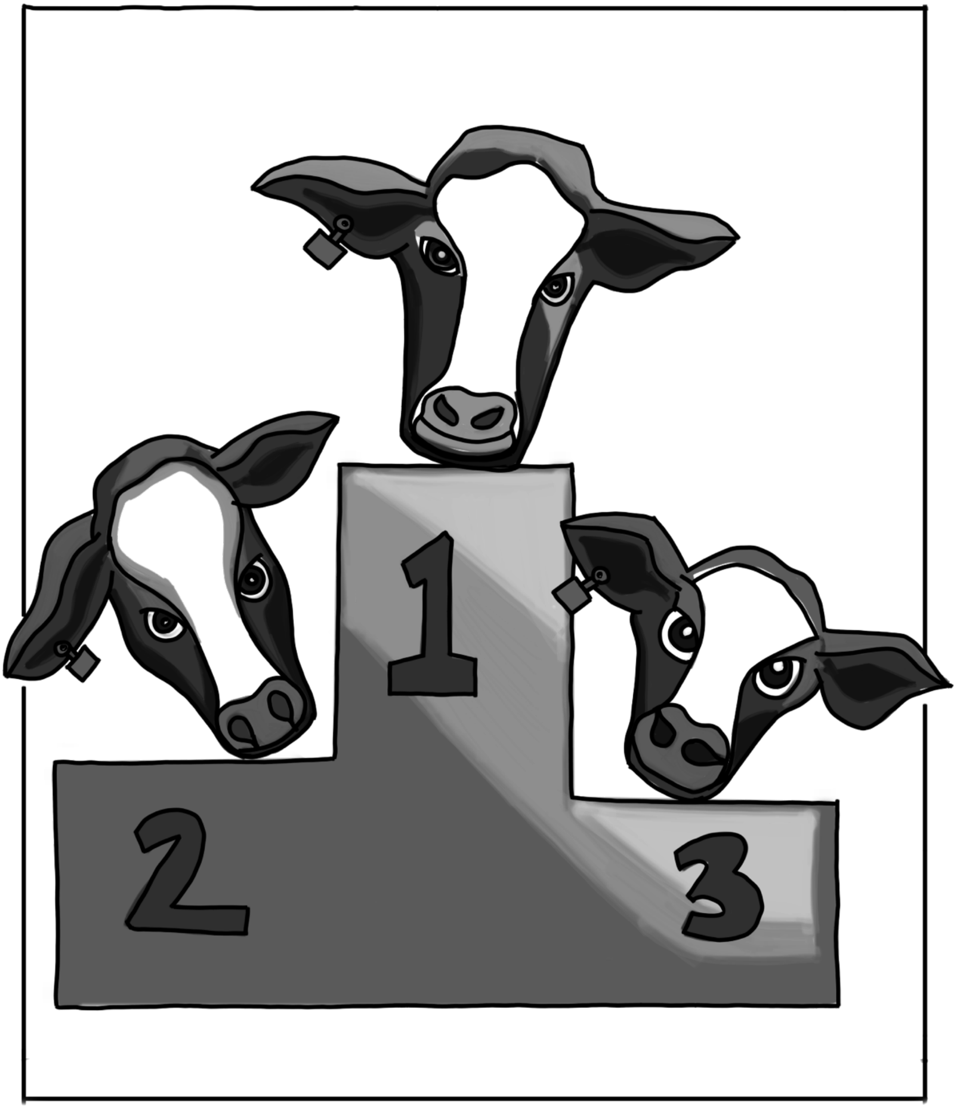
Policy Periods

Factor	MQ		PMQ		PH	
	Time Ratios [log(T)]	Std Err.	Time Ratios [log(T)]	Std Err.	Time Ratios [log(T)]	Std Err.
Parity						
1st parity	Ref					
2nd parity	0.296	0.001	0.291	0.001	0.302	0.001
3-4 parities	0.632	0.001	0.627	0.001	0.642	0.001
> 4 parities	1.052	0.001	1.026	0.001	1.040	0.001
LV ±						
below average	Ref ±					
average	0.114	0.000	0.116	0.001	0.113	0.001
above average	0.201	0.001	0.203	0.001	0.185	0.001
SCC (X 1000)						
less than 200	Ref					
between 200 to 600	-0.049	0.000	-0.040	0.001	-0.038	0.001
between 600 and 1000	-0.078	0.001	-0.062	0.001	-0.051	0.001
more than 1000	-0.141	0.001	-0.126	0.001	-0.104	0.001
highFPR						
< 50%	Ref					
≥ 50%	0.039	0.002	0.038	0.003	0.024	0.004
lowFPR						
< 50%	Ref					
≥ 50%	-0.050	0.009	-0.045	0.010	-0.021	0.009
Insem						
< 2	Ref					
2 to 5	0.074	0.001	0.068	0.001	0.060	0.001

> 5	0.112	0.002	0.095	0.002	0.095	0.002
AIC (LogLik)	46881680			DF	34	
Log Normal distribution						
Loglik(model) = -23441634 Loglik(intercept only) = -26684539						

± Different reference level in LV factor compared to Table 2.3 of Results section

CHAPTER 3



Associations between dairy farm performance indicators and culling rates under policy-driven herd size constraints

Kulkarni P. S., Mourits M. C. M., Nielen M., Steeneveld W.

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Abstract

This article aimed to study cross-sectional associations between the performance of dairy farms and their corresponding culling proportions under the herd size constraint as imposed in 2018 by the new phosphate regulation in the Netherlands. To this end, production data from 10,540 Dutch dairy farms were analyzed to capture the inflow and outflow of both primiparous and multiparous cows. Farm performance was measured by 10 indicators structured in four areas of longevity, production, reproduction, and udder health. Farm culling proportions were represented by the overall culling (OC) and the number of culled primiparous cows in relation to (i) the total number of producing cows (PC), (ii) the number of producing primiparous cows (PPC), and (iii) the number of culled producing cows (POC). Spearman's rank correlation and weighted logistic regression were adopted to study associations. In 2018, on average, 28% of producing cows were culled (OC). The number of primiparous cows culled represented 4.5% of the total number of producing cows (PC) and the mean proportion of culled primiparous cows was 18.8% of the total number of producing primiparous cows (PPC), and, of the total number of producing culled cows, 15% were primiparous cows (POC). However, the variance around the mean, and among individual farms, was high (SD 4–15% for all four culling proportions). Results from rank correlation showed very low-rank conformity (<12%) between the areas of production, reproduction, and udder health to the culling proportions. Results from logistic regression showed that higher farm levels of production and higher percentages of cows with poor udder health were associated with more overall culling but with less primiparous culling. For reproduction indicators, the associations were similar for overall and primiparous culling. However, except for the average age of culled animals, the odds ratios for indicators were close to 1 (range: 0.92–1.07 and 0.68–1.07 for OC and PPC, respectively), indicating only weak associations to culling proportions. In conclusion, although the introduction of phosphate regulation resulted in an increased outflow of cattle, corresponding culling proportions were not associated with the level of farm performance measured in terms of production, reproduction, or udder health.

Keywords

longevity, replacement, phosphate herd characteristics, performance, fertility, udder health, primiparous cows

3.1 Introduction

Culling of dairy cows is one of the most complex aspects of dairy herd management. In accordance with their specific management styles, farmers follow different strategies in their decision-making process to cull dairy cows. Various studies have shown that the variation in the culling decision is not only related to individual cow performances and herd-level risk factors but also to factors such as farmers' behavior and management styles (Beaudeau et al., 1996; Haine et al., 2017; Nor et al., 2014a; Raboisson et al., 2011). Apart from these, changes in national or global policies regarding livestock production can alter the farmers' long-term strategies regarding the culling of dairy cows. A recent survival analysis of dairy cows in the Netherlands indicated that culling intensity may vary over the years due to changes in agricultural policy, while the reasons for the culling of individual cows remained the same (Kulkarni et al., 2021).

In the current Dutch dairy production landscape, we see an increase in environmentally driven regulations, generally constraining the herd size. One example of such is the introduction of the phosphate regulation in 2018, which allows dairy farmers to produce phosphate from livestock manure only in accordance with the rights they have been granted (Government of Netherlands, 2022). The number of phosphate rights granted to a dairy farmer was based on the number of cows kept in July 2015, subjected to a generic reduction of 8.3% (Rijksoverheid, 2018). As a result, many farmers were forced to immediately reduce their livestock numbers, temporarily increasing the efflux of dairy cows (Kulkarni et al., 2021) and youngstock. Nor et al. (2014) and Haine et al. (2017) found that in the Netherlands and Canada, the long-term culling rate of dairy farms was associated with herd-level factors such as the proportion of cows with elevated somatic cell count, herd average 305-day milk, and the herd average calving intervals. Results from Armengol and Fraile (2018) suggested that variation between farm characteristics and the performance of herds could be important for culling differences between herds. However, these studies were aimed at the long-term associations between herd performance indicators and the magnitude of culling. There is a lack of literature on associations between herd performance and culling rate on dairy farms directly affected by policy-driven herd size constraints.

Previous research highlights that the cost of rearing a replacement heifer is not recovered until the second lactation (Archer et al., 2013); therefore, it is imperative that primiparous cows survive to their second lactation. Primiparous cows represent, as such, the potential by which the strategic performance goals set by the farmers' need to be achieved. With the introduction of a herd size restriction, such as with the phosphate regulation, youngstock and producing cows compete for the same production asset. Consequently, it is expected that primiparous cows, in particular, will not be culled upon the introduction of the phosphate rights system to give farmers some time to rebalance the ratio of youngstock needed for replacements to producing cows. Therefore, the culling of primiparous cows needed to be investigated when the phosphate rights system was introduced.

This study aimed to gain insights into the cross-sectional associations between annual performance indicators of Dutch dairy farms and their corresponding magnitudes of (i) overall culling and (ii) primiparous cow culling after the introduction of the herd size restricting phosphate regulation in the Netherlands. To study the associations between herd performance and intensified culling, 2018 production data from 10,540 Dutch dairy farms were used to capture the maximal policy influence on the inflow and outflow of both primiparous and multiparous cows.

3.2 Materials and Methods

3.2.1 Data

The anonymized farm data used in this study were obtained from the Dutch cattle breeding company—Cattle Improvement Cooperative, CRV (CRV stands for “Coöperatie Rundvee Verbetering” in Dutch which is “Cattle Improvement Cooperative”). The data consisted of four datasets of farm-level records of Dutch dairy farms from the year 2018. These four datasets included herd composition data, production data, udder health data, and fertility data. In addition to these datasets, individual cow-level data of test-day MPR (MPR stands for Milk Production Registration which registers individual cow parameters at certain intervals) (CRV, 2021a) from the year 2018 were obtained to evaluate the culling proportions of interest. Details of the individual datasets are presented in Appendix 1, Table A. Overall, the data contained recordings on 14,609 Dutch dairy farms.

3.2.2. Data editing and variable selection

Active farms (active as in having at least four recordings in MPR data in 2018) were selected for analysis (n = 14,291 Dutch dairy farms). Farms that were not represented in all four farm-level datasets as well as farms with erroneous data records (for example, herd annual milk-fat percentage of 12%, etc.) were filtered out. Moreover, a commercial dairy farm was defined as a farm with 30 to 500 producing cows, hence excluding farms with less or more producing cows from further analysis. Farms with <30 cows are generally not commercial dairy farms, whereas farms with more than 500 cows are atypical in the Dutch dairy system (representing for instance, research farms). The final data included records of 10,540 farms (see Appendix 1, Table B for more detail on data editing steps).

The farm-level data on production and udder health were recorded at test-day intervals, whereas the herd composition and the fertility data consisted of annual recordings. The test-day records on production and udder health were converted to annual recordings by averaging over the number of test days in the MPR to make all four datasets reflect an annual scale. From the cow-level MPR data of the CRV, the number of primiparous cows culled was determined for all farms in the final dataset. These records, together with the total number of producing cows, total number of producing culled cows, and total number of primiparous cows (see Table 3.1; herd size variables), were used to calculate the following culling proportions for the year 2018:

(i) Overall culling (OC), the proportion of the total number of producing cows culled (n_culled) to the overall number of producing cows (n_tot) present in the herd of the farm in the year 2018, given by,

$$OC = \frac{n\_culled}{n\_tot} \quad (1)$$

(ii) Primiparous culling (PC), the proportion of the number of 1st parity cows culled (primi_culled) to the overall number of producing cows present in the herd of the farm in the year 2018, given by,

$$PC = \frac{primi\_culled}{n\_tot} \quad (2)$$

(iii) Primiparous–primiparous culling proportion (PPC), the proportion of the number of 1st parity cows culled (primi_culled) to the total number of 1st parity cows present in the herd (n_primi) of the farm, given by,

$$PPC = \frac{primi\_culled}{n\_primi} \quad (3)$$

(iv) Primiparous-overall culling proportion (POC), the proportion of the number of 1st parity cows culled (primi_culled) to the total number of dairy cows culled, given by,

$$POC = \frac{primi\_culled}{n\_culled} \quad (4)$$

From the available data, farm-level performance indicators were selected as a representative of four performance areas, namely, longevity, production, reproduction, and udder health. In any given performance area, when two variables were highly correlated (|r| > 0.75), the most relevant of the two was chosen. The final list of variables and their descriptions are shown in Table 3.1. Missing data were found in indicators of the reproduction area. Given the small proportion of missing to complete data, these records were excluded in all subsequent analyses except for descriptive statistics.

Table 3.1. Description and summary statistics of culling proportions and farm-level performance indicators grouped per performance area of the evaluated dairy farms.

	Description	Min-max	IQR	Median
Culling proportions				
OC	Proportion of number of cows culled to overall number of producing cows	0.13-0.48	0.22-0.34	0.28
PC	Proportion of number of 1st parity cows culled to overall number of producing cows	0.0-0.41	0.02-0.07	0.04
PPC	Proportion of 1st parity cows culled to the number of 1st parity cows	0.00-1.00	0.10-0.27	0.18
POC	Proportion of 1st parity cows culled to total number of culled cows	0.00-0.83	0.09-0.23	0.15
Longevity				
Age_tot	Age of the dairy herd (days)	1,137-3,143	1,582-1,778	1,672
Age_culled	Age of culled dairy cows (days)	1,204-3,995	1,896-2,243	2,055
Life_prodn[a]	Lifetime production (kg)	5,379-41,365	19,604-24,898	22,183
Production				
avg_FPCM[a,2]	Annual fat-protein corrected daily milk production (kg)	13.79-47.20	27.86-32.43	30.3
Reproduction				
Services_per_conception (nulliparous) [a]	Number of inseminations per calving for 0th parity cows (nulliparous)	0.50-7.00	1.35-1.85	1.6
Services_per_conception [a]	Number of inseminations per calving for ^{3} 1+ parity cows	0.00-5.50	1.52-2.12	1.8
AFC[a,]	Age at 1st calving (days)	651.2-1266	748.3-803.5	772
Avg_DIM_first service[a,]	Interval in days in milk between last Calving and first Insemination (days)	41-490	79.27-103.91	89

Calv_int[a]	Calving Interval (days)	353-781	392-420	404
Udder health				
Avg_high_SCC	Annual percentage of cows having high Somatic Cell Count[3] (%)	1.6-94.5	10.79-18.18	14.2
Herd demographics				
n_tot	Total number of producing cows in the farm in 2018	31-500	66-118	89
n_culled	Number of culled cows	5-228	17-35	25
n_primi	Total number of 1st parity cows	1-252	15-31	22
primi_culled[4]	Number of culled 1st parity cows	0-31	1.5-8.5	4

[a] Variables are farm averages calculated from the individual performance data of the producing cows on the farms from the data provided by CRV. n = 10,540.

[1] Abbreviations OC = Overall culling proportion; PC = primiparous culling proportion; PPC: primiparous-primiparous culling proportion; POC: primiparous-overall culling proportion

[2] Farm average milk yield on test-day converted to Fat-Protein corrected milk (FPCM) by formula from Yan et al. (2011): FPCM (kg) = (0.337 + 0.116 x fat % + 0.06 x protein %) x milk production (kg).

[3] High somatic cell count is defined as cows having more than 150,000 cells/ml milk for primiparous and 250,000 cells/ml for multiparous cows.

[4] Calculated from the cow-level MPR data obtained from CRV (2021).

3.2.3 Descriptive statistics

The minimum-maximum, median, and interquartile range (IQR) of the performance indicators in four areas and the four culling proportions were calculated from the final data sample (Table 3.1). Similarly, the minimum-maximum, median, and IQR of herd demographics such as the number of producing cows, number of culled cows, and number of primiparous cows in the herd were calculated (Table 3.1).

To describe the culling proportions with respect to the herd size of the farms, farms were divided into six herd size groups of 31–50, 51–70, 71–90, 91–110, 111–150, and 151–500 producing cows. All four culling proportions (OC, PC, PPC, and POC) were plotted against the herd size groups by means of a boxplot.

3.2.4 Rank correlations

The performance indicators in all four areas were scaled and centered to the mean. Spearman's rank correlation test was performed to check for conformity in the ranking of farms based on these different performance indicators. In addition, rank correlation tests were performed between scaled indicators and the defined culling proportions (not scaled). The results of this procedure were interpreted as the degree of conformity between the ranking of farms based on performance indicators and the ranking based on culling proportions. Before the rank correlations, scatter plots of scaled indicators against culling proportions were drawn to investigate if any non-monotonic relationships exist.

3.2.5. Logistic regression model

To investigate the association of the (i) overall culling and the (ii) primiparous culling proportion to the performance indicators in a systematic format, two weighted logistic regression models were developed. In the first model, OC was the dependent variable. It was interpreted as the proportion of cows culled (binomial successes) to the total number of dairy cows (n-trials) with a binomial outcome. In the second model, PPC was selected as the dependent variable. PPC was interpreted as the proportion of primiparous cow culling (binomial successes) to total primiparous cows (n-trials) with a binomial outcome. The performance indicators shown in Table 3.1 were fitted in the model as associated independent variables. Due to a large amount of difference in the scales, the independent variables (performance indicators) were scaled and centered to the mean before fitting in both models. Herd effects were not included as random effects since only one annual record of each variable per farm was present. Post-modeling, the estimated effects were exponentiated to give the odds ratio per unit change in the scaled indicators. These effects were interpreted as the associations between the performance indicators and OC or PPC.

All the analyses and the data editing were performed in Rstudio with R 3.6.3 (R Core Team, 2020).

3.3 Results

3.3.1 Descriptive statistics

The mean herd size among the selected dairy farms was 105 producing cows with a median of 92 cows (Table 3.1). Over the year 2018, 28% of producing cows were culled on average (OC). The number of primiparous cows culled represented 4.5% of the total number of producing cows (PC). The mean proportion of culled primiparous cows was 18.8% with respect to the total number of producing primiparous cows (PPC), and of the total number of culled cows, 15% were primiparous cows (POC). The average herd longevity (Age_tot) was 1,688 days (~4 years, 7 months), whereas the average age of culled cows (Age_culled) was 2,089 days (~5 years, 9 months).

Figure 3.1 shows the variation in the evaluated culling proportions per herd size group. In general, the means of four culling proportions were similar between all the herd size groups. The variables PPC and POC were almost equal in means among the groups but the variation around the mean was different. The variation in all four proportions was higher for the smaller herd size groups and smaller for larger herd size groups. The smallest variation in all four proportions was in the 151–500 producing cow group. It was also seen that there was high variation within each herd size group. From Figure 3.1, the mean of PC was considerably lower than that of OC for all the herd size groups. Moreover, the overall mean of POC, which was the proportion of primiparous cows culled to total culled cows, was 16%. This showed that the primiparous cows were a minority in the group of cows that were culled in 2018.

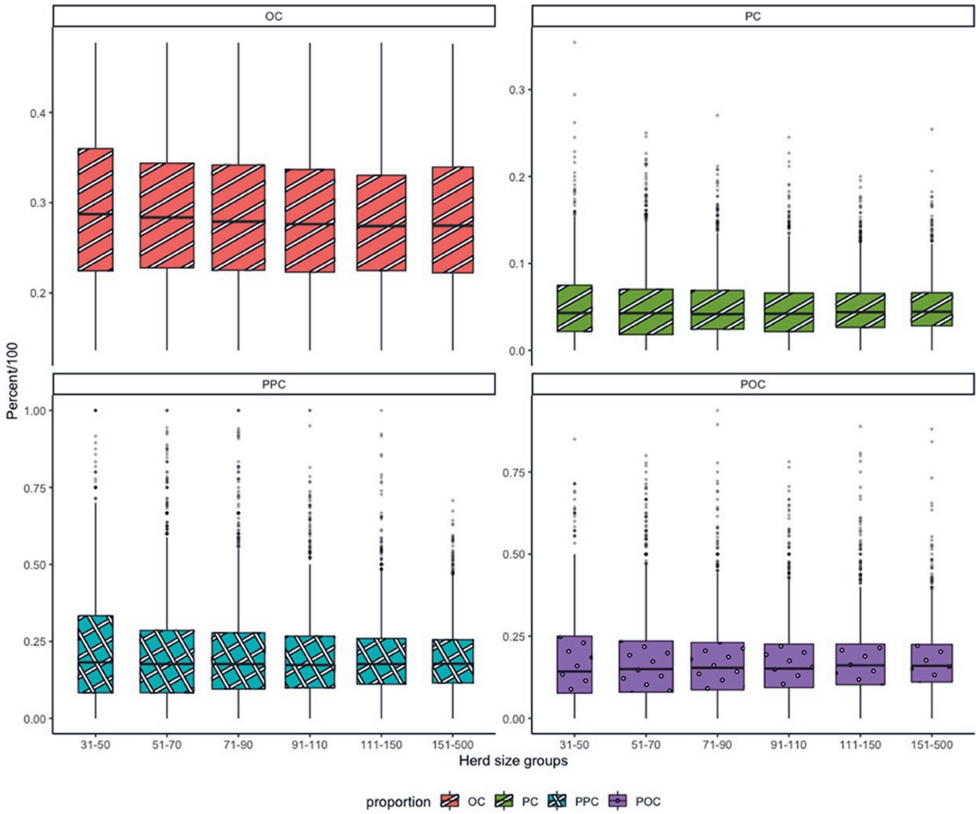

Figure 3.1. Distribution of culling proportions across herd size groups.

Note: OC, overall culling proportion; PC, primiparous culling proportion; PPC, primiparous-primiparous culling proportion; POC, primiparous-overall culling proportion. Herd size groups (x-axis) represent the number of producing cows in the farms in 2018.

3.3.2 Rank Correlations

Spearman's rank correlation coefficients of scaled performance indicators and the culling proportions were calculated. From Figure 3.2, longevity indicators of herd average age and lifetime milk production had higher correlation coefficients of −0.39 and −0.25 with overall culling proportion (OC) compared with the three primiparous culled cow proportions (PC, PPC, and POC). Similarly, the average FPCM had a slightly higher rank correlation of 0.12 with OC compared with the primiparous culled cow proportions. In the reproduction area, services per conception for nulliparous and multiparous cows, age at first calving, and calving interval had opposite but very weak correlations with OC compared with PC, PPC, and POC.

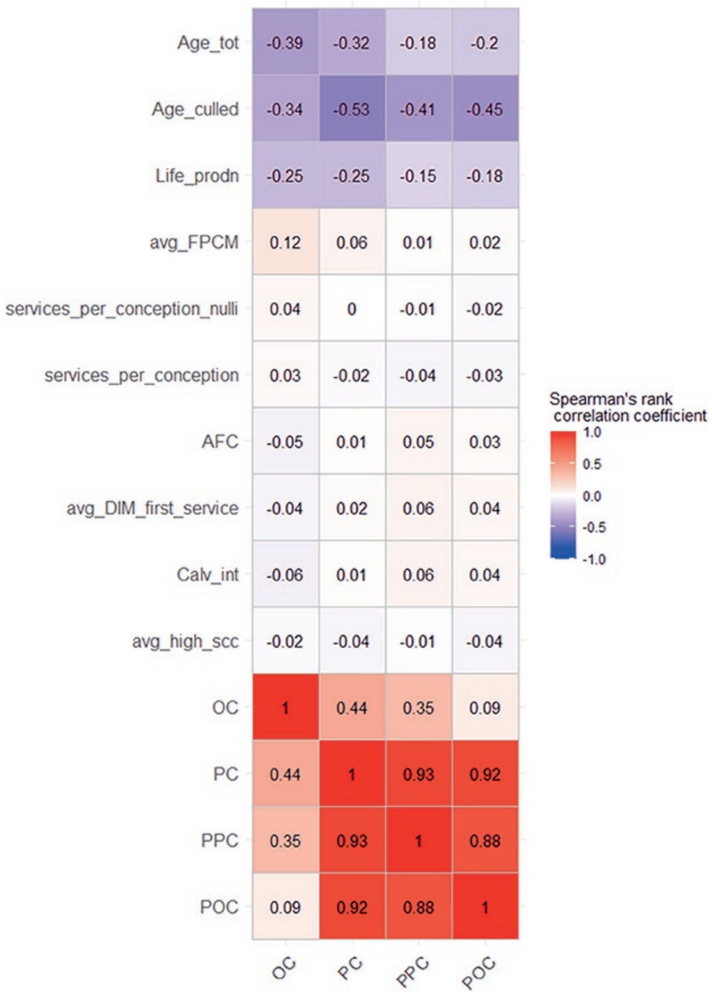

Figure 3.2. Spearman's rank-correlation matrix of correlations between the four culling proportions and performance indicators.

Note: Age_tot, total herd average age; Age_culled, herd average age of culled cows; Life_prodn, lifetime production of milk; Avg_FPCM, herd average daily fat-protein corrected milk; services_per_conception_nulli, mean number of inseminations per calf (in nulliparous cows); services_per_conception, mean number of inseminations per calf (in multiparous cows); AFC, age at first calving; avg_DIM_first_service, interval of days in milk (DIM) between last calving and first insemination; Calv_int, herd average calving interval; avg_high_scc, proportion of cows in herd with high somatic cell count; OC, overall culling proportion; PC, primiparous culling proportion; PPC, primiparous-primiparous culling proportion; POC, primiparous-overall culling proportion.

There was a high-rank correlation (> 0.8) between the primiparous culled cow proportions, namely, PC, PPC, and POC. The rank correlation between the overall culling proportion (OC) and PPC, PC, and POC was 0.35, 0.44, and 0.09, respectively. From Figure 3.2, rank correlations between all longevity indicators and all four culling proportions were moderately high to low (range: −0.53 to −0.15), indicating a different approach to primiparous and multiparous cow culling. For all other performance indicators, the rank correlations with culling proportions were very low (rho <0.2; Figure 3.2). This showed that there was very little rank conformity between the performance areas (except the longevity area) and primiparous culling proportions.

Scatter plots drawn between scaled performance indicators and culling proportions did not show any non-monotonic relationship between the indicators and proportions (Appendix 1, Figures A–D).

From Figure 3.3, the rank correlations between the indicators belonging to the longevity and reproduction areas ranged between 0.3 to 0.57 and −0.46 to 0.73, respectively. Rank correlations higher than 0.75 were not present, as these were used as threshold settings in the variable selection. The areas of production and udder health had only one indicator each. The rank correlations between indicators belonging to different performance areas were generally low, as indicated by the range varying from an absolute minimum of 0.01 (rho = 0.01) between calving interval and lifetime milk production to an absolute maximum of 0.5 (rho = 0.5) between herd average lifetime production and herd average FPCM yield (Figure 3.3).

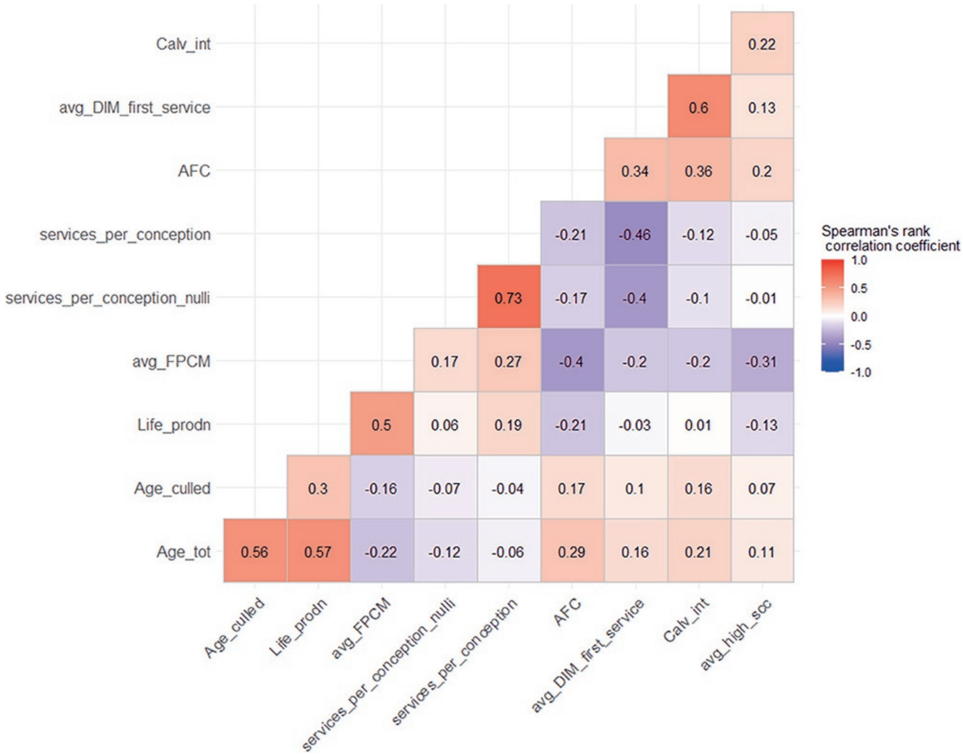

Figure 3.3. Spearman's rank-correlation matrix (lower triangle) of performance indicators.

Note: The variables in rows and columns are the 10 performance indicators in four areas.

Note: Age_tot, total herd average age; Age_culled, herd average age of culled cows; Life_prodn, lifetime production of milk; Avg_FPCM, herd average daily fat-protein corrected milk; services_per_conception_nulli, mean number of inseminations per calf (in nulliparous cows); services_per_conception, mean number of inseminations per calf (in multiparous cows); AFC, age at first calving; avg_DIM_first_service, interval of days in milk (DIM) between last calving and first insemination; Calv_int, herd average calving interval; avg_high_scc, proportion of cows in herd with high somatic cell count.

Note: Diagonal (self-correlations) not shown.

3.3.3 Logistic Regression Model

In the weighted logistic regression model, the associations between the performance indicators and the culling proportions of OC and PPC were tested by odds ratio and the results are shown in Table 3.2. An odds ratio of more than 1 is associated with a higher culling proportion, whereas an OR < 1 is associated with a lower culling proportion.

Table 3.2. Summary of results: Multivariable fractional logistic regression models with Overall culling (OC) or Primiparous-primiparous culling proportion (PPC) as dependent variable against scaled herd performance indicators in 4 areas

	OC		PPC	
Indicator [a]	OR (95% CI) [b,c]	p.value	OR (95% CI) [b,c]	p.value
Intercept	0.39 (0.38-0.39)	<0.001	0.23 (0.22-0.23)	<0.001
Reproduction [b]				
Services per conception (nulliparous)	1.01 (0.99-1.02)	0.81	0.99 (0.98-1.01)	0.69
Services per conception (multiparous)	1.01 (0.99-1.02)	0.20	0.99 (0.97-1.01)	0.28
Average DIM at first service	1.00 (0.99-1.00)	0.60	1.03 (1.01-1.04)	<0.001
Calv_int	1.02 (1.01-1.02)	<0.001	1.12 (1.10-1.14)	<0.001
AFC	1.01 (1.00-1.02)	<0.001	1.01 (0.99-1.02)	0.08
Longevity [b]				
Age_tot	0.96 (0.95-0.96)	<0.001	1.11 (1.10-1.13)	<0.001
Age_culled	0.92 (0.92-0.93)	<0.001	0.63 (0.62-0.64)	<0.001
Life_prodn	0.92 (0.91-0.93)	<0.001	0.95 (0.93-0.97)	<0.001
Production [b]				
avg_FPCM	1.08 (1.07-1.08)	<0.001	0.99 (0.97-1.01)	0.50
Udder health [b]				
avg_high_SCC	1.01 (1.00-1.01)	<0.001	0.97 (0.96-0.98)	<0.001

Note:

[a] All indicators were scaled (centered to mean) due to differences in scale

[b] Abbreviations: OR-odds' ratios, services per conception – Number of inseminations/services per calving, average DIM at first service- Interval in days in milk (DIM) between last calving and first insemination, AFC- Age at first calving, Age_tot- Total herd average age, Age_culled – Herd average age of culled cows, Life_prodn – Lifetime production of milk, Avg_FPCM – Average Fat-protein corrected Milk, Avg_high_SCC – Average percentage of high SCC cows in the herd

[c] All values rounded to 2 digits after decimal

In the OC model, higher herd averages of the calving interval, FPCM, and proportion of cows with high SCC were associated with higher overall culling from reproduction, production, and udder health areas, respectively. Three of the four longevity indicators, namely, higher herd average age of cows, higher average age of culled cows, and higher herd average lifetime production were associated with less overall culling (Table 3.2). In the PPC model, longer intervals between the last calving to first insemination and longer calving interval were both associated with higher primiparous culling from the reproduction area. Moreover, in the PPC model, unlike in the OC model, the production indicator and the udder health indicator were negatively associated with primiparous culling risk. In the PPC model (Table 3.2), one longevity indicator, higher age of culled animals, was associated with less primiparous culling (OR = 0.69), whereas higher herd average age of cows and higher herd average age of culled cows and age at first calving were associated with higher primiparous culling proportion.

3.4 Discussion

This study aimed to gain insights into the cross-sectional associations between annual performance indicators of Dutch dairy farms and their corresponding magnitudes of (i) overall culling and (ii) primiparous cow culling under the herd size restriction induced by the introduction of phosphate regulation in the Netherlands. The number of phosphate rights granted to a dairy farmer was based on the number of cows kept in 2015, subjected to a generic reduction of 8.3% (Rijksoverheid, 2018). As most dairy herds expanded after the abolishment of the milk quota in 2015, where the average dairy herd size increased from 85 in 2014 to 97 producing cows in 2016 (WECR, 2022), it was expected that most dairy farmers had to adjust their culling magnitude in response to the new policy.

The results indicated an overall culling rate (OC) of 28% (SD 8%), which was only slightly different than the OC in the previous years in 2015, 2016, and 2017 of 22% (SD 7%), 24% (SD 8%), and 30% (SD 8%), respectively (Unpublished data; OC calculated on the same sample size of 10,540 herds). Dairy farmers could reduce herd sizes by culling dairy cows without replacement and/or by increasing the outflow of youngstock. According to official census data (Central Bureau of Statistics), the total number of dairy cows in the Netherlands reduced between April 2017 and April 2018 by 4% to 1.62 million dairy cows (CBS, 2021; ZuivelNL, 2019). During the same period, the number of youngstock, however, decreased by 14% to 1.03 million cows (CBS, 2021). This indicates that in the year of the policy introduction, farmers responded initially by adjusting the herd size of their youngstock, explaining the moderate increase in OR.

Only 16% (SD 9%) of the culled cows were primiparous (POC) which is comparable to the 17.5% measured in the years 2007–2012 (CRV, 2021a). This indicated that primiparous cows formed a minor proportion of the overall culling magnitude effected by the farmers on their herds. This was in line with the earlier findings of Archer et al. (2013). From Figure 3.1, there was a large variation around the mean for all four culling proportions (OC, PC, PPC, and POC) in all herd sizes, indicating that farmers varied in their culling strategies and that there was no indication of a uniform response with respect to the policy changes.

Unfortunately, we did not have access to the data regarding the culling of primiparous cows in the years 2016 and 2017. Moreover, the available data on performance indicators were in the form of annual summaries either on the cow or farm level and not on a monthly or quarterly basis. Therefore, it was not possible in this study to compare or track changes in farm performances or the culling rates for primiparous cows before and after the application of the phosphate rights system in the Netherlands. Rather, this study focused on the immediate associations between the overall and primiparous cow culling and the performance of farms after the policy changed. Further study representing changes or alterations in the culling rate before and after the application of the phosphate rights system is required to completely assess the effect of the new policy on dairy farm management in the Netherlands.

The rank conformity between production, reproduction, and udder health indicators and the four culling proportions was weak to non-existent (Figure 3.2), indicating that the variation in culling magnitude was not associated with the annual herd performance. From Table 3.2, reproduction, production, and udder health indicators were found to be significantly associated with primiparous and overall culling (OC and PPC), in contrast to the rank correlation findings. Particularly, production and udder health indicators had opposite associations (positive for OC and negative for PPC) to the culling proportions. This was in line with the findings of Oltenacu et al. (1984), who found that primiparous cows were at higher risk of culling due to health problems compared with older cows. Nevertheless, based on the odds ratios, all significant associations ranged between weak and moderate at best. This indicated that the extent of primiparous and overall culling varied irrespective of farm performance. Based on this, we theorized that the variation in culling was not driven by farm performance level.

In all the statistical analyses, only longevity indicators were consistently found to be associated with the culling proportions. However, these associations can be explained numerically (not causally) since there is a direct functional relationship between current longevity and previous culling (Dallago et al., 2021). For example, the indicators such as herd-average age of culled animals (Age_culled) and herd average age of cows (Age_tot) were directly influenced by the proportion of young animals such as primiparous cows being culled on the farm in previous years. On the other hand, these associations may be suggestive of differences in the management and behavior of farmers. For example, some farmers give more chances to primiparous cows, and culling for performance goals is focused on 2nd parity cows when policy changes are applied. Whereas some farmers may judge 1st parity cows more critically, leading to premature culling and so on to reduce herd sizes. This is irrespective of which strategy is best for maximum overall performance. Therefore, it was not possible to provide a straightforward interpretation of the evaluated rank conformity between the longevity area and the primiparous cow culling proportions.

It can be argued that the effects of policy changes such as the phosphate regulation affect farm performance in the medium to long term instead of the short term. Especially when considering the difference in the relative decrease in youngstock compared with dairy cows, disturbing the influx–efflux balance on a farm (Kulkarni et al., 2021). Longitudinal data on longer term effects were, however, not available during this study. Hence, targeting mid- to long-term associations was beyond the scope of the study but is certainly very interesting. The lack of longitudinal data might also explain the weak relationships found between the performance areas and culling proportions compared with the results of long-term studies such as that by Nor et al. (2014).

Figure 3 indicated that there was no monotonic relationship between the performance indicators from different areas. This finding agrees with the insights obtained from the factor analyses on longitudinal data of Haine et al. (2017) and the findings of Brotzman et al. (2015) who used a combination of principal component and cluster analyses. It seems that farms are not ranked high or low consistently among the different areas, and integrative approaches such as factor analyses would not solve the underlying issue. There seems to be a gap in approaches or methods to describe overall farm performance in many areas independently.

3.5 Conclusion

In conclusion, there was a rise in overall culling on Dutch dairy farms during the year 2018 after the introduction of the phosphate rights system in national agricultural policy. Moreover, there was a high degree of variation between the culling rates of Dutch dairy farms around the national mean. Primiparous cow culling formed a minor proportion of the overall culling rates of the farms, indicating that young producing cows were not targeted by farmers for altering herd size post-policy change in the year of study. However, overall primiparous cow culling was not systematically related to the performance level of dairy farms in reproduction, production, and udder health areas in the same year.

Appendix 1: Supplementary Material

Table A. Details of CRV[a] datasets used in this study

Name of dataset [a]	Description	Variables [1]	Recording moment
Herd composition data	Annual figures of herd averages and number of animals on farms	UBN [2], Age_tot, Age_culled, Age_primi, Life_prodn, n_tot, n_culled, n_primi, Calv_Int	Annual, farm level
Fertility data	Annual figures of reproduction and fertility related indicators	UBN [2], Primi/Multi, ICI, AFC, insem/calf	Annual, farm level
Udder health data	Test-day farm level figures of udder health	UBN [2], test_date, test-day SCC, %high_SCC, %new_inf	Test-day, farm level
Production data	Test-day farm level recordings of milk yield related indicators	UBN [2], test_date, test-day milk, test-day fat, test-day protein, 305-day milk, 305-day fat, 305-day protein, BSK, net value	Test-day, farm level
Milk Production registration	Test-day cow level records on milk production of cows	Animal Identifier, UBN[2], test_date, parity, test-day milk, Lactation Value, etc.	Test-day, cow level

[a] Names of datasets translated into English from original Dutch names

[1] Detailed description and full names of relevant variables in Table 3.1 of manuscript

[2] UBN is farm identifier number anonymized at source by CRV

Table B. Steps of data selection and editing performed to CRV farm-level data of 2018

Step	Process	Number of farms
0	Raw data from CRV: - 4 data sets representing farm-level records 1 data set representing MPR records on cow level	14,609
1	Exclude farms with < 4 MPR recording moments	14,291
2	Exclude farms with < 30 or >= 500 producing cows	12,920
3	a. Calculate annual averages of test-day records on production and udder health b. Exclude farms with erroneous and unrealistic values (eg. Annual Farm milk-fat yield of 12%, etc.) c. Include only farms that are represented in all 4 herd level datasets	12,652
4	a. Calculate culling proportion variables OCR, PCR, PPC, POC [1] b. Include only farms with OCR value between 5-95% interval (90 percentile)	10,540

Note: Abbreviations OCR: proportion of number of cows culled to overall number of producing cows in the Farm, PCR: proportion of number of 1st parity cows culled to overall number of producing cows, PPC: proportion of 1st parity cows culled to the number of 1st parity cows producing in the Farm, POC: proportion of 1st parity cows culled to total number of culled cows

[1] Refer to Eqn 1 to 4 in main body text for formulae

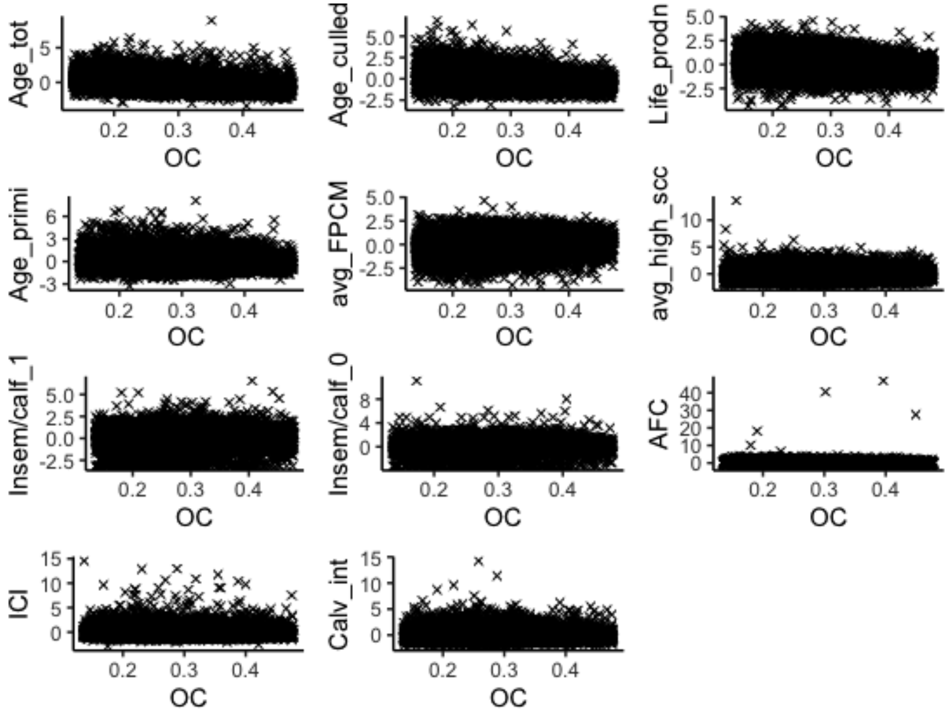

Figure A. Scatter plots of scaled performance indicators (y-axis) against overall culling proportion OC (x-axis; unscaled)

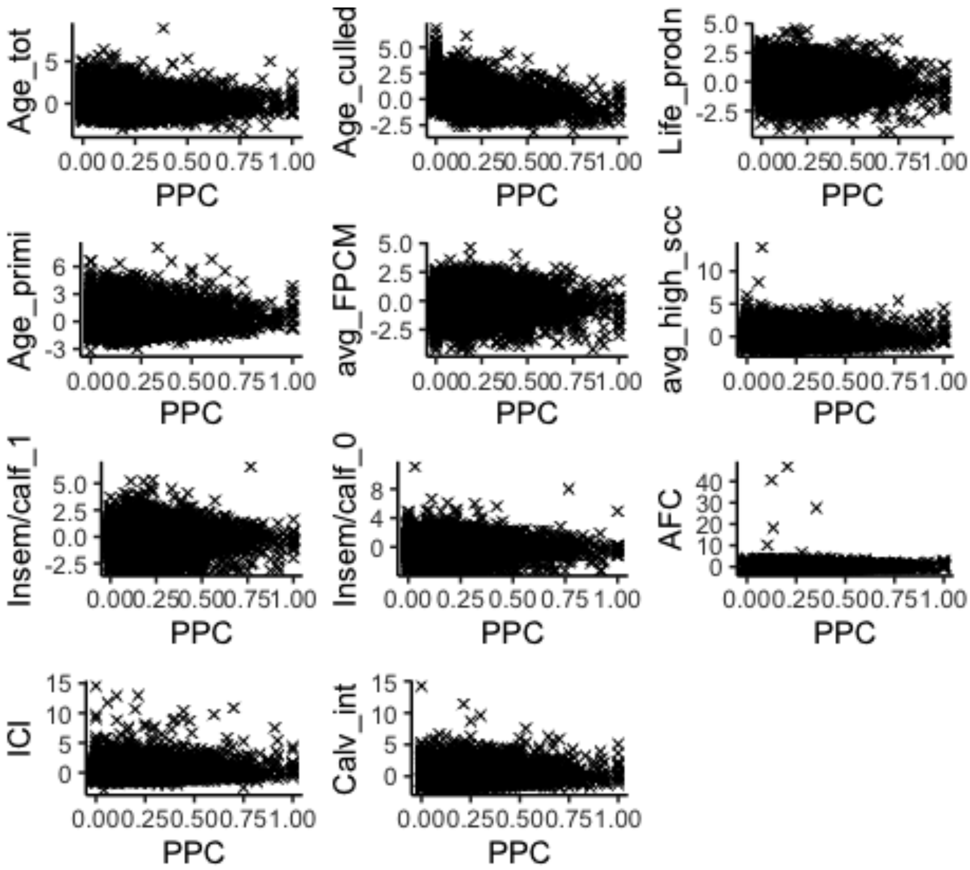

Figure B. Scatter plots of scaled performance indicators (y-axis) against Primiparous-primiparous culling proportion PPC (x-axis; unscaled)

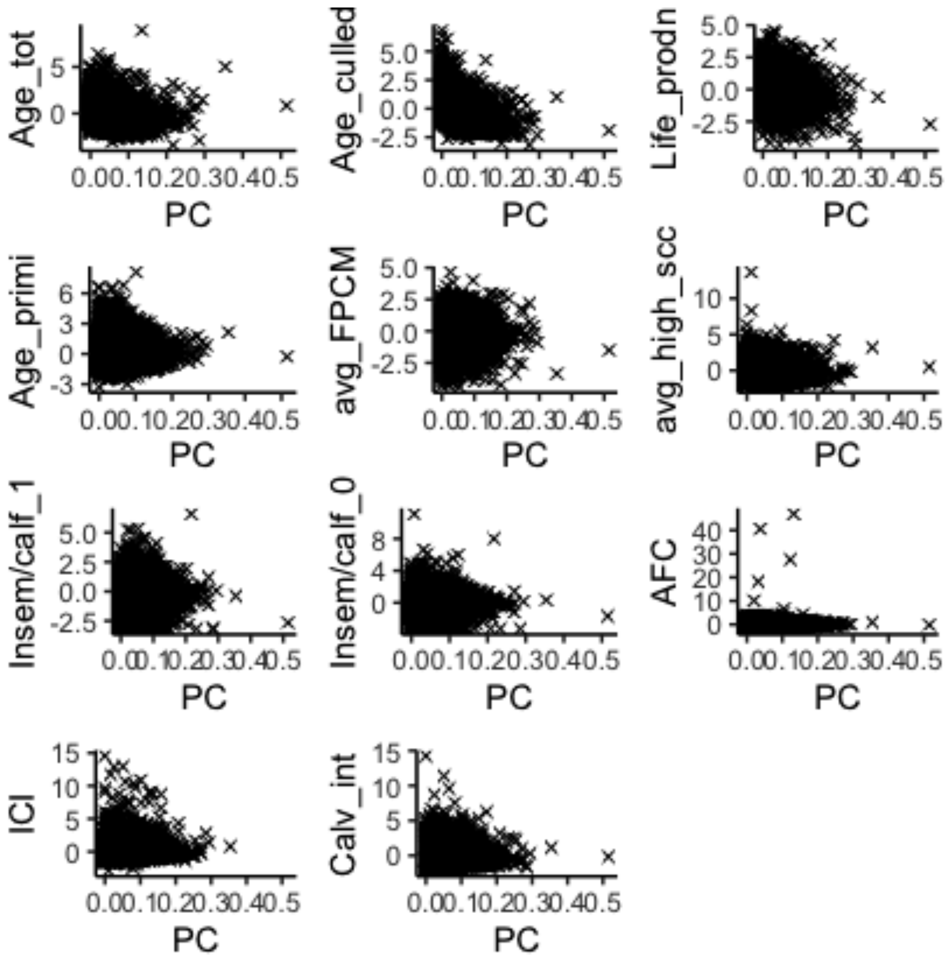

Figure C. Scatter plots of scaled performance indicators (y-axis) against Primiparous culling PC (x-axis; unscaled)

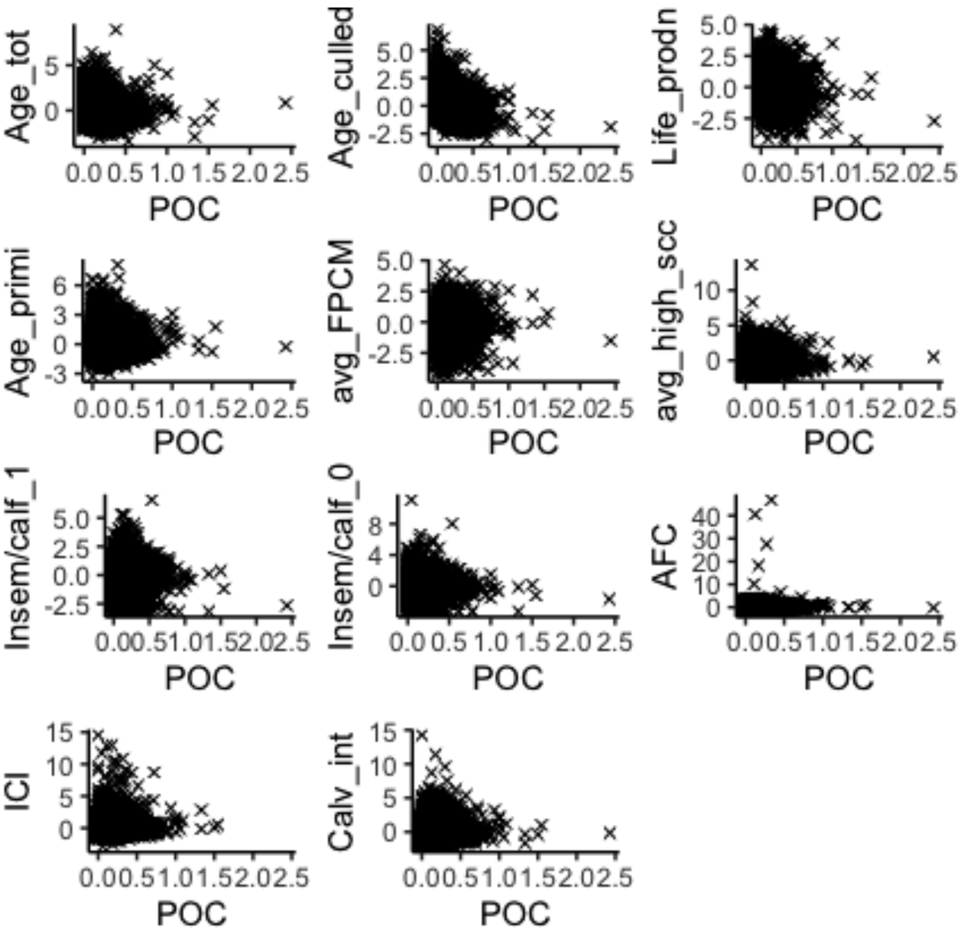

Figure D. Scatter plots of scaled performance indicators (y-axis) against Primiparous-overall culling POC (x-axis; unscaled)

CHAPTER 4

Dutch dairy farmers' perspectives on culling reasons and strategies

Kulkarni P. S., Mourits M. C. M., Slob J., Veldhuis A. M. B., Nielen M., Hogeveen H., van Schaik G., Steeneveld W.

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Abstract

Since the abolishment of the milk quota system in Europe in 2014 and the introduction of environmental policies such as the phosphate rights system in the Netherlands, the reasons for culling dairy cows might have changed. The aim of this study was to determine the culling reasons for dairy cattle and to identify farmers' culling strategies and their intentions regarding the alteration of indicated culling strategies. To this end, an online questionnaire was distributed among dairy farmers nationally that resulted in 207 responses. Results showed that the most frequent culling reasons were related to problems with reproduction, udder, and hoof health. Primiparous cows were primarily culled for miscellaneous reasons such as injury, reproduction failure, and low milk yield. Multiparous cows were culled predominantly for reproduction failure, udder health and hoof health reasons. Most respondents indicated that they consider formulating a culling strategy, based on certain rules of thumb regarding the most common reasons for culling. Most farmers also reported that culling decisions on their farms were perceived to be unavoidable, though reproductive culling decisions are primarily voluntary. Most respondents stated that they intended to reduce the culling rate for better economic gain did not intend to alter the amount of replacement stock reared. The applied rules of thumb regarding culling strategies do not seem to have changed since the policy changes in dairy farming. The question remains whether farmers' rules of thumb might have made them unaware of the actual economic consequences of their culling strategies under the altered situation.

Keywords

Culling, dairy, reasons, intentions, survey, longevity

4.1 Introduction

Culling and replacement of dairy cattle have an impact on the economic performance of dairy farms. According to Fetrow et al. (2006), culling is either biologically or economically driven. Biological culls refer to those cows for which a productive future is absent due to serious physical disorders such as permanent infertility or irreparable injuries. In these cases, the decision to cull is actually forced on the farmer. Economic culls refer to those cows for which replacing them is considered a smart economic option for the dairy farm. Fetrow et al. (2006) argued in favour of using this distinction between biological versus economic culling and against using the traditional distinction between voluntary and involuntary culling. Few studies have investigated the specific reasons for culling behind the decisions made by dairy farmers in recent years (reviewed by Compton et al., 2017; De Vries and Marcondes, 2020). In general, reproductive fitness, poor udder health and hoof disorders or lameness were found to be the main causes of culling cows. However, the specific reasons differed between countries (Ahlman et al., 2011; Dallago et al., 2021; Gussmann et al., 2019; Heise et al., 2016; Kerslake et al., 2018; Rilanto et al., 2020).

Various studies have observed that when deciding to cull a cow, multiple reasons may come into play whereas often in practice only one reason is recorded in national animal registration databases (de Vries and Marcondes, 2020). This restricts further insights into the complexity of culling management. Moreover, it was noted that the reasons for culling primiparous and multiparous cows may differ. Whereas the primiparous cows are often culled for udder non-conformity, lack of production, injury or behavioural issues, multiparous cows are culled for more systematic reasons such as poor reproductive performance, udder and hoof health (Gussmann et al., 2019).

In the past, Boer et al. (2013) reported the most frequent reasons for culling in the Netherlands as being similar to those found in other countries. However, since the introduction of environmental policies such as the phosphate rights system in the Netherlands, the importance of reducing the number of youngstock has increased and consequently, culling decisions may have been changed. The reasons behind dairy cattle culling followed by Dutch dairy farmers in the new policy climate have not been investigated or documented.

Since the majority of cows culled by dairy farmers are for "economic" reasons (Fetrow et al., 2006), it might be the case that farmers follow specific plans or strategies for making such decisions. Beaudeau et al. (1996) indicated that having a specific culling plan or strategy was part of general management practices as applied by French farmers and that these plans differed significantly between the farmers depending on their "style". Contrary to that, Bergeå et al. (2016) found in their survey that multiple Swedish farmers felt that their culling decisions were unavoidable or "forced" and hence did not permit a decision space to adopt a specific culling strategy. Previous studies investigated the link between culling magnitude (culling rate) and farm-specific characteristics (Alvåsen et al., 2012; Han et al., 2022; Kulkarni et al., 2021; Nor et al., 2014a) but these associations did not completely explain the variation in culling magnitudes or reasons for culling between different farms. Nor et al. (2014) pointed out that the majority of studies on culling reasons focus on the performance of individual cows whereas the farmer's style, culture and individual herd management might play a role in culling decisions as well. Dairy farmers might use rules of thumb as proxies for their culling strategies.

Furthermore, culling decisions are intimately linked with the longevity of dairy cows (Dallago et al., 2021). Currently, improved longevity is favored by most dairy-producing countries (Bell et al., 2011; Hadley et al., 2006; Schuster et al., 2020). Consumers are pushing for dairy farming practices where cows are bred and reared more "naturally" (Spooner et al., 2014). Countries like the Netherlands have introduced new environmental policies such as phosphate regulation in 2018 which are aimed at improving the sustainability of dairy farms. Therefore, to improve the longevity of dairy cows, efficient management and culling are important (Schuster et al., 2020). Han et al. (2022) discovered that longevity on farms could be improved without impacting herd performances to a large degree. Further research into the perspectives behind the culling strategies of dairy farmers, and their intentions to alter these strategies in near future is needed. Such insights can add to the discussion of improving cattle longevity in the future. Therefore, the aim of this study was to (1) determine the reasons behind the culling of cattle on Dutch dairy farms, (2) to determine whether Dutch dairy farmers follow specific culling strategies (plan) and (3) if so, to evaluate whether they intend to change their strategies in the near future.

4.2 Materials and Methods

4.2.1 Questionnaire

Data on culling reasons, strategies and future intentions were collected from Dutch dairy farmers by means of an online questionnaire. The link to the survey was distributed to farmers who subscribed to the online monthly newsletter of Royal GD, called 'Actueel Rund' (Royal GD, 2021). This newsletter was sent to around 12,000 Dutch dairy farmers, or approximately

80% of the total number of Dutch dairy farms (CBS, 2021). Respondents could voluntarily participate in the study by completing the survey. Responses were collected between 9th December 2021 and 10th January 2022. To enhance participation, farmers were incentivized by the chance of winning one of twenty €25 gift cards. The study protocol and consent procedure complied with the Netherlands Code of Conduct for Scientific Practice and were approved by the Social Sciences Ethics Committee of [Wageningen University & Research (CoC number 09131098)]. For participation in the gift card raffle, email addresses were provided by the responding farmers voluntarily. This private information was stored separately from the data of the questionnaire. The contact details and IP addresses of the respondents were masked and were unavailable to the research team. The cover letter part of the survey contained a summary of the research intent along with a privacy and data management statement.

Throughout the survey, culling was defined as the removal of cows to the slaughterhouse excluding sales to other farms, natural death, or euthanasia on the farm, for the sake of consistency. The body of the questionnaire consisted of four parts. The questions in the first part (n = 11) related to the most recently culled cows on the respondent's farms. Questions such as if they remembered the most recently culled cow (yes/ no), time of deciding when to cull (in terms of stage of lactation of the cows; multiple choice), whether it was an unforeseen culling (unforeseen defined as <1 week between the decision to cull and actual culling; yes/ no), and the reasons for culling (multiple choice with multiple answers) were asked. These questions were duplicated for primiparous (1st parity) and multiparous (> 1 parity) cows. The second part consisted of questions about the culling strategies of respondents (n = 8) if present. Respondents were asked to state their three most frequent and least frequent occurring culling reasons (multiple choice with rank). A series of four statements were asked to be rated on a 5-point Likert scale, ranging from "totally disagree" to "totally agree", to identify the use of a culling strategy. For example, "I have a clear long-term culling plan on my farm" was one of the statements. If the response was positive, additional questions regarding rules of thumb or guidelines for culling decisions were explored.

The third part consisted of statements and questions (n = 5) regarding the intentions of the respondents to alter their existing culling strategy. For example, "I intend to alter the percentage of culled cows in the next year" was one of the statements. The possible positions for this statement were "Yes, I will decrease…", "Yes, I will increase…" or "No, I don't intend to…" (multiple choice). Depending on the response, an additional question (multiple choice) was posed to address the motivation of the respondent behind the indicated intentions. In the fourth part of the questionnaire, general questions (n = 14) about the characteristics of the farm/ herd and the farmer were asked. In terms of information on herd size and the number of current young stock, respondents were given the option to provide their herd ID which would allow the automatic collection of entry/exit data for the animals from the Netherlands Enterprise Agency (RVO), which is a government entity that collects such data. Of those respondents who consented to this option, automatically received data was anonymized by Royal GD before being integrated with the survey questionnaire responses due to potential privacy concerns.

Before distribution, the survey was pilot tested on four farmers and relevance, estimated duration of completing the survey and difficulties encountered while filling out the survey were investigated. We conducted unstructured face-to-face interviews with these farmers for feedback regarding the relevance of the questions and the perceived meaning of the questions as they appear in the survey to avoid ambiguity and confusion in the interpretations by the responding farmers. The full survey can be viewed in Appendix 1: Questionnaire.

4.2.2 Data editing

Responses were checked for missing data in all four parts of the survey questionnaire. In addition to that, responses were checked for illogical entries (for example, herd average 305-day milk production of 100,000 kg) and these responses were recoded as missing values. From the answers in the responses, numerical and categorical variables were generated for descriptive analyses (Table 4.1, Table 4.2). Secondary variables such as self-reported culling rate (ratio of the number of cows culled to rolling herd size including milking and dry cows in the year of the survey) and farm intensity (ratio of the number of producing cows including milking and dry cows to the area of farmland in hectares) were generated from the responses. All steps of data editing and further analyses were conducted in R statistical package 3.6.3 (R Core Team, 2020).

4.2.3 Descriptive analyses

Summary tables of numerical variables were generated including median, minimum, maximum, mean, standard deviation and the number of responses. Categorical variables were summarized by the number of categories and the proportion of answers per category.

4.3 Results

4.3.1 Response to survey

In total, 207 responses were recorded between 9th December 2021 and 10th January 2022. Considering that the newsletter was sent to approximately 12,000 dairy farmers, the response rate of the survey was less than 2%. Of these 207 responses, 201 responses were finally used in the analyses of this study. Of these 201 responses, 72 respondents completed the full survey, while 55% of the 201 responses had complete answers in at least three out of four parts of the survey questionnaire. 47 respondents consented to using their ID information for retrieving herd size statistics from the RVO database. Of these, 46 were retrieved (1 had a possible error in the ID provided), anonymized, and integrated into the database.

4.3.2 Descriptive statistics

Table 4.1 shows that 73% of the respondents were below the age of 55 years old. Also, 61% of the respondents were completely responsible for the culling decisions made on their farms. Most of the respondents had a conventional farming system, and 28% of the respondents had an automatic milking system (AMS). 78% of the respondents adopted a closed farming system where they breed and rear their own replacement heifers, while 12% of the respondents had an arrangement with other farmers for rearing their replacement stocks. Roughly two-thirds of respondents of the farms had an average first calving age between 20 and 24 months.

Table 4.1. Descriptive summary of categorical variables based on the responses from dairy farmers to the questionnaire.

Variable	N[1]	Levels/ Categories	Counts (n^2)	Per cent (%)
Age of farmer in years	116	18-35 years	46	39.7
		36-55 years	39	33.6
		> 55 years	31	26.7
Type of farm	116	Conventional	108	93.1
		Organic	5	4.3
		Other	3	2.6
Type of milking system	116	AMS (Automatic Milking System)	33	28.5
		CMS (Conventional Milking System)	83	71.5
	115	20-24 months	75	65.2
		25-27 months	39	33.9

Avg. age at first calving		28-32 months	1	0.9
Decision responsibility	74	Yes	45	60.8
		Partly	29	39.2
		No	0	0.00
Replacement stock type	115	I breed and rear my own replacement stock	90	78.3
		I breed my own replacement stock; however I also purchase replacement animals	9	7.8
		My own bred replacement stock is reared on another location by someone else and will be back on my own farm as heifers	13	11.3
		my own bred replacement stock is reared by someone else, and I purchase replacement animals	1	0.9
		I purchase all my replacement stock	2	1.7

[1] N = Number of responding farmers

[2] n = number of answers by responding farmers

From Table 4.2, it can be seen that the average dairy herd size of the responding sample population was 146 cows (SD 80) and the average age of cows in the dairy herd was 5 years and 5 months (64.5 months; SD 10 months). The average number of calves and heifers reared on the respondent's farms accounted for roughly 25% and 22% of the average number of producing cows (herd size), respectively. The self-reported culling rate, which excluded the dairy sale of cows (sold alive), was on average 15% (SD 10%). Based on the reported farm area in hectares (mean approximately 61ha, SD 28 ha; are not shown in Table 4.2), the mean farm intensity on the responding farms was 2.39 dairy cows per ha (SD 1.16 dairy cows per ha). All numerical variables, except herd average 305-day milk production in kilograms, were not normally distributed.

Table 4.2. Descriptive summary of numeric variables based on the responses from dairy farmers to the questionnaire

Variable	N[1]	Mean (SD)	Min	Median	Max
Avg. herd age (months)	112	64.5 (10.7)	49	63	99
Number of milk-producing cows	109	146 (80)	31	126	536
Number of heifers (1-2 years of age)	109	32 (24)	0	27	150
Number of female calves (0-1 years of age)	109	37 (22)	3	33	106

Number of culled milk-producing cows (excluding dairy sale)	108	21.9 (19.7)	1	16	150
Number of purchased heifers (per year)	109	2 (6)	0	0	37
Farm intensity[2]	104	2.39 (1.16)	0.833	2.13	10.7
Avg. 305-day milk production in Kgs	112	9,341 (1,385)	5,700	9,400	12,500
Avg. self-reported culling rate [3]	108	0.15 (0.10)	0.004	0.14	0.73

[1] N = Number of responding farmers

[2] farm intensity = milk-producing cows/ area in hectares

[3] culling rate = ratio of number of culled cows (excluding dairy sale) to number of producing cows in the herd

A summary of responses regarding recently culled cows distributed by the parity group can be seen in Table 4.3. From the primiparous category, most respondents reported culling cows for reproduction issues (27.1%, N = 35 of 99) followed by other reasons (20.9%, N = 27 of 99). The other reasons included self-reported explanations such as post-partum complications, injuries and trauma or were labour related. In the case of multiparous cows, the most common reasons for culling were related to reproduction (N = 57 of 131), poor hoof health (N = 39 of 131) and high somatic cell count or the presence of mastitis (N = 37 of 131). Most responding farmers reported only one main reason for culling, while some reported two and rarely three reasons for each parity group (Table 4.3). Less than half of culling decisions were considered unforeseen by the farmer irrespective of the parity of the cow. Also, it was clear that most farmers decided to cull cows after attempting to treat them, irrespective of the age of the producing cow.

Table 4.3. Parity groupwise summary of recently culled cows on the responding farms

	1st parity		> 1 parity	
Factor	Count	%	Count	%
Culling reasons [1]	N = 99; n =129		N = 131; n = 181	
Reproduction	35	27.1	57	31.5
Somatic Cell count/ Mastitis	14	10.9	37	20.4
Hoof health/ Lameness	13	10.1	39	21.5
Low Milk yield	17	13.2	15	8.3
Reducing herd size	2	1.7	13	7.2
Udder defects/ Conformity	6	4.5	0	0
Aggression/ Undesirable Behaviour	15	11.6	2	1.1
Others	27	20.9	18	10
Foreseen/Unforeseen [2]	N = 98		N = 133	

Foreseen	58	59.2	96	72.2
Unforeseen	40	40.8	37	27.8
Culling decision time	N = 84		N = 83	
After Calving	23	27.4	23	27.7
After Insemination	12	14.3	11	13.3
After Unsuccessful treatment	27	32.1	27	32.5
Others	22	26.2	22	26.5
Number of reasons reported	N = 99		N = 131	
Only 1 reason	75	75.7	91	69.5
2 reasons	18	18.2	33	25.2
3+ reasons	6	6.1	7	5.3

[1] N = number of responding farmers; n = number of answers (multiple answers to the question allowed per respondent)

[2] Question of whether this culling decision was made in < 1 week (unforeseen) or > 1 week (foreseen) before actual cull date

From Figure 4.1, the most frequent culling reasons as indicated by the responding farmers were related to reproduction problems or issues, somatic cell count or the presence of mastitis and hoof health issues or lameness. On the other hand, the least frequently occurring culling reasons were the availability of a replacement heifer, behavioral issues, and conformity of the udder. The top three most frequent reasons coincided with the top reasons reported for a recently culled cow in Table 4.3.

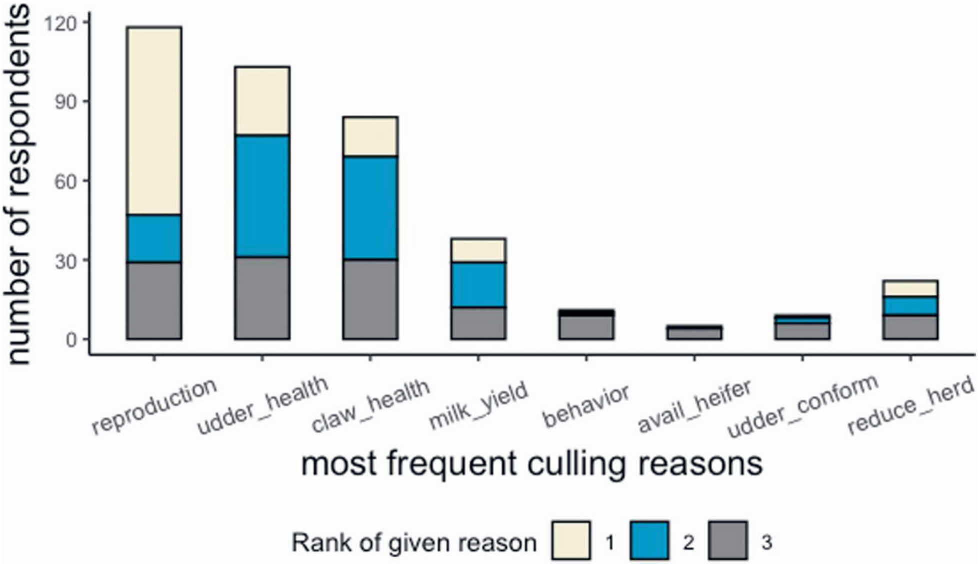


Figure 4.1. Farm specific top 3 most frequent culling reasons reported by the responding farmers.

Note: X axis glossary: reproduction = reproductive issues, udder_health = udder health issues/ SCC, claw_health = hoof health issues/ lameness, milk yield = low milk yield, behaviour = behavioural issues/ aggression, avail_heifer = availability of suitable replacement heifer, udder_conform = udder conformation issues, reduce_herd = reducing herd size

Note: N = 130 (number of responding farmers)

As indicated by Figure 4.2, the majority of responding farmers indicated that they have a clear long-term culling plan (72.8%) and follow specific rules of thumb regarding culling decisions (agreement = 61.7%). Also, the majority of responding farmers (55.5%) believed that their culling strategy is optimal. Most respondents (80.2%) also reported that the culling decisions on their farm were unavoidable.. Of those farmers who agreed with the statement that they have specific rules of thumb for culling, 22 (12%) responded that they use the same rule of thumb for primiparous and multiparous cows (Table 4.4). In general, most rules of thumb were related to reproduction, udder health (somatic cell count or mastitis) and hoof health (lameness).

Table 4.4. Specific rules of thumb graph followed by respondents to make culling decisions.

General Criteria for specific rule of thumb	For primiparous cows		For multiparous cows	
	n[1] = 156	%	n[1] = 187	%
Reproduction	56	36	51	27
Udder health	36	23	46	25
Claw health	18	12	36	19
Milk production	21	13	21	11
Breeding value	3	2	0	0
Body conformation	4	3	3	2
Other	18	11	8	4
Same rules as primiparous cows	-	-	22	12

(Number of respondents = 85)

[1] n = number of answers by the respondents (multiple answers allowed per response)

Table 4.5 shows, that the majority of responding farmers (62.4%) had no intention of altering their primiparous cow culling strategy soon. Similarly, most of the responding farmers (53.5%) had no intention of altering their multiparous cow culling strategy. Also, 56.9% did not intend to alter the amount of young stock that they kept for replacement. However, 64.7% of the respondents agreed that they wished to reduce the culling rate on their farms. In the follow-up question on their motivation behind the preference of reducing the culling rate, 37.2% of these respondents indicated improving the economic results on their farms as motivation, 29% indicated improving the longevity of their cows and 15.2% indicated improving the environmental sustainability.

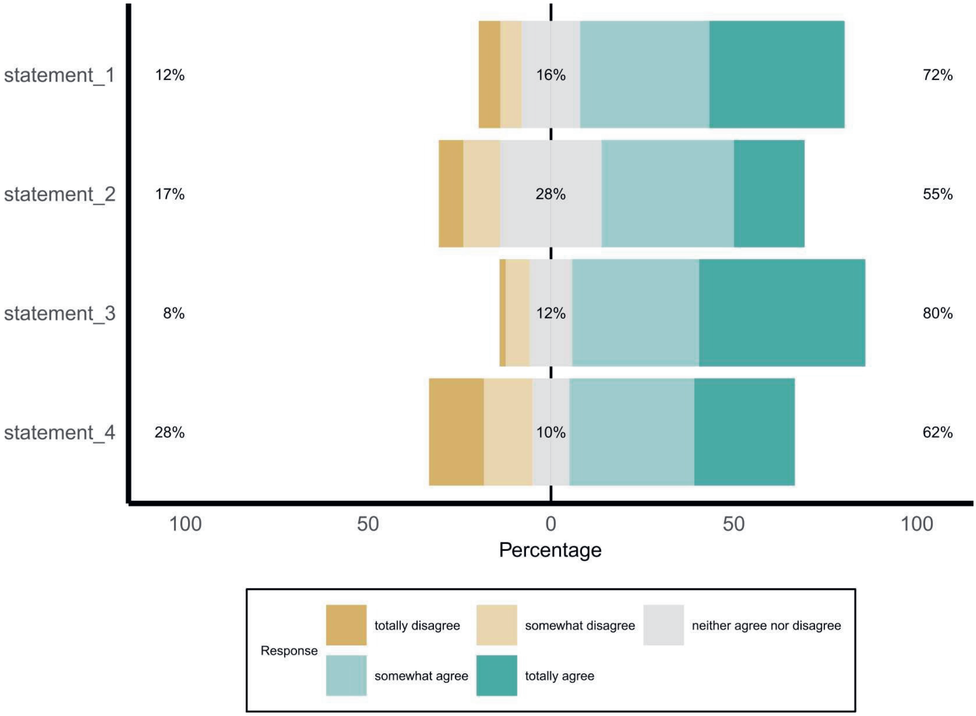


Figure 4.2. Likert scale graph of responses to strategy statements

Note: Glossary of statements

Statement_1 = "I have a clear long-term culling plan on my farm"

Statement_2 = "I consider the culling strategy on my farm to be optimal"

Statement_3 = "The culling decisions I make are unavoidable"

Statement_4 = "When deciding to cull a cow, I follow specific rules of thumb/ guidelines"

Note: percentages on extreme left and right indicate the total percentage of those who disagree (totally + somewhat) and those who agree (somewhat + totally) respectively

Table 4.5. Summary of responses reported on Intention statements by responding farmers

	Intention Statements	Number of responses	Percentage (%)
1	"I intend to alter my culling strategy for primiparous cows" (N = 117)		
	Yes, I will cull primiparous cows more quickly	0	0.0
	No, I don't want to alter my strategy	73	62.4
	Yes, I will cull primiparous cows less quickly	44	37.6
2	"I intend to alter my culling strategy for multiparous cows" (N = 116)		
	Yes, I will cull multiparous cows more quickly	7	6
	No, I don't want to alter my strategy	62	53.5
	Yes, I will cull multiparous cows less quickly	47	40.5
3	"I intend to alter the percentage of culled cows in the next year" (N=116)		
	Yes, I will increase the percentage of culled cows	5	4.3
	No, I don't intend to alter this percentage	36	31
	Yes, I will decrease the percentage of culled cows	75	64.7
4	"I intend to alter the amount of replacement stock in the next year" (N = 116)		
	Yes, I will increase the amount of replacement stock	25	21.5
	No, I don't intend to alter this amount	66	56.9
	Yes, I will decrease the amount of replacement stock	25	21.5

4.4 Discussion

The main purpose of this study was to survey Dutch dairy farmers regarding their culling decisions. We asked farmers about their most recently culled cows, as recent events are easier to remember. Moreover, by referring to these recent cases, we avoided socially desirable answers to questions regarding culling reasons. This method was the same as the method employed by Robbers et al. (2021) to study colostrum management of Dutch dairy farmers. In addition to the most recently culled cows, we asked about the most and least frequent culling reasons on the farm to detect if the recent events were in line with the general situation.

Based on the descriptive analyses, Dutch farmers cull their cows mostly for health reasons such as problems with reproduction, udder health issues and lameness. These findings were similar to the findings of Boer et al. (2013) who investigated the main reported culling reasons in the Netherlands during the years 2011–2012, before the abolition of milk quotas and the implementation of environmentally driven policies. This was also consistent with previous studies performed in other countries (Gussmann et al., 2019; Heise et al., 2016; Kerslake et al., 2018; Rilanto et al., 2020; Workie et al., 2021). Responding farmers tended to cull cows mostly after attempting treatment or after parturition. This finding was consistent with the findings reviewed by Beaudeau et al., (2000). Previous literature suggested that farmers might cull cows for multiple reasons (de Vries and Marcondes, 2020). However, despite the opportunity to report multiple reasons for culling, the majority of respondents in this study reported only one reason for culling. It is possible that dairy farmers perceive one primary reason for culling along with other less important factors. Besides this, most of the respondents also indicated that they have a clear long-term culling plan and that they consider their culling decisions to be optimal. Most of the respondents indicated that they intended to reduce the culling rate on their farm in the near future, mostly for economic gains and to improve the longevity of cows in the producing herd but did not intend to alter the amount of young stock maintained for replacement.

In the survey, we asked farmers for culling reasons which excluded permanent health issues, natural death, or euthanasia which form biological culling as defined by Fetrow et al. (2006). However, forced culling decisions such as due to infertility might have been included in the responses to the study under culling reasons "issues related to reproduction" and could not be easily separated from "economic culling reasons". Regardless of this, the survey was based mostly on "economic culling reasons" (per Fetrow et al., 2006 definition), wherein the farmer had the agency to make the culling decisions. However, most farmers responded that they found their culling decisions to be unavoidable. Considering these responses, we theorized that although farmers have a culling plan in place, they perceive a lack of decision space for making rational economic decisions. This finding was consistent with the findings of Bergeå et al. (2016) in Swedish dairy herds. So, within the perspectives of Dutch dairy farmers, the ambiguity within which decisions are voluntary (economically driven) and which are involuntary (forced) still exists. For example, culling for health reasons such as clinical mastitis might be forced and biological in nature or might be economic when the farmer has a chance to decide to treat the diseased cow for a longer duration. Or, when culling due to reproductive reasons, infertility can be a forced decision whereas culling due to reproductive failure after a fixed number of inseminations can be viewed as economic. A recent study has shown that it is possible to increase the longevity of Dutch dairy cows but that can lead to a higher mortality rate, a higher bulk milk somatic cell count and a higher antimicrobial use (Bisschop et al., 2023). Advisors to the farmers need to be aware of this perception and the fact that although most culling decisions might be economic in nature, they should be balanced for health, welfare, and use of antimicrobials in the herd.

Indicated rules of thumb corresponded to the most frequent culling reasons. Since the culling reasons reported by farmers have not changed in the new policy environment, it seems that the rules of thumb followed by farmers have remained the same. This may have been caused by the nature of rules of thumb that may be linked to cognitive anchors. Such cognitive anchors could result in conservatism, indicating the tendency to revise initial beliefs insufficiently in new decision situations (Tversky and Kahneman, 1974). Hence, it is important for farmers and their advisors to be aware of this potential pitfall of conservatism within common rules of thumb and constantly evaluate the effectiveness of these rules of thumb and the associated culling strategy (Radke and Lloyd, 2000). This is especially important when farming circumstances change, such as the implementation of the phosphate legislation in the Netherlands.

In terms of the response rate, out of 12,000 subscribers to this newsletter, only 207 (less than 2%) did participate in the survey. Of these, only 71 farmers completed the whole survey. This low response rate can be attributed to the fact that the target population was not actively invited but rather had to opt into participation. We also do not know how many farmers actively read the newsletter.

Most of the respondents were relatively young farmers between the ages of 18 to 55 years. This was in contrast to the national statistics where most farmers were older and above the age of 55 years (Beldman et al., 2020). This was also reflected in the fact that 40% of the respondents were not completely responsible for the culling decisions (Appendix 2: Figure A). This indicated that there was a selection bias in this study. One possible explanation for this could be the fact that the survey was sent out through an online newsletter whereas the older farmers might prefer a printed version of the newsletter. A result of this deviation from the national average might result in bias in the views reported by the farmers. For example, younger farmers might show more readiness to change their culling strategy and adjust their replacement stock quantities. Another consequence might be that since some of the reporting farmers were young and not completely responsible for the culling decisions (see Table 4.1; Decision responsibility variable), the views expressed by this group might represent the future perspectives of dairy farmers. Future surveys on this subject could be presented in printed postal forms or through focus groups to avoid selection bias in age of target population.

Moreover, the self-reported herd size mean of the responding farmers was 146 cows compared to the national average herd size of 106 indicating that the participating farms were of larger size (CBS, 2021). The average intensity of the responding farms was 2.39 dairy cows per ha which was slightly higher than the national average intensity of 1.77 cows per hectare in 2021 (CBS, 2021). Most of the herd average age at first calving reported (20–24 months) was also lower than the national average of 26 months. These comparisons suggested that the responding farmers might have more intensive farms compared to the overall situation in Dutch dairy farms. This deviation from the national average could mean slightly different perspectives on culling compared to the general situation in the Netherlands. The self-reported culling rates by the responding farmers had a mean of 15%. This figure was excluding the sale of animals to other farms and death or euthanasia on the farm. Considering the exclusion, which accounts for about 5% of all dairy culling, the reported culling rate was comparable to the culling rate of 2021 which was 22% (CBS, 2021). Therefore, although the sample means for herd size and farm intensity in respondents were different from national data, the overall culling rate was representative of the current Dutch dairy farming situation.

4.5 Conclusion

In general, this study provided insights into the perspectives of dairy farmers regarding the culling decisions (reasons and strategies) that they make on the farm. As such, the responding farmers did have the intention to alter the culling rate on their farms for improving the economic gains and the longevity of cattle on their farms. The perceptions regarding the main culling reasons and strategies seem to not have changed since the implemented policy changes that have imposed additional production restrictions. Given the altered production circumstances, the question remains whether not changing the culling reasons and strategies results in economically beneficial decisions for the farmers. It is, therefore, important that farmers and their advisors are aware of this and regularly evaluate the economic effectiveness of applied culling reasons and strategies while taking the health and well-being of the herd into account.

Appendix 1

Survey Questionnaire: Royal GD/ Actueel Rund newsletter (December 2021)

<English Version>

Cover letter

First of all, thank you for taking the time to complete this questionnaire!
For this research we are looking for Dutch dairy farmers who want to share their experience and opinion about the considerations they make when deciding to remove/cull dairy cows. With your answers you will help us gain insight into the culling reasons and strategies used within the Dutch dairy sector.
It will take you ±15 minutes to complete and the questionnaire is divided as follows:

- Reasons for culling recently culled dairy cows
- Using Culling Strategies
- General information of your company

This questionnaire is part of a joint study by the Faculty of Veterinary Medicine of Utrecht University, Wageningen University and Royal GD. The results are exclusively analyzed at national level, which guarantees your anonymity.
If you are interested in the results, you can enter your e-mail address at the end of the questionnaire.
20 choice gift cards of €25 will be raffled among the completed questionnaires.
You can start the questionnaire by clicking the arrow at the bottom right of the screen.

Introduction

Information about the purpose, time, and content of the survey.

1 Culling reasons of recent culled cows

Q1.1 The next questions are about recent culled cows.

In this research we are curious about reason(s) why a cow leaves your farm. We are not interested in cows who died a natural dead, were euthanized, or bred for export.

Q1.2 According to your estimation, how many cows did you replace in 2021? (Please exclusive the cows which were bred for export, died a natural dead or were euthanized.)

_____________ Dairy cows

Q1.3 Are you responsible for the culling decisions on the farm?

Yes (1)

Partly, I am responsible together with someone else. (2)

No, someone else takes these decisions. (4)

Q1.4 Do you remember your most recently culled primiparous cow?

(We are not interested in culled cows which were bred for export or culled because of a natural death of euthanasia.)

Yes (1)

No (2)

Display this question: If Q1.4 = No is not selected

Q1.5 What were the reasons specifically for culling this cow?

Problems related to reproduction (1)

Elevated somatic cell count or mastitis (2)

Lameness or hoof disorders (3)

Low milk production (4)

Maladjusted behavior such as aggressiveness (5)

Udder conformation and/or size (6)

Reducing herd size for example due to phosphate rights (7)

Others:_______ (8)

Display this question: If Q1.4 = No is not selected

Q1.6 When did you decide to cull this cow?

After calving (1)

After insemination (2)

At the end of the lactation (5)

After treatment (did not recover) (3)

Other:__________(4)

Display this question: If Q1.4 = No is not selected

Q1.7 Was the cull of this cow a sudden unforeseen event? (In other words, was the decision for culling this cow made within a week before the actual culling date?)

Yes (1)

No (2)

2. Multiparous cow

Q2.1 Do you remember your most recently culled multiparous cow?

Yes (1)

No (2)

Display this question: If Q2.1 = No is not selected

Q2.2 What was the parity number of this cow?

2nd (1)

3rd (2)

4th or more (3)

Display this question: If Q2.1 = No is not selected

Q2.3 What were the reasons specifically for culling this cow?

Problems related to reproduction (1)

Elevated somatic cell count or mastitis (2)

Lameness or hoof disorders (3)

Low milk production (4)

Maladjusted behavior such as aggressiveness (5)

Udder conformation and/or size (6)

Reducing herd size for example due to phosphate rights (7)

Others:_______ (8)

Display this question: If Q2.1 = No is not selected

Q2.4 When did you decide to cull this cow?

After calving (1)

After insemination (2)

At the end of the lactation (5)

After treatment (did not recover) (3)

Other:__________ (4)

Display this question: If Q2.1 = No is not selected

Q2.5 Was the cull of this cow a sudden unforeseen event? (In other words, was the decision for culling this cow made within a week before the actual culling date?)

Yes (1)

No (2)

3. Culling strategies

Q3.1 In this section, we would like to know more about the usage of culling strategies on your dairy farm.

Q3.2 According to you, which reasons are the most frequent with respect to the risk of culling? (Please indicate your top 3)

Problems related to reproduction (1)

Elevated somatic cell count or mastitis (2)

Lameness or hoof disorders (3)

Low milk production (4)

Maladjusted behavior such as aggressiveness (5)

Udder conformation and/or size (6)

Availability of good replacement heifer (7)

Reducing herd size for example due to phosphate rights (8)

3.3 According to you, which reasons are the least frequent with respect to the risk of culling? (Please indicate your top 3)

Problems related to reproduction (1)

Elevated somatic cell count or mastitis (2)

Lameness or hoof disorders (3)

Low milk production (4)

Maladjusted behavior such as aggressiveness (5)

Udder conformation and/or size (6)

Availability of good replacement heifer (7)

Reducing herd size for example due to phosphate rights (8)

Q3.4 The next questions are represented as statements regarding your current culling strategy. Please indicate the degree to which you agree or disagree with the statements by selecting the suitable option.

Q3.4_1 "I have a clear long term culling plan on my farm"

Strongly agree (1)

Somewhat agree (2)

Neither agree nor disagree (3)

Somewhat disagree (4)

Strongly disagree (5)

3.4_2 "I consider the culling strategy on my farm to be optimal"

Strongly agree (1)

Somewhat agree (2)

Neither agree nor disagree (3)

Somewhat disagree (4)

Strongly disagree (5)

Q3.4_3 "The culling decisions I make are unavoidable"

Strongly agree (1)

Somewhat agree (2)

Neither agree nor disagree (3)

Somewhat disagree (4)

Strongly disagree (5)

Q3.4_4 "When deciding to cull a cow, I follow specific rules of thumb/ guidelines (laid down criteria)"

Strongly agree (1)

Somewhat agree (2)

Neither agree nor disagree (3)

Somewhat disagree (4)

Strongly disagree (5)

Display this question if Q3.4_4 = strongly agree; Or Q3.4_4 = somewhat agree; Or Q3.4_4 = neither agree nor disagree is selected.

Q3.9 Which criteria are mainly used by the decision for culling a primiparous cow?

Reproduction (1)

Milk production (2)

Udder health (3)

Body conformation (4)

Claw health (5)

Breeding value (6)

Other:____ (7)

Display this question if Q3.4_4 = strongly agree; Or Q3.4_4 = somewhat agree; Or Q3.4_4 = neither agree nor disagree is selected.

Q3.10 Which criteria are mainly used by the decision for culling a multiparous cow?

The same criteria as for primiparous cows (1)

Reproduction (2)

Milk production (3)

Udder health (4)

Body conformation (5)

Claw health (6)

Breeding value (7)

Other:____ (8)

4. Future strategies

Q4.1 In this section, we would like to know your intentions regarding prospective culling strategy. A few statements will be displayed regarding the changes to the culling strategy. Select the appropriate intention as per your preference.

Q4.2 Statement 1: "I intend to alter my culling strategy for primiparous cows"

Yes, I will cull primiparous cows quicker (1)

Yes, I will cull primiparous cows less quick (2)

No, I don't want to change my culling strategy (3)

Q4.3 Statement 2: "I intend to alter my culling strategy for multiparous cows¨

Yes, I will cull the multiparous cows quicker (1)

Yes, I will cull the multiparous cows less quick (2)

No, I don't want to change my culling strategy (3)

Q4.4 Statement 3: "I intend to alter the percentage of culled cows in the next year"

Yes, I will increase the percentage of culled cows (1)

Yes, I will decrease the percentage of culled cows (2)

No, I don't intend to alter this percentage (3)

Q4.5 Statement 4: "I intend to alter the amount of replacement stock in the next year"

Yes, I will increase the replacement stock (1)

Yes, I will decrease the replacement stock (2)

No, I don't intend to alter this amount (3)

Display this question if Q4.4 = Yes, I will decrease the percentage of culled cows.

Q4.6 Why do you think reducing the culling on your farm will be advantageous for you in the future? (Select all choices that apply.)

Culling less cows ensures...

A farm management which matches better with my current vision (1)

An improved longevity (2)

An improved environmental sustainability of my farm (3)

An increased economic result. (Expanding is part of this choice) (4)

Other:_____ (5)

5. Basic information

In the last part we would like to know more about you and your farm.

Q5.1 What is your age group?

18-35 years old (1)

36-55 years old (2)

More than 55 years old (3)

Q5.2 What is the type of your dairy farm?

Conventional (1)

Organic (2)

Other: (such as research/education, etc) (3)

Q5.3 How much land is in use for your dairy farm?

Please provide in hectares. _________ha

Q5.4 Does your farm have an automatic milking system (AMS)?

No, I use a conventional milking system (1)

Yes, I use AMS (2)

Partly, I use and AMS and a conventional milking machine (3)

Q5.5 Do you also breed and rear your own replacement stock?

Yes, I breed and rear my own replacement stock (1)

Yes, I breed my own replacement stock, however I do also purchase replacement animals (2)

No, my own bred replacement stock is reared on another location by someone else and will be back on my farm as heifer (3)

No, my own bred replacement stock is reared by someone else, and I purchase replacement animals (4)

No, I purchase all the replacement stock (5)

Q5.6 What is the average age of first calving (ALVA) in months on your farm?

20 to 24 months (1)

25 to 27 months (2)

28 to 32 months (3)

Older than 32 months (4)

Q5.7 What was the herd average 305-milk production of your farm in 2021?

______________ kg milk

Q5.8 What is the average herd age on your farm?

Please provide in years + months ________________

Q5.9 The last questions are about data that is also available in I&R (entry/exit data) namely, the amounts of cattle on your farm. If you give permission for usage of the I&R data by providing your UBN, you will skip these questions.

Q5.10 Do you give permission for the use of the I&R data of your dairy farm for this research?

Yes (1)

No (2)

Display this question if Q5.10 = Yes is selected

Q5.11_4 What is your uniek bedrijfsnummer (UBN)? (Unique Identifier of farms)

____

Display this question if Q5.10 = Yes is not selected

Q5.11_1 How many milking cows are present on your dairy farm currently? (Inclusive the dry cows)

__________ Dairy cows

Display this question if Q5.10 = Yes is not selected

Q5.13 How many own bred female calves, younger than 1 year, are available for replacement of your dairy cows?

__________ Young stock

Display this question if Q5.10 = Yes is not selected

Q5.14 How many own bred heifers/replacement animals, older than 1 year, which have not calved before are available for replacement of your dairy cows?

_________ Replacement animals

Display this question if Q5.10 = Yes is not selected

Q5.14 How many replacement animals did you purchase in 2021?

_________ Cows

6. End

Q6.1 This is the end of the survey; we would like to thank you a lot for filling in the survey.

Q6.2 Would you like to be provided with a follow up and participate with the drawing of the gift cards?

Yes, I want both (1)

I would only like to be provided with a follow up of the research (2)

I would only like to participate with the drawing of the gift cards (3)

No, I'm not interested (4)

Display this question if Q6.2 = No, I'm not interested) is not selected

Q6.3 Please fill in your e-mail address below.

Q6.4 We would like to thank you for finishing this survey.

Appendix 2

Associations

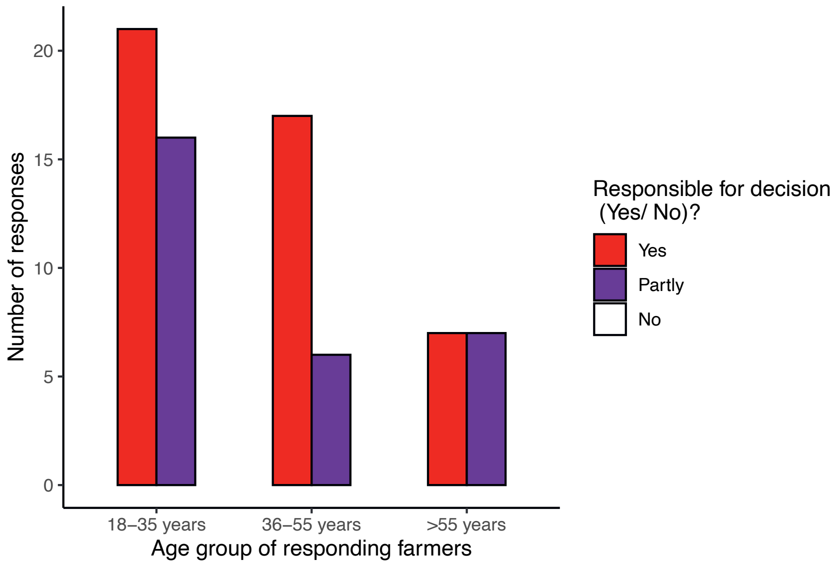
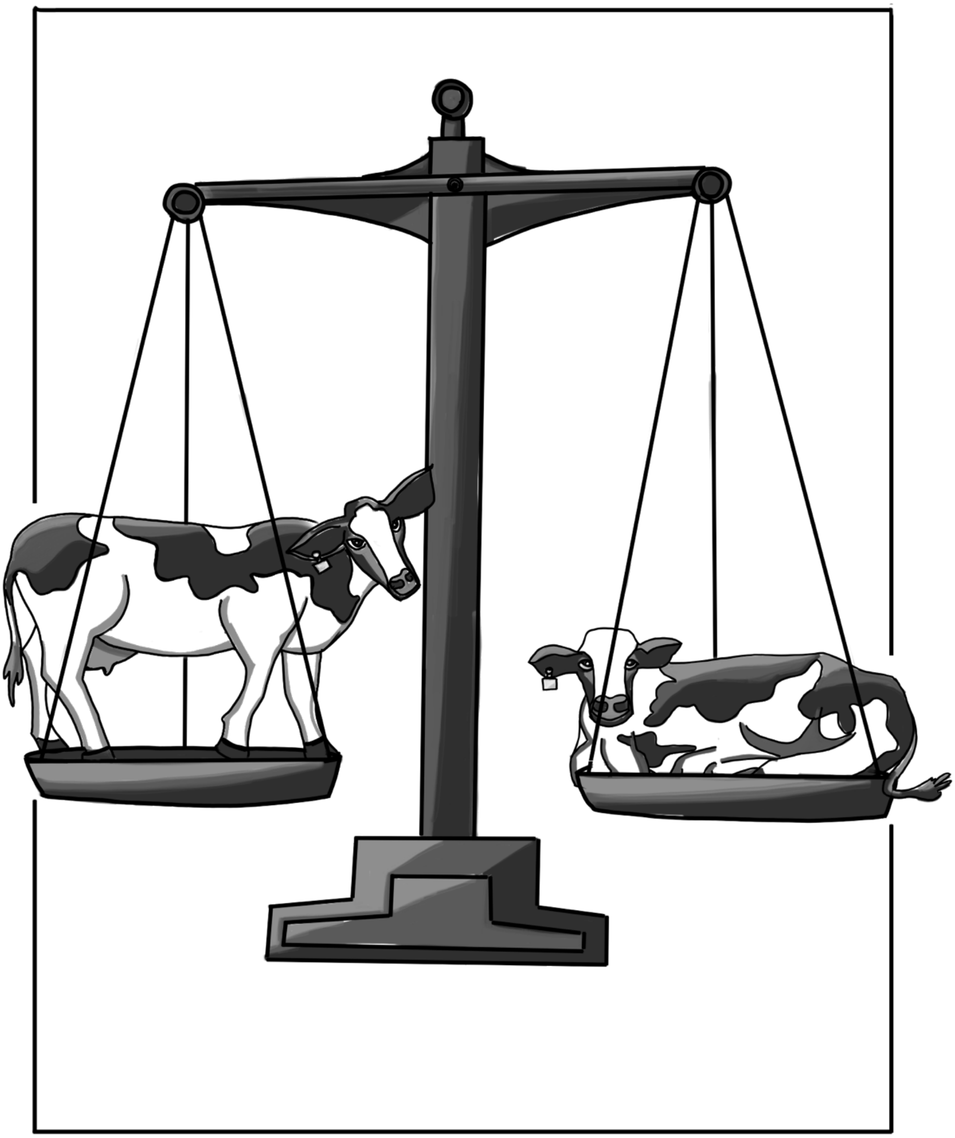


Figure A. Distribution of culling decision responsibility vs. age group of responding farmers

CHAPTER 5



Economic impacts of constrained replacement heifer supply in dairy herds

Kulkarni P. S., Haijema R., Hogeveen H., Steeneveld W., Mourits M.C.M

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Abstract

In recent years, environmental policies, especially in North-western European countries have put pressure on the total livestock on a dairy farm. On closed dairy farms this primarily has resulted in a reduction of the heifer rearing unit to maintain the production unit. The economic consequences of constrained replacement heifer supply on herd level have not been investigated. The objective of this study is to study on herd level the economic impact of suboptimal replacement decisions due to a constrained replacement heifer supply. In this study, we combine a single-cow MDP (Markov Decision Process) optimization model with dairy herd dynamics simulation of 10 years to account for the interdependency among dairy cows within the herd of 100 cows. Besides the base scenario of following optimal replacement policy, we simulated three input scenarios of constrained, excess, and variable replacement heifer supply. In the base scenario, optimal replacement policy resulted in a herd gross margin of €260,000, 17% voluntary replacement rate, 14% involuntary disposal rate annually for a herd of 100 cows. Constrained as well as excess heifer supply resulted in lower gross margins of €164,000 and €245,000 respectively, compared to the base scenario. Constrained heifer supply also resulted in 36% reduction of herd size, increase in involuntary disposal (17%) and no replacements (0.2%) on average per year. Variable heifer supply scenario resulted in slightly lower gross margins (€250,000), lower voluntary replacement rate (12%), higher involuntary disposal rate (17%) but did not result in reduction of herd size, compared to the base scenario. In conclusion, we developed a combination of cow level optimization with a herd level simulation to study the economic impacts of constrained replacement heifer supply. We found that severely constrained, excess, and variable heifer supply result in reduced herd average gross margin. A direct trade-off between replacement stock and producing cows as well as increase in risk of involuntary disposal without replacement were observed. Optimization replacement policy in case of limited heifer availability requires an inter-cow comparison to determine which cows need to be replaced first as this study shows. By demonstrating a simplified approach of combining individual cow optimization with herd dynamics simulation, we accounted for the inter-dependencies within herd. Such an approach can be instrumental in studying environmental impacts, longevity, and welfare of cows when heifer supply is constrained on a herd level.

Keywords

Heifer supply, cow replacement, multi-component optimization, retention pay-off, inter-cow comparison.

5.1 Introduction

Replacement decisions have a major effect on dairy farm profitability. Dynamic programming and marginal net revenue maximization have been used in the past (De Vries, 2004; Groenendaal et al., 2004; Kristensen, 1987; Van Arendonk, 1985) to identify optimal replacement decisions by maximization of the present and future profitability of the producing cow. These cow level (or cow place) models were built under the framework of asset replacement theory in industrial inventory management (Dijkhuizen et al., 1985; Lehenbauer and Oltjen, 1998). However, dairy cow replacements differ from regular industrial assets due to non-identical replacement heifers, presence of genetic improvement in subsequent generation of cows, unpredictability in length of lactation, variability in production and reproduction performance, seasonality of performance and presence of risk for forced disposal of producing animals due to health issues (van Arendonk, 1991; Van Arendonk, 1985). Due to these systematic differences, a vast amount of long-term modelling data on production, reproduction and health performance of cows is required to sufficiently represent a diverse group of producing cows. Over the past 5 decades, several attempts have been made to optimize replacement decisions for a single cow within a herd (detail review by Nielsen and Kristensen, 2015).

An underlying key assumption of these single cow replacement models is a 100% availability of a full-grown replacement heifer when a culling decision is made. This makes the determination of the optimal replacement moment of an individual cow independent of the state of other cows in the herd, as there is no competition for the same limited resource (replacement heifer availability). This single-cow assumption provides optimal replacement guidance by comparing the expected future profitability (discounted net present value) of the cow currently in the herd with that of a replacement heifer entering the herd, resulting in the so-called retention pay off (RPO) values. However, most dairy farming practices in western Europe follow a closed herd system wherein, replacement heifer supply stems from the breeding and rearing of own female calves. In practice this can result in a surplus or shortage of replacement heifers, depending on herd dynamics.

At present, new agricultural policies in North-western Europe are being implemented to reduce the environmental impact of dairy and other livestock farming systems. For example, the phosphate rights system (Kulkarni et al., 2021, 2023) as implemented in the Netherlands since 2017-18 puts pressure on dairy farmers to reduce the total number of livestock (i.e., to reduce mineral excess from manure) on their farms. Such an environment-oriented policy will motivate farmers to especially restrict the number of non-productive youngstock and thus the availability of replacement heifer stock on dairy farms. Consequently, optimization of replacement decisions based on the assumption of 100% heifer availability is increasingly at odds. A reduction in the replacement heifer supply might mean that farmers are unable to make optimal or near-optimal replacement decisions and therefore incur losses due to a sub-optimal replacement policy.

Formerly, Ben-Ari and Gal (1986) attempted to reformulate the optimization of replacement decisions with constraints on supply of replacement heifers by approximating a multi-component parameter optimization setup. By a multi-component setup all dairy cows in a herd are simultaneously considered for replacement, hence accounting for the interdependency among dairy cows competing for the same limited supply of replacement heifers. Kristensen (1992) further developed these multi-component approaches by a combination of optimization and simulation strategy to find an approximately optimal policy. However, these studies showed that obtaining optimal solutions was computationally prohibitive and did not provide exact solutions. A simplified decision support tool based on Markov chain simulations was developed by Cabrera (2010) to circumvent the complexity of the multi-component optimization models. Other attempts using techniques such as linear programming, genetic algorithm and network modelling improved the modelling approaches in literature but remained theoretical (de Vries, 2005; Houben et al., 1995; Yates and Rehman, 1998). Therefore, optimization of dairy cow replacement decisions under constraints on availability of suitable heifers was not considered in existing replacement decision-optimization models. De Vries and Marcondes (2020) noted a lack of objective formulation precisely for a herd of cows in the optimization problem. It is difficult to account for herd level constraints on a single cow replacement without increasing the complexity of the optimization model. It is also equally problematic to account for herd level factors such as whether replacing a cow immediately is better than retaining the cow a while longer when there is a lack of heifer supply. Therefore, the question remained to what extent a single component (cow-level) optimal replacement policy is applicable on a multi-component (herd-level) decision problem.

The aim of this study is to study on herd level the economic impact of suboptimal replacement decisions due to a constrained replacement heifer supply by combining a single-cow MDP (Markov Decision Process) optimization model with dairy herd dynamics simulation modelling to account for the interdependency among dairy cows within the herd.

5.2 Materials and Methods

5.2.1 Modelling framework

In this study, the modeling framework employed consists of three modules: (i) a cow-place optimization module, (ii) an inter-cow decision module, and (iii) a herd simulation module, as depicted in Figure 5.1.

decision policy and a Retention Pay-Off (RPO; see 5.2.1.1 for details) value for a single cow place. The inter-cow decision module decides subsequently whether the individually optimized decisions for each cow can be exercised given the number of available heifers at herd level. To account for the interdependency among dairy cows competing for the same limited supply of replacement heifers, this module ranks the dairy cows within the herd by their RPOs (as derived from the cow place optimization module). If not, enough heifers are available, only those cows with the highest ranks (lowest RPO values) are replaced. Finally, in the herd simulation module the state dynamics of each cow is simulated, driven by the for the heifer supply corrected optimal decision policy. The final cow state transition results and the expected candidate cows for replacement are fed back to the inter-cow decision module to start the next month's evaluation, explaining the indicated interaction between the modules in the Figure 5.1. The main purpose of the herd simulation module is to evaluate the economic impact of the replacement decision policy at the herd level.

Detailed information about the three modules is provided in 5.2.1.1, 5.2.1.2 and 5.2.1.3 respectively.

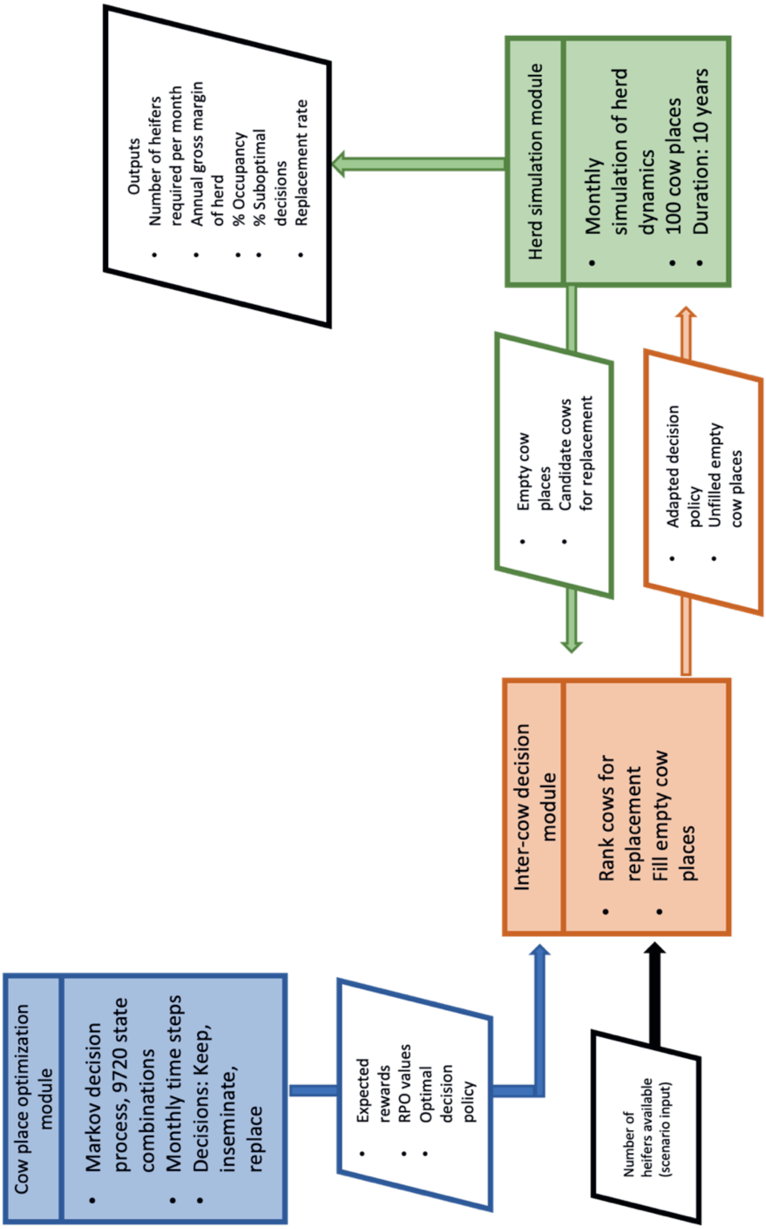

Figure 5.1. Modelling framework of this study with three modules and their direction of interaction showing inputs and outputs

The cow place optimization module optimizes the monthly reoccurring decisions on whether to keep, keep and inseminate, or replace a cow occupying a cow place, under the assumption of 100% heifer availability. This module will output an optimal replacement and insemination

5.2.1.1 Cow place optimization module

The functionality of this module (Figure 5.1) is to indicate the best decision to make for a single cow place, assuming there is always a heifer available to implement the best decision. The modelled optimization problem fits to the framework of Markov Decision processes (MDP; Puterman, 2014). Below we discuss the main components of the modelled MDP.

States and Decisions

The state of a cow place reflects the state of the cow that occupies the cow place, which is defined in this study by a 4-dimensional state vector $s = (s_1, s_2, s_3, s_4)$, where:

- $s_1 \in S_1 = \{1,2,\ldots,12\}$ = lactation number,
- $s_2 \in S_2 = \{1,2,\ldots,18\}$ = number of months in lactation,
- $s_3 \in S_3 = \{0,1,\ldots,9\}$ = number of months in pregnancy,
- $s_4 \in S_4 = \{1,2,\ldots,10\}$ = relative milk production capacity.

The above state description captures all relevant historic information on the cow.

The state space is denoted by S and indicates with combinations of s_1, s_2, s_3, and s_4 are feasible. Note s_4 is discretized as the relative milk production in 10 classes, which of milk yield between 76% to 124% of the mature herd average milk production.

Biologically feasible combinations of levels of the four state variables resulted in a state space of 9,720 unique state combinations for each cow place. The formulation of state variables was in line with previous works of Demeter et al. (2011) and Van Arendonk (1985), details can be found in Appendix 1.

Every month, the following decisions (d) for a cow currently occupying the cow-place in the herd are considered:

- $d = 1$: “Keep”: decision to keep the cow.
- $d = 2$: “Inseminate”: decision to keep and (re-)inseminate the cow.

- $d = 3$: “Replace”: decision to replace the cow by a new heifer.

$D(s)$ is the decision space, that limits the possible decision to those that are feasible in state s. The decision to inseminate ($d = 2$) is only possible in certain states (s: $\{s_1 < 12\ AND\ s_2 \in \{3,4,5,6,7,8,9\}\ AND\ s_3 = 0\}$) i.e. when the month in lactation (s_2) is between 3rd and 9th month and the cow is non pregnant ($s_3 = 0$ months). Decisions to keep and replace are possible in all the state combinations.

State transitions, transition probabilities and events

For the cow place, the current state s transitions into state s' when a decision d is made, depending on the transition probabilities for each feasible state s. These $s \rightarrow s'$ transition probabilities are derived from the probability matrix $P(s'|s,d)$ which depends on the current state, the decision, and the marginal probabilities of two separate stochastic events, i.e., involuntary disposal (e_{ID}) and successful conception upon insemination (e_C).

Involuntary disposal is defined as forced disposal of the cow for all the reasons other than a voluntary replacement decision (replace). Failure to conceive within the insemination window of 9 months (i.e., between 3rd and 9th month in lactation) also resulted in involuntary disposal after end of the current lactation (s_2= 18). The monthly marginal probabilities of the involuntary disposal event are based on an expansion of marginal probabilities of involuntary disposal used by Demeter et al. (2011) for 18 months in lactation (see Appendix 1). The event of conception is defined as successful conception of the cow in the cow place after insemination decision (inseminate). The marginal probabilities of conception are also adapted from Demeter et al. (2011) (see Appendix 1).

Expected immediate rewards.

Based on the decision made, the cow place transitions into a new state while generating a corresponding reward. The expected rewards for each decision in each stage depends on the monthly milk production of the cow occupying the cow place, the price of milk (fixed input) and the feed requirement of the cow. The monthly milk yield and the feed requirement are state dependent inputs and are calculated for each state combination (see Appendix 1). Economic inputs in terms of milk price, feed cost, cost of rearing a replacement heifer, calf revenue, monthly cost of insemination and carcass value of replaced cow are presented in Table 5.1.

Table 5.1. List of economic inputs used in the modelling framework with sources.

Input variable	Unit	Price	Source
Milk price	€/kg	0.355	Average from WECR for standard milk (4.36% fat; 3.54% protein); (WECR, 2021)
Feed cost	€/1000 VEM	0.1779	Average of summer and winter ration from (Mostert et al., 2018)
Calf revenue	€/animal	45	(WECR, 2021)
Carcass Value	€/kg slaughter weight	2.4	Agricultural prices 2020 (WECR, 2020)
	€/1st parity animal	784.8	Body weight of 545kg (60% dressing percentage)
	€/2nd parity animal	856.8	Body weight of 595kg (60% dressing percentage)
	€/3+parities animal	936	Body weight of 650kg (60% dressing percentage)
	Involuntary disposal	0	Assumption; authors' expertise
Heifer rearing cost	€/heifer	1567	(Mohd Nor et al., 2012)
Heifer market price	€/heifer	1077	(WECR, 2021)
Insemination costs	€/month	42.9	(WECR, 2021)

The rewards per decision were calculated by using the following equations:

$$R(s,d) = \begin{cases} MR(s) - FC(s) - \sum_{s' \in S} H \cdot P(s'|s,d), & if\ d = 1\ AND\ s_3 \neq 9 \\ MR(s) - FC(s) + CR - \sum_{s' \in S} H \cdot P(s'|s,d), & if\ d = 1\ AND\ s_3 = 9 \\ MR(s) - FC(s) - IC - \sum_{s' \in S} H \cdot P(s'|s,d), & if\ d = 2 \\ MR(s) - FC(s) + CV(s) - H - \sum_{s' \in S} H \cdot P(s'|s,d), & if\ d = 3 \end{cases} \quad (1)$$

In Equation (1), $R(s,d)$ represented the immediate expected reward when decision $d \epsilon \{1,2,3\}$ is taken in the current stage s , and $MR(s) - FC(s)$ are the milk returns (milk revenues minus feed costs) from the cow or a heifer in the cow place. $P(s'|s,d)$ is the probability of encountering the involuntary disposal event in the current stage, H is the cost of rearing a replacement heifer, CR is the calf revenue, IC are the monthly insemination costs, $CV(s)$ is the carcass revenue of culled cow in the current state.

Bellman equations

The stochastic decision process follows the Markov property. Typically, an optimal decision depends on the state of the cow (place) and maximizes the sum of the expected immediate and the expected discounted future rewards. Like previously developed optimization models for replacement decisions (for example, see Kristensen, 1987), this single component module assumes unrestricted availability of replacement heifers suitable for immediate replacement when a replace decision is taken.

The output from the optimization module is in terms of optimal decision policy for all feasible state combinations. The optimal replacement and insemination policy is obtained by solving the relative state values $V(s)$ from the set of Bellman equations (Bellman, 1953; Bellman and Kalaba, 1957) using a value iteration algorithm (Puterman, 2014).

$$\forall s \in S: \quad V(s) = \max_{d \epsilon D(S)} \left[R(s,d) + \textstyle\sum_{s' \epsilon S} P(s'|s,d) \cdot \gamma \cdot V(s')\right] \tag{2}$$

where, $P(s'|s,d)$ is the transition probability of going to state s', when in state s decision d is taken. The immediate reward associated to these transitions is $R(s,d)$, see equation (1). γ is the discount factor for rewards and $V(s')$ is the value of the new state s'. The discount factor γ in this study was set at $0.95^{\frac{1}{12}}$ per year (0.46% per month; see van Arendonk, 1985).

The module was developed and deployed using R 3.6.3 and the package “MDPtoolbox” version (Chadès et al., 2014).

Retention Pay-off (RPO) values.

Along with the optimal decision policy, the Retention Pay-off (RPO) values of the states are also calculated. RPO is defined as the expected rewards from keeping a cow for at least one more month instead of immediate replacement with a heifer (Demeter et al., 2011; Houben et al., 1994).

$$RPO(s) = \left[R(s,d=1) + \textstyle\sum_{s' \epsilon S} P(s'|s,d=1) \cdot \gamma \cdot V(s')\right] - \left[R(s,d=3) + \textstyle\sum_{s' \epsilon S} P(s'|s,d=3) \cdot \gamma \cdot V(s')\right] \tag{3}$$

In Equation (3), the RPO represents the Retention Pay-Off, which is the difference in present value of the current and future rewards, given the state and decision to either keep or replace. Therefore, an RPO below zero indicates the optimal decision to replace.

5.2.1.2 Inter-cow decision module

To study the effects of constrained heifer supplies, the inter-cow decision module was developed (Figure 5.1). This inter-cow decision module uses the input information from the cow place optimization and from the herd simulation modules (details in 5.2.1.3). The required input information consists of the optimal decision policy assuming unlimited heifer supply, the number of candidate cows for replacement in each month (RPO < 0), the number of empty places in the herd (because of an involuntary disposed cow without replacement in previous month) and the number of available heifers as defined by scenario input.

In each time step, the module first attempts to fill the empty places in the herd with the available heifers. Secondly, depending on the number of heifers remaining available after filling those empty places, it compares the candidate cows for replacement based on their RPO values by ranking them in ascending order. Based on the number of heifers available, the top ranked candidate cows (cows with the lowest RPOs) are replaced, whereas for all the remaining candidate cows, the optimal “replace” decision is altered to a “keep” decision in the simulation. Subsequently, the inter-cow decision module, conveys the adapted decision policy to the herd simulation module as depicted in Figure 5.1.

5.2.1.3 Herd simulation module

The herd simulation module (Figure 5.1) represents a dairy herd with a fixed herd size of 100 cow places. Cows in the herd simulation module are represented by the same four state variables (i.e., lactation number, months in lactation, months in pregnancy and relative milk production level) as defined in the cow place optimization module. Based on a random sample of 100 actual producing herds in the Netherlands (unpublished data from Kulkarni et al. 2021), a distribution of initial values of the four state variables was established (see Appendix 2). The purpose of this distribution is to simulate cow places containing cows in different stages of life as is seen in herds in practice.

Herd level simulation consisted of monthly time steps with a total duration of 10 years (120 months). A burn-in period of 15 months was incorporated in the simulation before actual recording output. When following the optimum decision policy for each individual cow in the herd, the herd dynamics are simulated assuming a fixed herd size of 100 producing cows and an unlimited supply of replacement heifers.

The simulation of the herd dynamics is driven by the decision policy of the cow place optimization module (optimal policy) and the inter-cow decision module (adapted policy) applied to all the cow places in the herd. At the start of each time step, for each producing cow in the given cow place, a decision specific state transition is simulated based on the combination of state variables and the corresponding cow place optimal policy as derived from the optimization module. Whenever a cow occupying a cow place was replaced or disposed, if a new heifer is available, it immediately occupied the empty cow place represented by a starting state combination $s\colon \{s_1 = 1, s_2 = 1, s_3 = 0, s_4 \epsilon \{1,2, \dots 10\}\}$. If a heifer is unavailable, the cow place remained empty for the next particular time step. This process was repeated for all cow places after which the simulation proceeded to the next time step. At the end of each time step the cumulative gross margin of the whole herd were calculated based on the sum of individual realized rewards per cow per month over 10 years. In the end, the gross margin is averaged for each year thereby generating annual gross margin of the whole herd. Along with that, the number of events of involuntary disposal, the number of events of conception, and the number of voluntary replacements based on the optimal policy were recorded.

The simulation process was rerun for 10,000 simulations to generate the averages and standard deviations of the annual gross margin of the herd, the replacement rate, rate of involuntary disposal, herd average calving interval, herd average 305-day milk production, and annual average number of heifers required for replacement.

5.2.2 Evaluated heifer supply scenarios

In the base scenario, the herd simulation module simulated herd dynamics by following the optimal decision policy from the cow place optimization module without the adaptation by the inter-cow decision module. In this scenario, an unlimited heifer supply is assumed. In other words, whenever a cow is replaced, a replacement heifer immediately takes its place in the herd.

To account for variation in heifer supply, three distinct scenarios are analyzed in addition to the base scenario. In the first scenario, a constant supply of one heifer per month is considered. This severely limits the annual availability of heifers for replacement within a herd of 100 cows (replacement of not more than 12% feasible. If the total of cows involuntary disposals exceeds this rate, it results in empty cow places.

In the second scenario, a constant supply of 5 heifers per month is available for replacement. This translates to a supply of 60 heifers per year for a herd of 100 cows (replacement capacity of 60%). This scenario emulates an excess supply of heifers in the herd.

In third scenario, a variable supply of 0 to 5 heifers per month is assumed to be available for replacement. This supply is based on a discrete monthly distribution such that in total, 30 heifers are made available each year in simulation to the herd of 100 cows (distribution in Appendix 2).

All three scenarios are analyzed by performing 10,000 herd simulations similar to the base scenario (including the burn-in period of 15 months). At the end of the herd simulations of each heifer supply scenario, the same outputs as the base scenario are calculated, namely, annual gross margin of the herd, replacement rate, rate of involuntary disposal, herd average calving interval and herd average 305-day milk production. Additionally, average number of empty places in the herd per year is calculated and converted to annual percent-occupancy (where all places filled meant 100% occupancy). The average number of suboptimal decisions made per year is also calculated and converted to percent-suboptimal decisions (where, 0% suboptimal decisions means that the herd followed the optimum policy as generated by the individual cow optimization module). Moreover, the excess number of heifers remaining after each time step is recorded. The model assumes that each excess heifer is sold to the market incurring a loss of € 490 since that is the average difference between the estimated heifer rearing cost and the purchase price of replacement heifers from the market. This loss is subtracted from the annual gross margin of the herd resulting in reduced gross margin due to presence of excess heifers for replacement. At the end of the simulations, the resulting outputs are compared to the results of the base scenario to evaluate the herd-level impact of heifer availability on cow replacement.

5.2.3 Sensitivity analysis

The results of the base scenario are tested for sensitivity to uncertainty in input values such as milk prices, feed prices, carcass value and heifer rearing costs. Previous studies like Demeter et al. (2011) have shown that these variables often influence farmers' decisions to keep or replace cows in their dairy herd. A variation of ± 20% in the value of the above four variables is used in the base scenario to evaluate the sensitivity in output of the voluntary replacement rate and the annual gross margin.

5.3 Results

From Table 5.2, the overall replacement rate in the base scenario was 30.5% (voluntary replacements + involuntary disposal). Since, in the base scenario, the simulation followed the optimal policy, none of the decisions were suboptimal. Similarly, occupancy was at 100% in the base scenario since no cow places were left unoccupied. The annual gross margin of the herd was €260,700 per year in the base scenario. 62% of conceptions resulted in successful calving. Also, in the base scenario, the annual mean milk production per cow was 8,784 kg.

Table 5.2. Modelling results per heifer availability scenario indicating herd averages based on 10,000 simulations of 10 years

Output [1]	Base scenario	Heifer supply scenarios		
		1 heifer /m	5 heifers /m	0-5 heifers /m
Voluntary replacement (%)	**16.6 (1.2)**	0.2 (0.1)	17.5 (1.3)	11.6 (2.6)
Involuntary Disposal (%)	**13.9 (1.1)**	17.1 (0.6)	14.0 (1.2)	16.9 (1.5)
Suboptimality (%)	**-**	6.8 (0.5)	0.1 (0.1)	5.3 (1.9)
Occupancy (%)	**100 (0)**	64.7 (3.2)	100 (0)	99.4 (0.6)
Annual GM of herd (€/y)	**260,714 (2,447)**	164,368 (9,582.5)	245,005 (1,612)	251,070 (6,325)
Successful calving (%)	**62.3 (0.9)**	66.9 (1.4)	62.5 (1)	63.1 (1.1)
Annual milk production per cow place in herd(kg)	**8,784 (24.1)**	5,446 (28.4)	8,753 (21.1)	8,563(130)

* SD in brackets

[1] Explanation of terms in output column: Voluntary replacement, is the number of cows replaced per 100 cow-years; Involuntary Disposal, is the involuntary disposal of cows due to all reasons other than voluntary decision to replace; Suboptimality, is the percent proportion of suboptimal decisions to the total number of decisions in each simulation (100 cows X 120 months = 12,000 decisions); Occupancy, is the percent proportion of occupied cow places in a herd with 100 cow places available (100 – unoccupied cow places %); Annual GM of herd, is the annual gross margin of the herd in euros; Successful calving, is the percent proportion of conceptions that successfully result in calving at the end of gestation period; Annual milk production per cow, is the average annual milk production of cows in the simulated herd.

Compared to the base, the overall replacement rate was lower (~17%) in the scenario where one heifer was available per month (Table 5.2). Unlike that, the overall replacement rates for scenarios of five heifers available per month and variable heifer availability per month had comparable overall replacement rates of 31.5% and 28.5% respectively (Table 5.2). One heifer availability per month had the lowest estimated average annual gross margin of € 164,368.

The scenario of one heifer available per month and the variable heifer supply scenario showed some proportion of suboptimality in replacement decisions. In the one heifer available per month scenario, the herd occupancy was around 65% resulting in almost 1/3rd of the cow places in the herd being empty per year. In the remaining two scenarios, the herd occupancy was almost complete. For all of the four scenarios including the base scenario, the calving intervals did not change as per heifer availability and were around 411 days (13 months 21 days: results not shown). However, from Table 5.2, the calving success was highest for the one heifer available per month scenario (67%) but were similar for the remaining two scenarios as well as the base scenario (~63%).

5.3.1 Sensitivity analysis

From Table 5.3, the estimated average annual gross margin of the herd was highly sensitive to milk prices and heifer rearing costs. Reduction in the milk prices resulted in reduced gross margin since milk revenues formed the main part of gross margins. Increased heifer rearing costs increased the overall cost of replacement and were therefore decreased the gross margins. The voluntary replacement rate from the base scenario (optimal replacement rate) was sensitive to all four economic inputs but was highest for the carcass value and the heifer rearing costs (Table 5.3). The sensitivity to the carcass value and the heifer rearing costs stems from the fact that the replacement costs (carcass value – rearing costs) were dependent on these two inputs. Similarly, for involuntary disposal rate, sensitivity was observed mostly in carcass value and heifer rearing costs. The sensitivity of involuntary disposal to the carcass value and heifer rearing costs were opposite to the sensitivity of voluntary replacement. If heifer rearing costs increased or carcass value decreased, there was an increase in the replacement costs which discouraged the voluntary replacement rate thereby increasing the involuntary disposal rate.

Table 5.3. Summary of sensitivity analyses of base scenario to inputs of milk price, feed costs, carcass value and heifer rearing costs varying between +20% and -20%

Outputs	Base scenario	Milk price			
		80%	**90%**	**110%**	**120%**
Annual gross margin of herd	€ 260,714	-24%	-12%	+11.5%	+23%
Voluntary replacement	16.6%	-22%	-10%	+27%	+54%
Involuntary disposal	13.9%	0%	0%	0%	0%
Outputs	**Base scenario**	**Feed cost**			
		80%	**90%**	**110%**	**120%**
Annual gross margin of herd	€ 260,714	+2%	+1%	-0.8%	-1%
Voluntary replacement	16.6%	-3.5%	-4%	0%	+2%
Involuntary disposal	13.9%	-0.5%	-1.5%	-3%	-2%
Outputs	**Base scenario**	**Carcass Value**			
		80%	**90%**	**110%**	**120%**
Annual gross margin of herd	€ 260,714	-7%	-7%	0%	+2%
Voluntary replacement	16.6%	-75%	-73%	+9%	+26.5%
Involuntary disposal	13.9%	+133%	+126%	-5%	-12%
Outputs	**Base scenario**	**Heifer rearing cost**			
		80%	**90%**	**110%**	**120%**
Annual gross margin of herd	€ 260,714	+5%	+2%	-10%	-15%
Voluntary replacement	16.6%	+40%	+15%	-75%	-97%
Involuntary disposal	13.9%	-16%	-12%	+140%	+187%

5.4 Discussion

This study presents a novel approach of combining single-cow optimization and herd simulation to study on herd level the economic impact of suboptimal replacement decisions due to a constrained replacement heifer supply. The combined model considered dairy herd dynamics and interdependencies among dairy cows within the herd. In addition to the base scenario where the optimum replacement decisions were simulated assuming unlimited supply of replacement heifers, three distinct scenarios of heifer supply were simulated in the herd.

From the results, it could be seen that the annual gross margin on herd-level was lower for all three heifer supply scenarios compared to the base scenario (Table 5.2). Since the involuntary disposal was at 17% in the base scenario following optimal policy, it stands to reason to assume that at least two heifers per month are needed on average to avoid empty cow places.

To maintain optimal or near optimal gross margin of the herd required an average of three heifers per month. The reduction in gross margin in the scenarios with excess heifers (5 heifers per month and 0-5 heifers per month) were attributed to the difference in the rearing cost of heifer and the market price at which the excess heifer could be sold (€1567 - €1077 = € 490). When the heifer supply was constrained the majority of the cow replacements occurred due to involuntary disposal, whereas almost none of the voluntarily replacement decisions resulted in actual replacements. In the constrained heifer supply scenario, a lot of cow places in the herd remained empty (1/3rd of the herd size), due to the occurrence of involuntary disposal and the lack of available heifers, resulting in a forced reduction in herd size. This also resulted in lower milk production per cow place in the herd and consequently, lower gross margins of the herd (Table 5.2).

Literature on effects of excess or lack of replacement heifer supply on replacement rates is limited thereby making comparison of our results to previous studies difficult. The increase in empty cow places and subsequent decrease in gross margin of the herd, found in the heifer supply scenario of 1 heifer per month was similar to the findings of Mohd Nor et al. (2015) in which keeping less than optimal heifer stock resulted in empty cow places. In the base scenario where no constraints on heifer supply, the results could be more easily compared to the literature. The total replacement rate including involuntary disposal was 30.5% in the base scenario. This was comparable to the 28.4% culling rate estimated by the model from Demeter et al. (2011). The total replacement rate was comparable to the national culling rate reported by CRV (CRV, 2021b) of 28% in the year 2020-2021 from which most of the inputs were defined. Similarly, several studies, reported an average culling rate of 25% in the Netherlands in the past two decade which was slightly lower than the results of our base scenario (Han et al., 2022; Kulkarni et al., 2021; Nor et al., 2014b)

From the sensitivity analyses (Table 5.3), it was clear that the base scenario was sensitive to the economic inputs such as milk prices, carcass value and heifer rearing costs but not to the feed costs. This showed that the consequences of changes in market prices could change the optimal policy for replacement regardless of constrained heifer supply, which agreed with the findings of Demeter et al. (2011) and, Kalantari et al. (2010).

Unlike previous attempts to optimize the replacement decisions of cow in a multi-component system as seen in Ben-Ari and Gal (1986), de Vries (2005), Kristensen (1992) or, Yates and Rehman (1998), in the present study, the replacement decisions were optimized by a single-component optimization module and the resulting optimal policy was applied in a herd simulation module. This way, we circumvented the issue of precisely formulating the replacement decision objective on a multi-component level. The interdependency between the cows in the herds was addressed by creating an inter-cow decision module which ranked cows for replacement. Since the cow rankings are based on their RPOs, the replacement policy followed was the best possible policy (for maximizing economic gains) in presence of a constraint on replacement heifer supply. The ranking strategy was similar to the RPOs based ranking used by many previous studies (for example, see De Vries, 2006 or Kalantari et al., 2010). Since RPOs account for future profitability, in theory, the RPOs based ranking strategy should have distinct advantage over heuristic and ad-hoc replacement decisions (Groenendaal and Galligan, 2005). Kalantari and Cabrera (2012) concluded from their dairy DP model study that replacing cows with the lowest RPOs results in increased gains at herd level by improving the value of individual cow places over time.

As such, for calculating the RPOs in our optimization module, it was assumed that in the next stage the optimal policy was followed and therefore a cow with a negative RPO is replaced in the next stage assuming a heifer is available for replacement which might not be realistic (Kristensen, 1992). Thus, the negative RPOs were numerically small with not much variance which led to tied rankings in the Inter-Cow Comparison module. However, the solution of Kristensen (1992) to extend the RPOs until the next calving could not be incorporated in this study as the exact duration of calving interval varied between 13 to 18 months by design and was therefore unknown at the time of decision in the simulation module.

The optimization module designed in this study is more straightforward compared to previously published optimization models. This simplification also means that the optimization module is easier to deploy and to scale up for a herd level simulation study that accounts for interdependency between herd mates. The maximum number of feasible state combinations in the Markov decision process (MDP) of the optimization module was 9,720 with only a single level of decision optimization in an ordinary process. For example, compared to our optimization module, Demeter et al. (2011) had four levels of hierarchic MDP with 1,480,651 state combinations and Cha et al. (2014) had a three levelled MDP with 2,095,425 state combinations while incorporating health parameters. One of the major reasons for the limited success of previous optimization models being used in commercial decision support tools is the lack of user-friendliness and computational complexity (Groenedaal et al., 2004). Although the aim of this study was not to create a commercial product, in theory, the optimization module of this study can be expanded upon while being easier to understand and quick to deploy in larger more encompassing dairy models.

The constraint on supply of replacement heifers has become relevant in the recent years due to the increasing pressures from agricultural policies. For example, the Phosphate regulation of 2017 in the Netherlands, created direct competition between the producing dairy cow unit and the non-producing youngstock rearing unit to reduce phosphate production on dairy farms (Kulkarni et al., 2021). Consequently, youngstock reared by dairy farmers for future replacements was severely reduced (CBS, 2019). Future policies concerning nitrogen excretion and Greenhouse Gas (GHG) emissions will only increase the pressure on farmers to reduce the non-producing stock while optimizing production. From the results of this study, it was seen that excess heifer supply scenario was economically better compared to constrained heifer supply scenario. In practical words, from an economic perspective, having a few extra heifers is better economically than having shortage of heifer supply.

However, the societal push for improved longevity and better welfare of producing dairy cows from the consumers has also become apparent in the recent years (Galama et al., 2020; Schuster et al., 2020). For improving longevity, the replacement and culling are driven downwards thereby reducing the demand for replacement heifers and youngstock. Moreover, in this study environmental consequences such as GHG emissions, phosphate and nitrogen production of excess heifers were not considered. Stocking rate (producing cows with youngstock) is associated with GHG emissions, increased use of fertilizers, nitrogen and phosphate production (Galloway et al., 2018; Kok et al., 2017; Mourits et al., 2000; Zehetmeier et al., 2014). Therefore, a scenario wherein minimum amount of youngstock is reared by dairy farmers to prevent losses due to involuntary disposal while avoiding as much voluntary replacement as possible can occur in the near future. Further research is needed on the impact of differing levels of heifer supply while taking environmental factors into account.

5.5 Conclusion

In conclusion, this study presented a new straightforward modelling approach combining single-component cow place optimization with multi-component herd simulation for replacement decisions. This study showed that severe constraints on replacement heifer supply as well as excess heifer supply resulted in suboptimal replacement policy that reduced the herd gross margin and increased the involuntary disposal. The results of this study indicate that optimization of replacement decisions under heifer supply constraints can be performed by accounting for inter-dependency between herd mates.

Appendix 1: Details of cow place optimization module

The optimization module optimizes the monthly (stage length = 1 month) decisions taken on a cow place regarding its replacement by a suitable replacement heifer by maximizing the net present discounted revenues of the cow place over an infinite planning horizon. The method used for this optimization is value iteration-dynamic programming fit to a single layer Markov decision process.

State variables

The state of a cow place is described by the following tuple:

$$s = (s_1, s_2, s_3, s_4)$$

Four state variables were designed to represent the state of the cow place in this optimization module. The four state variables were defined as follows:

Lactation number (s_1)

Current number of lactations the cow has produced corresponding to parities. Maximum 12 in a cow's lifetime

$s_1 \epsilon$ {1, 2, ...12}

Months in Lactation (s_2)

Number of months in milk/ months completed after the recent calving for a cow. Maximum of 18 months possible with end of 18^{th} month resulting in involuntary disposal if the cow has not calved.

$s_2 \epsilon$ {1, 2, ...18}

Months in pregnancy (s_3)

Months completed after successful conception event. Maximum of 9 months corresponding to gestation period of 9 months assumed in the module. An additional level of 0 months is also included in the state space to represent cows which are not pregnant. Important to note, the cow stays at 0 months until a successful conception event is recorded. Therefore, 10 possible levels from 0 to 9 possible in this state variable.

$s_3\ \epsilon\{0,1,2,...9\}$

Permanent milk production capacity (s_4)

Permanent level of milk production capacity relative to mature equivalent of herd average. This capacity describes the magnitude of production based on monthly average milk production of the herd. 10 levels are defined from 76% to 124% production of mature equivalent of herd average as seen in Table A

Table A. Levels of permanent milk production capacity (s_4)

Categories	Value (% milk in kg)
1	<= 76
2	77-83
3	83-88
4	89-94
5	95-100
6	101-106
7	107-112
8	113-118
9	119-124
10	> 124

Hence $s_4\ \epsilon\{1,2,...9,10\}$

Each new heifer entering the herd will have a level of permanent milk production capacity (based on discretized normal distribution) that does not alter throughout its herd life. In total, there were 9720 feasible state combinations based on the levels of the 4 state variables. 9720 is less than the maximum possible state combinations since certain combinations such as, for example, cow in 1st month of lactation and 8th month of pregnancy ($s_2 = 1\ AND\ s_3 = 8$) were infeasible.

Decision space

Three decisions were possible for each time step of the cow place optimization module. These were as follows,

Keep ($d = 1$)

The decision "keep" defined the possible decision of retaining the cow for 1 more month. This decision was possible in all possible states of the cow occupying the cow place

Inseminate ($d = 2$)

The decision "inseminate" defined the possible decision to retain and inseminate the cow occupying the cow place. This decision was state-dependent and was only possible when cow was in 3rd and 9th month of lactation ($3 \leq s_2 \leq 9$) and was not in its 12th lactation ($s_1 \neq 12$). This decision was also not feasible if the cow was already pregnant ($s_3 > 0$).

Replace ($d = 3$)

The decision "replace" signified the possible decision to immediately replace the cow occupying the cow place by a replacement heifer. The replacement heifer will enter the herd immediately after "replace" decision.

$$d \in \mathrm{D} = \begin{cases} \{1,2,3\}, & \mathrm{s}_1 < 12 \; AND \;\; s_3 = 0 \; AND \; 3 \leq s_2 \leq 9 \\ \{1,3\}, & \text{else} \end{cases}$$

Events

Two stochastic events were defined for each time step, independent of the decision taken which affected the state transitions. They were:

Event of involuntary disposal (e_{ID})

This event was defined the similar as in Demeter et al., 2011 wherein replacement for any reason other than low production was deemed as involuntary disposal. The marginal probabilities for this event occurring were also similar to the ones used by Demeter et al., 2011 but were extended for 18 months in lactation (Table B)

Based on the daily energy requirements for milk production, monthly requirements were calculated.

Energy requirements for growth (VEM_{growth}) were assumed to be an additional 660 VEM per day for growth in 1st lactation cows and an additional 330 VEM per day for 2nd lactation cows (CVB, 2021) over the energy requirements of milk production

Energy requirements for pregnancy were assumed to be as follows (CVB, 2021):

$$VEM_{preg} = \begin{cases} 440\ VEM, & if\ s_3 = 6 \\ 850\ VEM, & if\ s_3 = 7 \\ 1500\ VEM, & if\ s_3 = 8 \\ 2700\ VEM, & if\ s_3 = 9 \end{cases}$$

Where VEM_{preg} is the daily requirement of energy during pregnancy and s_3 is the month in pregnancy.

Feed prices for the required feed were averages of summer and winter rations derived from Mostert et al., (2018) such that, costs per kg DM of energy requirement in VEM were calculated (Table B)

Table B. Marginal probabilities per month in lactation for involuntary disposal of producing cows

Lactation levels	Months in lactation																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.024	0.01	0.009	0.009	0.01	0.011	0.012	0.012	0.011	0.009	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
2	0.026	0.011	0.009	0.01	0.011	0.013	0.013	0.013	0.012	0.01	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
3	0.028	0.012	0.01	0.01	0.012	0.014	0.014	0.014	0.013	0.011	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
4	0.03	0.012	0.011	0.011	0.013	0.015	0.015	0.015	0.014	0.012	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
5	0.034	0.014	0.012	0.013	0.015	0.017	0.017	0.017	0.016	0.014	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
6	0.034	0.014	0.012	0.013	0.015	0.017	0.017	0.017	0.016	0.014	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
7	0.036	0.015	0.013	0.013	0.016	0.018	0.018	0.018	0.017	0.015	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
8	0.038	0.016	0.014	0.014	0.017	0.019	0.019	0.02	0.018	0.016	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
9	0.042	0.018	0.016	0.016	0.018	0.021	0.022	0.022	0.02	0.018	0.01	0.011	0.011	0.011	0.011	0.011	0.011	0.011
10	0.046	0.019	0.017	0.018	0.02	0.023	0.024	0.025	0.022	0.02	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
11	0.05	0.021	0.019	0.019	0.022	0.026	0.026	0.027	0.025	0.022	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
12	0.056	0.024	0.021	0.022	0.025	0.029	0.03	0.031	0.029	0.026	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015

Event of successful conception (e_c)

This event was defined as the chance of conception upon decision to keep and inseminate (d=2). Since reproductive cycle for insemination is 3 weeks whereas the stage length is a month, marginal probabilities for conception were adjusted monthly for months in lactation in a given lactation number. For first two months and from 10th month to 18th month in lactation, a null marginal probability was used to signify that insemination was only possible between 3rd and 9th month of lactation. The marginal probabilities were drawn from Demeter et al. (2011) such that each monthly marginal probability was a combination of detection rate of oestrus and chance of successful insemination. The distribution of monthly marginal probabilities for successful conception can be seen in Table C.

Table C. Marginal probabilities for per month in lactation for successful concretion upon insemination

Lactation number	Months in lactation																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0	0	0.41	0.5	0.47	0.48	0.47	0.45	0.45	0	0	0	0	0	0	0	0	0
2	0	0	0.44	0.54	0.51	0.52	0.51	0.47	0.46	0	0	0	0	0	0	0	0	0
3	0	0	0.46	0.56	0.52	0.54	0.52	0.48	0.46	0	0	0	0	0	0	0	0	0
4	0	0	0.46	0.56	0.52	0.54	0.52	0.48	0.46	0	0	0	0	0	0	0	0	0
5	0	0	0.44	0.54	0.51	0.52	0.51	0.47	0.46	0	0	0	0	0	0	0	0	0
6	0	0	0.43	0.53	0.49	0.51	0.49	0.46	0.46	0	0	0	0	0	0	0	0	0
7	0	0	0.42	0.51	0.48	0.49	0.48	0.45	0.45	0	0	0	0	0	0	0	0	0
8	0	0	0.4	0.5	0.46	0.48	0.47	0.44	0.44	0	0	0	0	0	0	0	0	0
9	0	0	0.38	0.47	0.44	0.45	0.45	0.42	0.43	0	0	0	0	0	0	0	0	0
10	0	0	0.37	0.46	0.42	0.44	0.43	0.41	0.42	0	0	0	0	0	0	0	0	0
11	0	0	0.35	0.43	0.4	0.42	0.41	0.39	0.4	0	0	0	0	0	0	0	0	0
12	0	0	0.34	0.42	0.38	0.4	0.39	0.38	0.39	0	0	0	0	0	0	0	0	0

Constituents of the reward function

The reward function which defined the immediate expected rewards for each state transition were based on the following constituents

Milk revenue (MR)

Milk revenue was defined as a fixed non-seasonal price of per kg of milk produced by the cow occupying the cow place. Price of milk (Q_{milk}) was calculated such that the kilograms of milk produced was assumed to contain constant fat of 4.36% and constant protein of 3.54% based on the recent data estimates.

$$MR = Milk_m \times Q_{milk},$$

Where, $Milk_m$ was the monthly milk production in kg

Monthly milk production was estimated based on daily lactation curve of a standard cow from Milk Bot model developed by Chen et al. (2022). The milk curve of a standard cow daily production ($y_{i,l}$) has the following formula:

$$y_{i,l} = a_l \left(1 - \frac{e^{\frac{c_l - i}{b_l}}}{2}\right) e^{-d_l \times i}$$

Where, i is the days in milk (DIM) such that $1 \leq i \leq 540\, days$; l is the lactation number classified as $l \in \{1, > 1\}$; (a, b, c, d) are shape and magnitude parameters of the milk curve.

From the daily milk production, monthly milk was calculated for each cow occupying the cow place depending on the permanent relative milk production capacity of the cow (s_4).

$$Milk_{m,l} = \sum_{i=1}^{30} y_{i,l} \cdot s_4$$

Feed costs (FC)

Feed costs were based on average price of summer and winter rations of producing cows and the requirement of feed in terms of energy units (VEM); where $1\, VEM = 0.0069\, Mj$.

$$FC = VEM \times FP$$

Where, FC is the feed cost, VEM is the energy requirement and FP is the feed price.

The energy requirement in VEMs were based on three requirements, namely, energy for milk production, energy for growth and maintenance and energy for pregnancy.

The energy for milk production was calculated based on daily fat-protein corrected milk $(FPCM)$ (Yan et al, 2012[1]) such that,

$$FPCM = [0.337 + 0.116 \times fat + 0.006 \times protein] \times y_i,$$

Where, y_i is the daily milk yield and i is the days in milk (DIM)

Based on milk $(FPCM)$, energy for milk production was given by:

$$VEM_{milk} = [42.4 \cdot BW^{0.75} + 422 \cdot FPCM] \times [1 + 0.00165(FPCM - 15)]$$

Where, BW is the body weight of the cow.

Initial body weights of the cows per lactation were 525 kg, 545 kg and 650 kg for 1st, 2nd and 3 or more lactation(s) respectively with a daily growth factor of 0.18 kg per month in lactation. Based on the daily energy requirements for milk production, monthly requirements were calculated. Energy requirements for growth (VEM_{growth}) were assumed to be an additional 660 VEM per day for growth in 1st lactation cows and an additional 330 VEM per day for 2nd lactation cows (CVB, 2021) over the energy requirements of milk production Energy requirements for pregnancy were assumed to be as follows (CVB, 2021[2]):

$$VEM_{preg} = \begin{cases} 440\,VEM, & if\ s_3 = 6 \\ 850\,VEM, & if\ s_3 = 7 \\ 1500\,VEM, & if\ s_3 = 8 \\ 2700\,VEM, & if\ s_3 = 9 \end{cases}$$

Where VEM_{preg} is the daily requirement of energy during pregnancy and s_3 is the month in pregnancy. Feed prices for the required feed were averages of summer and winter rations derived from Mostert et al., (2018) such that, costs per kg DM of energy requirement in VEM were calculated (Table D)

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[1] Yan, M.J., Humphreys, J. and Holden, N.M. 2011. An evaluation of life cycle assessment of European milk production. J. Environ. Manage. 92(3), pp.372-379. DOI: https://doi.org/10.1016/j.jenvman.2010.10.025

[2] CVB Feed Table 2021, [WWW Document] https://www.cvbdiervoeding.nl. Accessed 6.1.23.

Table D. Costs per kg DM calculated from average summer and winter rations (Mostert et al., 2018)

Feed ingredient	Net energy of feed (MJ/kg DM)	VEM-equi	Feed price (€/kg DM)	Summer diet (%/kg DM)	Winter diet (%/kg DM)	Price X Summer diet	Price X Winter diet	Average price	Average price per 1000 VEM
Concentrates with standard protein	7.43	1076.81159	0.24	0.21	0.2	0.0504	0.048	0.0492	
Concentrates with extra protein	7.45	1079.71014	0.28	0	0.07	0	0.0196	0.0098	FP = €0.1779
Wet by-products	7.5	1086.95652	0.12	0.04	0.05	0.0048	0.006	0.0054	
Grass	6.95	1007.24638	0.11	0.39	0	0.0429	0	0.02145	
Grass silage	6.08	881.15942	0.18	0.25	0.55	0.045	0.099	0.072	
Maize silage	6.26	907.246377	0.17	0.11	0.14	0.0187	0.0238	0.02125	
Average energy	6.945	1006.52174			Total price	0.1618	0.1964	0.1791	

$$FC = \left[VEM_{milk} + VEM_{growth} + VEM_{preg}\right] \cdot 0.0069 \cdot 0.1779$$

Carcass value $(\boldsymbol{CV})$

The carcass value of the cow which was replaced depended on the slaughter weight of the cow. The carcass value was given by assuming the slaughter weight to be 60% of the median body weight per lactation. Hence, the carcass weight for 1st, 2nd and 3 or more lactations, was 0.6 times that of 545 kg, 595 kg and 650 kg respectively. Given the market price for slaughter of dairy cow was € 2.4 (WECR, 2021), the carcass values for 1st, 2nd and 3 or more lactation cows were € 784.8, € 856.8, € 936 respectively. For involuntary disposals, no carcass value was recovered (€ 0)

Heifer rearing cost $(\boldsymbol{H})$

The heifer rearing cost was taken to be € 1567 based on the estimation of Nor et al. (2012). This included labour, housing, treatment, feeding and other losses.

Insemination costs $(\boldsymbol{I})$

The costs of insemination were derived from the WECR, 2021 report. The costs were adjusted for monthly interval such that per cow, 1.3 inseminations per month are possible (given three-week reproductive cycle of cows). Therefore, the cost per month was taken to be € 42.9 for the cow occupying the cow place.

Appendix 2: Simulation module

Simulation module of the base model simulated a whole herd of fixed size of 100 producing cows. For each cow occupying one of the cow places in the herd of 100 places, four state variables were defined. These corresponded to the state variables of the optimization module and were, lactation number, months in lactation, months in pregnancy and permanent milk production capacity. Based on the combinations of these four variables, the current state of each cow in the herd was defined.

The initial state distribution

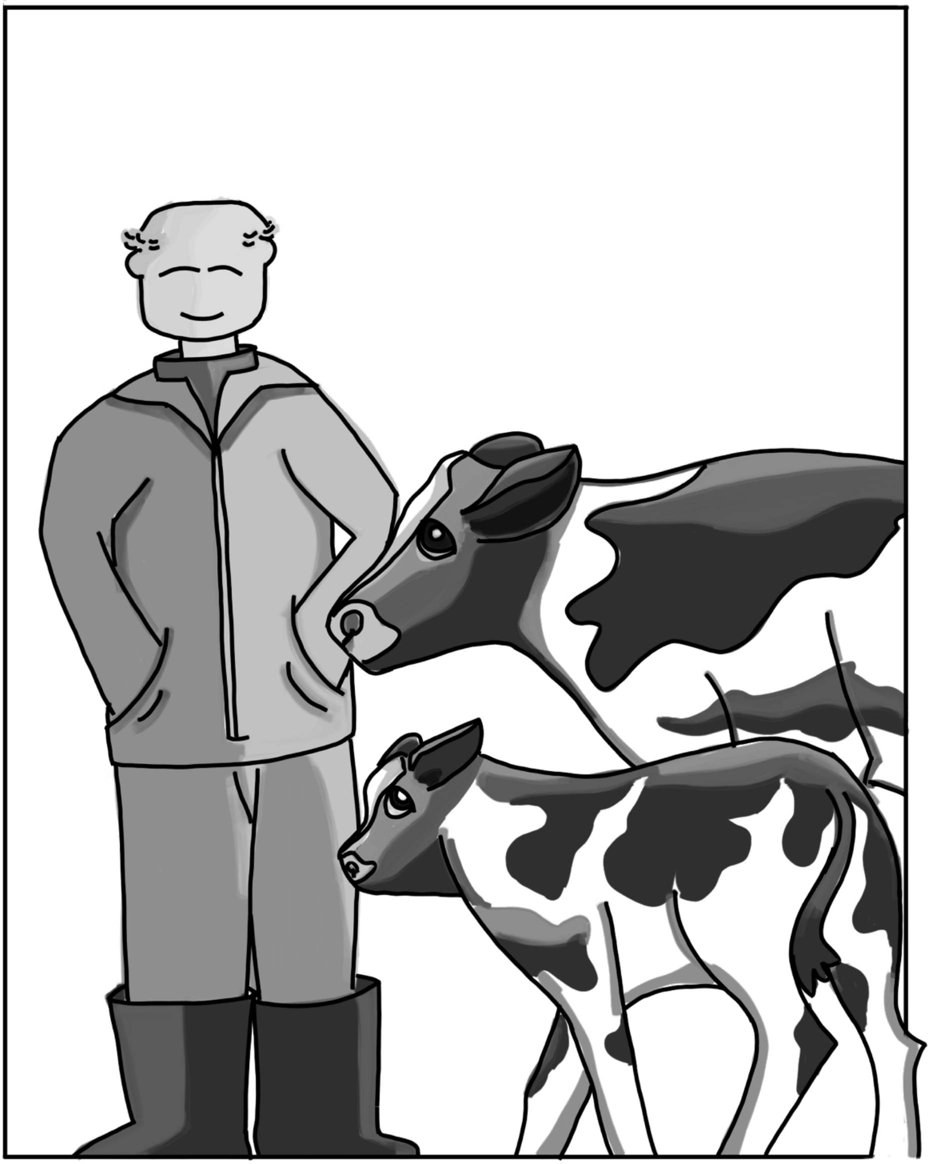
The starting states for all cows in the simulated herd were based on derived distribution observed in a random sample of 100 real-life Dutch dairy herds (CRV, 2018[3]). The resulting initial distribution can be seen in Table E.

[3] CRV. 2018. [WWW Document] Jaarstatistieken-NL. https://crvnl-be6.kxcdn.com/wp-content/uploads/2019/04/Jaarstatistieken-2018-NL-totaal.pdf. Accessed 9.5.20.

Table E. Distribution of states for initializing cows in the herd simulation

Lactation number	Months in lactation: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
1	0.0108	0.0215	0.0108	0.0215	0.0215	0.0323	0.0108	0.0108	0.0000	0.0108	0.0215	0.0215	0.0215	0.0000	0.0108	0.0000	0.0000	0.0000	0.2262
2	0.0000	0.0323	0.0107	0.0000	0.0216	0.0107	0.0107	0.0000	0.0216	0.0107	0.0107	0.0107	0.0107	0.0000	0.0000	0.0000	0.0000	0.0000	0.1505
3	0.0214	0.0108	0.0000	0.0108	0.0322	0.0214	0.0000	0.0000	0.0214	0.0214	0.0108	0.0000	0.0000	0.0000	0.0108	0.0000	0.0000	0.0000	0.1610
4	0.0215	0.0107	0.0000	0.0215	0.0000	0.0000	0.0107	0.0322	0.0215	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1181
5	0.0108	0.0000	0.0108	0.0108	0.0323	0.0216	0.0108	0.0108	0.0108	0.0000	0.0108	0.0000	0.0000	0.0000	0.0000	0.0108	0.0000	0.0000	0.1401
6	0.0216	0.0107	0.0323	0.0000	0.0107	0.0000	0.0107	0.0216	0.0107	0.0107	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0106	0.0000	0.1397
7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0110	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0110
8	0.0000	0.0110	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0110
9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0215	0.0000	0.0000	0.0000	0.0000	0.0108	0.0000	0.0000	0.0000	0.0000	0.0108	0.0000	0.0000	0.0430
10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0861	0.0970	0.0647	0.0645	0.1183	0.1185	0.0538	0.0754	0.0860	0.0537	0.0645	0.0322	0.0322	0.0000	0.0216	0.0215	0.0106	0.0000	1

CHAPTER 6



Reconsidering heifer rearing strategies under environmentally driven agricultural policies

Kulkarni P. S., Steeneveld W., Haijema R., Hogeveen H., Mourits M. C. M.

Abstract

In recent years, agricultural policies pertaining to dairy farming in high milk-producing countries such as the Netherlands have increasingly focused on reducing the environmental burden due to emissions. The Phosphate rights system of 2018 is one such example wherein each dairy farmer has limited “rights” for phosphate produced from manure on their farm. Consequently, the farmers could either reduce their producing herd or non-producing animals such as the youngstock to keep within the phosphate rights they own. In this study we aimed to gain insights in the economic consequences of environmentally driven agricultural policy such as the Phosphate rights system on replacement heifer rearing strategies. Results showed that by reducing the replacement heifer supply or the age at first calving of heifers, the phosphate production on farm can be reduced without having a huge decrease in gross margin. By taking phosphate rights system and its guidelines as an example, we demonstrated that policies pertaining to other environmental emissions can also be studied in a similar way. In conclusion, the study demonstrated that by reconsidering heifer rearing strategies for replacement supply, there is room to improve the gross margin of dairy herds within the policy-based constraints.

Keywords

Youngstock, phosphate production, environmental, dairy herds, culling

6.1 Introduction

Moving towards more sustainability, north-western European countries have started to introduce environmentally based agricultural policies that impact the management of livestock production. In the post-milk quota Netherlands, efforts are underway to establish rules and regulations for better manure management (CBS, 2019; Groeneveld et al., 2016). To improve water quality in the Netherlands by limiting phosphate production from dairy cattle manure and promote a shift to land-based farming, the Dutch authorities introduced a phosphate rights trading system in 2018 (Rijksoverheid, 2018). Due to this legislation system, famers are allowed to produce a maximum amount of phosphate in dairy manure that corresponds to the phosphate production rights they hold. Upon introduction, dairy farmers were given phosphate rights based on the composition of their herd on a reference date (e.g., 2015).

Farmers can increase the number of rights they have by purchasing additional rights (for long-term expansion) or leasing them (for short-term fluctuations) at the market. However, supply is limited, leading to unprofitable high market prices (Rijksoverheid, 2018; RVO, 2019). Consequently, this environmentally driven policy adds complexity to the management of livestock on dairy farms.

Managerially, the farmers could either reduce their producing herd size or reduce the youngstock reared for replacement or a combination of both, to keep within the phosphate rights they own. To achieve a reduction in youngstock, heifer rearing management needs to be reconsidered. For example, by reducing the number of replacement heifers reared (hence, reducing the replacement rate) or by shortening the age at first calving. Since, most farmers in the Netherlands follow a closed farm system (own youngstock breeding and rearing), the consequences of such a managerial trade-off would be on the economic gross margin (Mohd Nor et al., 2015). Insights in the interaction between the economic and the policy-imposed environmental goals of the farmers are essential for farmers to adapt and comply (Kuhn et al., 2019).

From 2017 onwards, there has been a steady decline in the number of replacement heifers reared on Dutch dairy farms (Kulkarni et al., 2021, 2023). When the number of replacement heifers is limited under the influence of environmentally driven policies, not all cows that need to be replaced as per optimal policy, can be replaced. In such situations, an inter-cow comparison is necessary to make replacement decisions that result in better economic gain while accounting for risks of involuntary disposal. In our previous study (Kulkarni et al., n.d.; Chapter 5), we developed a modelling framework that accounted for inter-dependency between the cows to study the herd-level economic impact of constraints on replacement heifer supply. In this study, we made use of this same modelling framework, to gain insights in the economic consequences of environmentally driven agricultural policy such as the Phosphate rights system on replacement heifer rearing strategies.

6.2 Materials and Methods

6.2.1 Model Overview

This study used the modelling framework developed in our previous study (Kulkarni et al., n.d.; Chapter 5). This modelling framework consists of three modules: (i) a cow-place optimization module, (ii) an inter-cow decision module, and (iii) a herd simulation module. The cow place optimization module optimizes the monthly reoccurring decisions on whether to keep, keep and inseminate, or replace a cow occupying a cow place, under the assumption of 100% heifer availability. This module provides an optimal replacement and insemination decision policy and a Retention Pay-Off (RPO) value for a single cow place as output. The inter-cow decision module decides subsequently whether the individually optimized decisions for each cow can be exercised given the number of available heifers at herd level. To account for the interdependency among dairy cows competing for the same limited supply of replacement heifers, this module ranks the dairy cows within the herd by their RPOs (as derived from the cow place optimization module). If enough heifers are not available, only those cows with the highest ranks (lowest RPO values) are replaced. Finally, in the herd simulation module the state dynamics of each cow is simulated, driven by the heifer supply and the corrected optimal decision policy. The final cow state transition results and the expected candidate cows for replacement are fed back to the inter-cow decision module to start the next month's evaluation and ranking of cows. The main purpose of the herd simulation module is to evaluate the economic impact of the replacement decision policy at the herd level.

For more details on the modelling framework refer to Materials and Methods of Chapter 5 (Kulkarni et al., n.d.).

6.2.2 Herd-level phosphate production estimation

In addition to the gross margin and the culling rate, the model was expanded to estimate the annual average phosphate production of the simulated dairy herd. We used the official fixed rates established by the RVO (RVO, 2019) to calculate the phosphate production of the producing herd as well as that of the youngstock reared for the replacement heifer supply.

Based on the estimated milk production of the cows in the simulated herd, per cow the phosphate production was calculated for each kilogram of milk by using the values presented in Table 6.1. The total phosphate production of the herd was the sum of phosphate output of all producing cows in each month over 10 years.

Table 6.1. Official fixed rates defined by RVO, 2019 for calculating phosphate production of livestock units on dairy farms per year.

Type of stock	Phosphate production (in kg)
Female calves (age between 2 weeks and 1 year)	9.6
Replacement heifers (age between 1 year and 2 years)	21.9
Producing cows in the herd	
Annual Milk Production (in kg)	Phosphate production (in kg)
< 5,624	32.4
5,625 – 5,874	34.0
5,875 – 6,124	34.8
6,125 – 6,374	35.5
6,375 – 6,624	36.2
6,625 – 6,874	36.9
6,875 – 7,124	37.7
7,125 – 7,374	38.4
7,375 – 7,624	39.1
7,625 – 7,874	39.8
7,875 – 8,124	40.6
8,125 – 8,374	41.3
8,375 – 8,624	42.0
8,625 – 8,874	42.7
8,875 – 9,124	43.5
9,125 – 9,374	44.2
9,375 – 9,624	44.9
9,625 – 9,874	45.6
9,875 – 10,124	46.4
10,125 – 10,374	47.1
10,375 – 10,624	47.8
> 10,624	49.3

The number of youngstock required to maintain a 100-cow milking herd – and hence the extent of phosphate output by the youngstock unit - varies with the maximum expected replacement rate, age at first calving and the mortality rate during rearing. The number of youngstock required is determined by the following equation:

$$Youngstock = \frac{AFC}{100} \cdot \frac{R}{100} \cdot N \cdot (1 + \frac{m}{100}) \qquad (1)$$

Where AFC is the age at first calving in months, $\frac{R}{100}$ is the maximum annual expected replacement rate based on heifer supply, N is the number of producing cows (herd size) and $\frac{m}{100}$ is the mortality rate of youngstock after the age of two weeks (only the calves needed for replacement are retained on the farm after 2 weeks of age while others are sold including male calves).

Using the conditions set by heifer rearing scenarios (see section 6.2.3) and the number of youngstock required eq. (1), the phosphate production of youngstock is calculated.

6.2.3 Heifer rearing scenarios

The decrease in phosphate production due to less youngstock can be exploited to increase the milk production of the herd by keeping extra producing cows (Klootwijk et al., 2016). To decrease the amount of youngstock reared on the farm, farmers can employ heifer rearing strategies such as (1) reducing the heifer supply for replacement i.e., reduce the maximum expected replacement rate of the producing herd by controlling heifer availability or by (2) reducing the age at first calving. The latter (2) results in less youngstock rearing as heifers enter the herd by calving younger than standard practice. The standard practice for Dutch dairy farms is defined in the base scenario (see subsection Base scenario below).

To simulate different heifer rearing strategies 12 different scenarios, namely, 8 scenarios on varying heifer availability for replacement per year and 4 scenarios on varying age at first calving for heifers entering the producing herd were tested. The scenarios utilized a pre-determined equation eq. (1) to calculate the amount of youngstock required for that particular heifer rearing strategy. All scenarios were simulated 100 times over the period of 10 years.

Base Scenario

To compare the various heifer rearing strategies, a base scenario reflecting the situation of an average Dutch dairy farm was defined (Table 6.2). In this scenario, the age at first calving was 26 months ($AFC = 26$), the mortality rate for youngstock (> 2 weeks of age up to age of 1 years old) set equal to 3.4% (m=0.034), while the number of replacement heifers available per year for a herd of 100 cows was equal to 30 (30% maximum expected replacement rate; $\mathrm{R} = 30$). Given these assumptions, a herd of 100 cows requires a youngstock unit of at least 67 animals in the age of 2 weeks to 26 months. Based on the total composition, this base farm requires on average, 5175 kg of phosphate rights annually. This number of required rights was taken as the threshold of phosphate production for comparison with the alternative heifer rearing scenarios.

Table 6.2. Heifer rearing scenarios with calculations showing total number of youngstock (heifers + female calves), number of heifers available per year and number of female calves reared for heifer supply per year for a herd of 100 cows with a calf mortality rate of 3.4% per year.

Age at first calving in months	Youngstock numbers [2]	Number of available replacement heifers per year (Age: 13 to 26 months)	Number of female calves retained per year (Age: 2 weeks to 12 months)
Scenarios: Variable replacement heifer availability			
26	49	22	27
26	54	24	30
26	58	26	32
26	63	28	35
26[1]	67[1]	30[1]	37[1]
26	72	32	40
26	76	34	42
26	81	36	45
Scenarios: Variable age at first calving			
24	62	30	32
26[1]	67[1]	30[1]	37[1]
28	72	30	42
30	78	30	48

[1] Base scenario defined for comparison.

[2] Calculated using Eq. (1)

Variable replacement heifer availability

For a herd of 100 producing cows, each year, 22 to 36 heifers were made available for replacement such that $\mathrm{R} \in \{22, 24 \ldots, 34, 36\}$. This signifies the maximum expected replacement rate of the herd which is the maximum possible number of replacements of cows given the heifer supply. R should not be confused with "optimal" replacement rate which is a policy defined by the optimization module explained in 6.2.1 which performs optimization of replacement policy by maximizing the gross margin of milk. The actual or realized replacement rate is determined by the simulation module explained in 6.2.1 subject to heifer availability defined in these scenarios.

The monthly availability of heifers was drawn randomly from a multinomial distribution. The age at first calving and the calf mortality rate were kept constant through all the scenarios at 26 months ($\mathrm{AFC} = 26$) and 3.4% ($\mathrm{m} = 0.034$) respectively. The phosphate production was calculated based on the annual milk production of the cows and the number of youngstock (calves + heifers) based on Table 6.1. The phosphate production of the variable replacement heifer availability scenarios is compared to that of the base scenario and difference was used to correct the gross margin based on the lease value of phosphate rights (€ 28/ kg PH). So, for each kilogram of surplus phosphate, a levy of €28 was subtracted from gross margin whereas for each kilogram of less phosphate produced, €28 were added to the gross margin annually.

Variable age at first calving

Age at first calving was varied between 24, 26, 28 and 30 months for heifers (AFC ϵ {24, 26…30}). The actual number of youngstock was calculated from equation (1) as seen in Table 6.2. The calf mortality rate was kept constant at 3.4% ($m = 0.034$) and the number of replacement heifers available annually was kept constant at 30 ($R = 30$). Like the heifer availability scenarios, the phosphate production was calculated based on Table 6.1 and compared to the base scenario. The difference was then used to calculate the correction for gross margin based on lease value of phosphate rights (€ 28/ kg PH).

6.3 Results

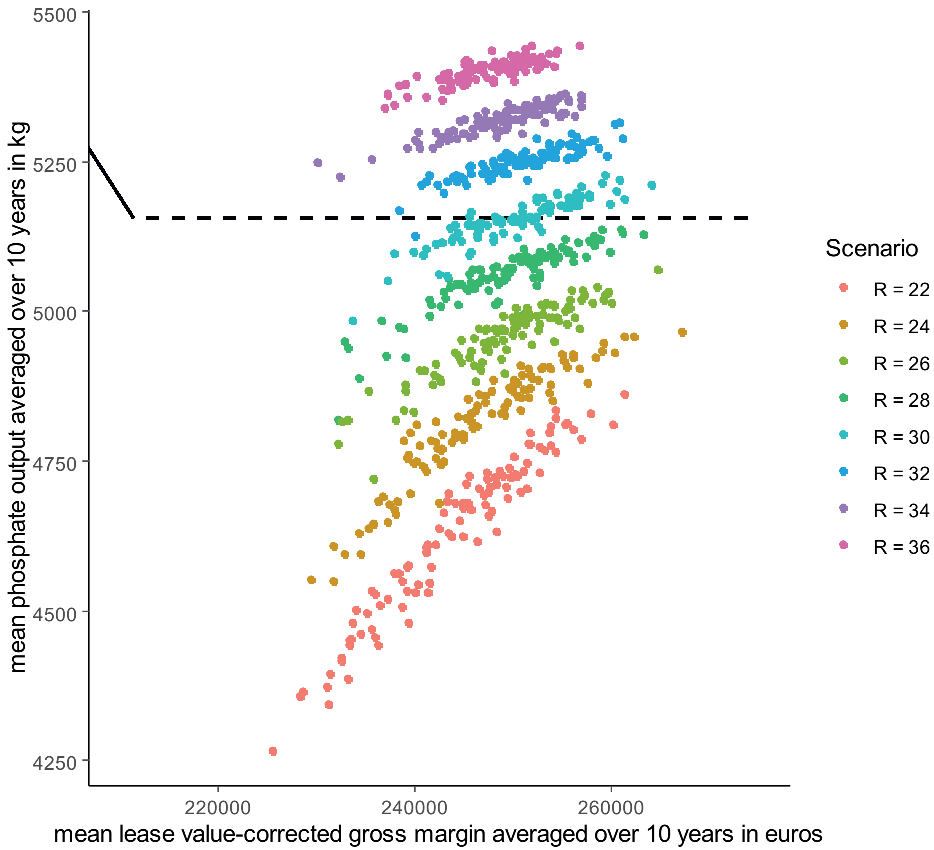


Figure 6.1. Results in terms of annual phosphate production (y-axis) and corrected gross margin (x -axis) of 100 simulations of 8 scenarios for 10 years with varying replacement heifer availability per year.

Note: R represents the number of replacement heifers available per year in each scenario. The correction for gross margin (x-axis) was done by adding or subtracting lease value of each kilogram of phosphate (€ 28/ kg PH) produced annually under or over the threshold (dashed line) set by the base scenario. The gross margin before correction represents all the costs and revenues from milk production of dairy cows as laid out in Chapter 5 (Kulkarni et al., n.d.)

Note: Base scenario: R = 30

6.3.1 Variable replacement heifer availability

The simulation of the base scenario ($R = 30$) resulted in slightly lower phosphate production with an annual mean of 5,155 kg (SD 38 kg) than the expected 5175 kg, possibly due to stochasticity in the simulation (Figure 6.1). The gross margin in the base scenario had an annual average of € 250,568 (SD € 5,806). From Figure 6.1, availability of 22 heifers per year resulted in the lowest annual phosphate production with a mean of 4,632 kg (SD 136 kg) as well as lowest lease value-corrected gross margin with an annual mean of €244,199 (SD €7,900). The highest lease value-corrected gross margin was achieved in the scenario with 32 heifers available annually ($R = 32$) with an annual mean of € 250,764 (SD € 4,931) and the phosphate production was slightly higher than the base scenario with an annual mean of 5,251 kg (SD 27 kg). The trend seen in Figure 6.1 showed that the annual phosphate production increased as the number of heifers available increased whereas, the gross margin first increased until the base scenario ($R = 30$) and then decreased subsequently. The annual means and SD of corrected gross margin and the phosphate production for each scenario are presented in Table A of Appendix 1.

6.3.2 Variable age at first calving

The simulation of the base scenario ($AFC = 26\, months$) resulted in phosphate production similar to the expected level with an annual mean of 5,174 kg (SD 24 kg) (Figure 6.2). The gross margin in the base scenario had an annual average of € 250,639 (SD € 4,656). Lowering age at first calving by 2 months ($AFC = 24\, months$) resulted in increased lease value-corrected gross margin with an annual mean of € 256,106 (SD € 8,193) as well as reduced phosphate production with annual mean of 5,102 kg (SD 54 kg) compared to the base scenario. By increasing the age at first calving by 2 or 4 months ($AFC = 28\, months, AFC = 30\, months$ respectively), the corrected gross margin decreased to an annual mean of € 228,937 (SD € 4,095) and € 214, 209 (SD € 5,222) respectively. However, the phosphate production in these two scenarios ($AFC = 28\, months,\ AFC = 30\, months$ respectively) was almost the same as the base scenario with an annual mean of 5,153 kg (SD 30 kg) and 5,181 kg (SD 47 kg), respectively.

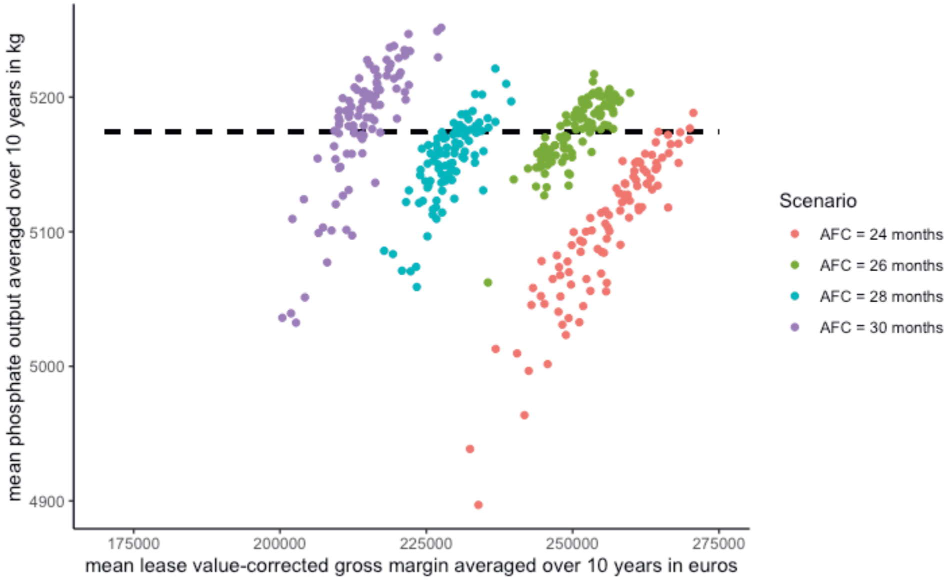


Figure 6.2. Results in terms of annual phosphate production (y-axis) and corrected gross margin (x -axis) of 100 simulations of 4 scenarios for 10 years with varying age at first calving.

Note: AFC represents the age of first calving in months in each scenario. The correction for gross margin (x-axis) was done by adding or subtracting lease value of each kilogram of phosphate (€ 28/ kg PH) produced annually under or over the threshold (dashed line) set by the base scenario. The gross margin before correction represents all the costs and revenues from milk production of dairy cows as laid out in Chapter 5 (Kulkarni et al., n.d.)

Note: Base scenario: AFC = 26 months

6.4 Discussion

In this study, we aimed to gain insights in the economic consequences of environmentally driven agricultural policy such as the Phosphate rights system on replacement heifer rearing strategies. The trade-off between the restrictions on phosphate production of dairy farms and their gross margin represent the influence of the policies on management strategies such as replacement heifer rearing.

From the results, it was clear that the amount of youngstock kept on the dairy farm has a small but important contribution to the overall phosphate production of the dairy farm. The results of scenarios pertaining to varying replacement heifer availability per year showed a clear trade-off between the phosphate production and gross margin from milk (Figure 6.1). The differences in youngstock numbers have a relatively larger effect on the herd's phosphate production compared to the gross margin of the herd. Based on Figure 6.1, it can be theorized that by reducing the expected replacement rate (annual heifer supply) by 2% or 4% can reduce the phosphate production without huge decrease in gross margin. For example, if the average expected replacement rate of the farm is reduced from 30% to 28%, this would result in 4 fewer head of required youngstock (assuming constant calf mortality and constant age at first calving for heifers), and in a reduction in phosphate production by 90 kg. Assuming an average cow produces 41 – 42.5 kg of phosphate per year (Table 6.1), approximately 2 extra cows can be milked per year, while remaining within the threshold of phosphate rights. Stocking density and subsequently, youngstock population was identified as a key management area to maximize milk production without increasing its environmental burden through life cycle assessment (Thomassen et al., 2009). The trade-off in number of youngstock and current producing herd represent the future production potential of the dairy farm. However, in this study, we account for the risk of involuntary or sudden disposal by utilizing the optimization-simulation modelling setup thereby reducing the risk of leaving empty cow places.

Taking another example, having an age of first calving at 24 months instead of 26 months, would reduce the required number of youngstock with 5 (3 calves and 2 heifers) and, subsequently the amount of phosphate production with on average 70 kg annually (Figure 6.2). Given this slack in phosphate production, approximately 1.5 extra cows with an average production could be milked per year. Therefore, the phosphate production from youngstock has an opportunity cost for milk production of the herd. Considering the current market prices for milk corrected for the variable costs (gross margin) and the average production of mature dairy cow, the milk opportunity cost for each kg of phosphate can be calculated to € 43 per kilogram of phosphate produced (WECR, 2021). Further reduction of age of first calving to 22 months was not possible to simulate as a scenario in this study. This was due to the fact that the modelling setup was sensitive to heifer rearing prices. When the heifer rearing prices are comparable to the carcass value generated from culling, the trade-off between selling off a producing cow for slaughter and keeping a cow for producing milk become less clear. In such a case, the optimal policy might reflect unrealistic culling and replacement policies (e.g. For a scenario with 22 months age at first calving, our model proposed a 55% replacement rate per annum: results not shown). Also, the health consequences of reducing the age at first calving such as reduced metabolic health, increase in prevalence of production diseases, reduced reproductive performance in lifetime (Pirlo et al., 2000; Wathes et al., 2008) are not considered here.

Grandl et al. (2019) showed that there is a clear link between the longevity and consequently the replacement policy of dairy farms and the economic gains as well as the emission intensity of the whole farm. Similar trade-offs have been indicated between farm economic performance and environmental emissions in terms of GHG elsewhere (Jayasundara et al., 2019). In this study, we used phosphate production per animal in dairy herd as an example to illustrate the effects of different heifer rearing strategies on a herd level since there are clear directives for calculating phosphate production given in the policy. The scenarios explored in this study can be easily expanded to include other environmental emissions such as nitrogen production from manure, GHG emission from enteric fermentation or manure, etc. on dairy farms that are relevant to future policies in dairy agriculture.

Although the results of this study show that there is a distinct advantage in keeping less youngstock to curb phosphate production on dairy farms, care must be taken to account for the opportunity costs of reducing the replacement rate on dairy farms. Optimal replacement policies boost the overall milk yield as well as the reproductive health of the dairy (Van Arendonk, 1985). Moreover, the addition of new heifers in the herd boosts the genetic merit of the herd through accelerated genetic improvements and breeding programs (de Vries, 2017). The balance between the producing herd and the youngstock reared on the farm also has consequences on efficiency of land use of the dairy farm. Therefore, such evaluations need to be further expanded by systematic optimization models that consider the minimization of phosphate production while maximizing the gross margins from milk production of the dairy herds.

The modelling setup used in this study does not account for minimization of environmental emissions such as phosphate production in their objective function per se. However, it is possible to extend such models by accounting for burden of emissions in terms of costs per cow or costs per kg milk in such models to optimize replacement decisions. Alternatively, a multi-objective optimization can be performed for maximization of gross margin and minimization of emissions for optimal cow replacement strategies under such environmentally driven policy constraints. Such empirical and formal analyses can help benchmark and support key management decisions that can help farmers exploit the trade-offs between economic and environmental outcomes of their operations (Van Passel et al., 2007).

6.5 Conclusion

Two scenarios of heifer rearing strategies to illustrate the consequences on economic and environmental outputs of milk producing herds under environmentally driven policies are explored. We demonstrated that by reconsidering heifer rearing strategies for replacement supply, there is room to improve the gross margin of dairy herds within the policy-based constraints.

Appendix 1

Table A. Summary of results in terms of means and standard deviations for all 12 heifer rearing scenarios showing corrected annual gross margin, phosphate production and replacement rate per year.

Scenarios	Mean corrected gross margin (€)	SD of gross margin (€)	Mean annual phosphate production (kg)	SD of annual phosphate production (kg)	Realized annual replacement rate (%/100)	SD of realized replacement rate (%/100)
R[1] = 22	244,199	7,907	4,632	136	0.24	0.009
R = 24	246,637	7,627	4,813	97	0.25	0.009
R = 26	249,217	6,403	4,956	61	0.26	0.010
R = 28	249,555	6,439	5,061	54	0.27	0.011
R = 30	250,568	5,806	5,155	38	0.27	0.013
R = 32	250,764	4,931	5,251	27	0.28	0.011
R = 34	248,826	5,172	5,320	26	0.28	0.014
R = 36	247,582	4,280	5,403	21	0.29	0.015
AFC[2] = 24	256,106	8,193	5,102	54	0.30	0.010
AFC = 26	250,639	4,656	5,174	24	0.25	0.013
AFC = 28	228,937	4,095	5,153	31	0.24	0.013
AFC = 30	214,209	5,222	5,181	47	0.25	0.013

[1] R = Number of heifers available annually (maximum expected replacement rate)

[2] AFC = mean age at first calving in months of the herd

CHAPTER 7

General Discussion

7.1 Background

The Netherlands is one of the world's leading countries in commercial dairy production. The Dutch dairy production system is driven by a high degree of economic efficiency which places at the same time a heavy burden on the environment. Given the increasing public demand for more sustainable production environmental policies in agriculture have become more stringent in recent decades.

Since most farms in the Netherlands are owned and operated by farmers and farmers' families, changes in the national policies require farmers to adapt their managemental planning and goals to sustain in the business. Examples of policy changes that affected the dairy farm structure and management were the Milk Quota (1984-2015) and the Phosphate regulation policy (2018-present).

Culling and replacement of dairy cows is one such aspect of management measures that is utilized by farmers to adapt their managemental goals and the structure of their farms. Culling of dairy cows, in theory, require that they are replaced with similar or better performing heifers. To do that, farmers require future knowledge or reliable predictions on the future productive performance of the cow to be culled and replaced as well as the potential of the heifer that will take its place in the dairy herd. Most of the dairy farms in the Netherlands follow a closed system. This means that actual replacement of dairy cows is accompanied by decisions to retain calves. This decision is based on the number of replacement heifers to be reared as well as which individual calves to retain. Breeding and rearing of replacement heifers have substantial economic consequences on the dairy farm economics. However, farmers tend to keep more youngstock than absolutely necessary, as a risk management tool to account for sudden or forced culling.

Considering that replacement decisions are complex and require long term planning, many attempts have been made in the past to optimize replacement strategies of dairy farmers. Some of the models developed were intended to be decision support tools while others were intended for research to address knowledge gaps. Despite the efforts, however, most of these tools have remained largely research based and theoretical and are not applied on actual farms. Instead, farmers tend to make decisions based on intuitive heuristics and specific rules of thumb.

Given that future farm goals must include a reduction in environmental burden while maintaining economic viability, a revisit of optimal replacement and heifer rearing strategies is sorely needed. Thus, the goal of this thesis was to (1) gain insights in the factors and reasons for replacement of Dutch dairy cows in changing agri-environmental policies and (2) to use these insights to explore the consequences of policy constraints on replacement strategies.

In this concluding chapter, I will discuss the key insights drawn from the studies of this thesis and how they are interlinked (Section 7.2), the data and methodological approaches (Section 7.3), the future implications of this thesis (Section 7.4) and finally, the conclusions drawn (Section 7.5).

7.2 Synthesis of the results

Chapters 2, 3 and 4 showed that farmers make culling and replacement decisions of individual dairy cows based on heuristics and rules of thumb with respect to health, reproduction and production performance measures that are conserved across time, irrespective of farm performance goals or national policy changes. Chapters 5 and 6 demonstrated that within the constraints of the agri-environmental policies there is room for changes in the replacement and the heifer rearing strategies without hampering the economic gains from milk production.

This thesis demonstrated that the culling and replacement decisions of dairy cows involve factors at three different dimensions, namely, individual cow-level, farm/ herd-level and, policy level (Chapters 2 and 3). By leveraging data-driven analyses and a survey, I found that factors such as production indicators (for e.g., milk yield), health indicators (for e.g., somatic cell count) and reproductive indicators (for e.g., services/ inseminations per calf) are associated with culling and replacement, not only at individual cow-level but also at a herd-level (Chapters 2, 3 and 4). At the cow-level, these factors represent the performance and fitness of the cow but at the herd-level, these factors represent the goal of the farm in terms of overall herd performance (Chapter 4). The individual cow-level findings of Chapters 2 and 3 were consistent with earlier Dutch studies that were performed on a herd level (Han et al., 2022; Nor et al., 2014a). The findings of Chapters 2, 3 and 4 regarding which factors are associated with culling are similar to the findings of Boer et al. (2013) which was a study performed 10+ years ago when the national agricultural policy was very different from current legislation in the Netherlands. Moreover, the relevance of reproduction, health, and production performance of cows for culling (Chapter 2 and 3) was also found by studies in other European countries (Gussmann et al., 2019; Rilanto et al., 2020).

The results of this thesis indicate that the culling patterns observed on dairy farms are heavily influenced by the management style and perspective of the dairy farmer, making the decisions irrespective of overall farm-level performance (Chapters 3 and 4). Farmers adopt certain culling plans and follow certain rules of thumb to facilitate their cattle replacement decisions (Chapter 4). Beaudeau et al. (1996) had similar findings on French dairy farmers. Since farmers stick to their plans and certain rules of thumb, their culling policy was often not adapted to changing policy or farm goals (Chapters 2 and 4). Although most cow replacement decisions are economic in nature, the farmers perceive a lack of decision-making space for radically changing their culling strategy (Chapter 4). Due to this perception, it may be difficult for farmers to adopt policies which reduce culling and improve longevity of dairy cows under the influence of agri-environmental policies. Another reason might be that most replacement decisions are made based on health and reproductive performance of cows (Chapters 2 and 4) which might be perceived as biological and therefore forced in nature. For example, dairy replacement for reproductive failure after imposing a rule of maximum 4 inseminations per lactation is not biological or forced but dairy replacement for infertility is. The third reason for the perceived lack of decision space might be because changing agri-environmental policies constrain the amount of youngstock that can be reared for replacements, thereby increasing the risk of loss due to health and reproductive problems (Chapters 5 and 6).

Even though dairy farmers intend to reduce their culling rate and improve the herd longevity of dairy cows, they do not intend to further reduce the youngstock reared (Chapter 4). Chapter 5 showed that this intention is not misplaced since it is economically better to have some surplus of heifer supply rather than less. However, results of chapter 6 demonstrated that slightly less heifer supply and slightly younger age at first calving can already reduce the environmental burden by reducing the phosphate production, while maintaining the gross margin from milk. For replacement of dairy cows to be not just economically sustainable but also sustainable in terms of environmental burden, the rearing strategies of young stock must be considered while formulating replacement strategies (Chapters 5 and 6). For example, by severely restricting the heifer supply for replacement in any particular year, the gross margin from milk decreases dramatically and the herd size reduces as cows are culled without replacement (Chapter 5). Changes in the heifer rearing costs radically influence the optimal replacement policy (Chapters 5 and 6). By lowering the average age at first calving for replacement heifers, heifer rearing costs can be lowered since the youngstock is kept for shorter amount of time. Replacement and heifer rearing strategies which are aligned not only increase the gross margin from milk but also keep the phosphate production lower (Chapters 5 and 6). Keeping slightly less youngstock than optimal, increases the gross margin of milk, whilst reducing the environmental burden of youngstock on the farm (Chapter 6). Stocking density and subsequently, youngstock population was identified as a key management area to maximize milk production without increasing its environmental burden (Thomassen et al., 2009). Therefore, coordination of replacement decisions with heifer rearing can be a key to adapt the dairy farm management to the current and prospective agri-environmental policies.

7.3 Methodological and data approach

7.3.1 Data

To achieve the aims of this thesis, I pursued a two-fold methodological approach, namely, the use of data-driven analysis based on existing longitudinal and collected cross-sectional data (Chapters 2,3 and 4) and use of mathematical models such as decision optimization using dynamic programming and scenario-driven simulation (Chapters 5 and 6).

For Chapters 2 and 3, secondary data recorded by CRV (cattle breeding cooperative of the Netherlands) was used. This extensive data set was recorded between years 2009 and 2019 comprising of almost 75% of all dairy farms in the Netherlands. In Chapter 2, a cow-level interval data of milk production registration (MPR) which recorded milk and milk-related indicators was used. In Chapter 3, herd level data made up of annual summary of year 2018 for the performance indicators was used. The presence of such a unique data set which spanned 10 years as well as encompassing the majority of the dairy farms in the Netherlands made it possible to generalize the results of chapters 2 and 3 to a national level along the policy changes that occurred during the decade.

The use of existing data reduces the time and resources spent collecting new data and contributes to the added value that can be derived from the data. Using secondary data certainly saved time and resources as well as allowed access to large number of dairy farms in the Netherlands which otherwise would have been infeasible in the time frame of this study. Also, since the cow-level data was longitudinal in nature, it could be employed to look at long-term relationship between the relevant risk factors for culling and survival of cows through the perturbations caused by three policy periods (milk quota era, post-milk quota era and the phosphate regulation era).

Since the data was collected by CRV, the choice of variables and parameters was limited. For example, in Chapter 2, I discussed the lack of fertility parameters such as prolonged lactation, age at first calving, presence of production diseases (mastitis, lameness, etc.) for individual cows. Considering that fertility factors are relevant to the culling policies of farmers (Bascom and Young, 1998; Rilanto et al., 2020), lack of data on such factors limited the scope of the findings in Chapter 2. In Chapter 3, I studied the association of farm performance measures and culling proportions under the effects of phosphate rights regulation that was implemented in January 2018 in the Netherlands. But since the CRV data on herd level constituted of complete records for year 2018 and only partial records for year 2019 (years in data after the policy was put in place), the longitudinal aspects of this association remained unexplored. This limited the scope of Chapter 3 to a cross-sectional analysis. Considering previous literature with similar studies, it is fair to assume that the relationship between culling and farm performance is on mid-term or long-term duration (Nor et al., 2014a; Vredenberg et al., 2021).

In Chapter 4, an online survey was conducted with partnership from Royal GD on dairy farmers who subscribed to their monthly newsletter called “Actueel Rund Nieuwsbrief” (Royal GD, 2021). Data in terms of responses was recorded on culling reasons, strategies, and intentions of farmers regarding their culling strategies. This primary data collection was to bridge the gaps left between the data-driven studies of Chapters 2 and 3 and the ground reality of dairy farmers making actual culling and replacement decisions. I limited the social desirability bias of responses by asking about the latest instance such as culling reasons for the most recently culled cow. This strategy was previously employed by Robbers et al. (2021). I paired these questions with general questions about the most and least frequent reasons for culling to get the specific as well as the general picture. However, since the survey was exclusively conducted in an online format, which might not have encouraged participation, the response rate was limited. Only 2% of the subscribing farmers responded to the survey with complete responses. Even though the response rate was limited, the respondents were fairly representative of the general dairy farming community in terms of their herd characteristics, thereby making a descriptive analysis of the survey data feasible to gain insights in the farmers’ perspectives regarding culling and replacement management. Retrospectively, a similar survey on larger scale with both offline and online formats can be beneficial to collect sufficiently voluminous data that can be then used to perform statistical analyses. In summary, the survey data, although smaller, bridged valuable gaps in the data-driven approaches of Chapters 2 and 3 in terms of farmers’ perspectives and strategies regarding culling.

7.3.2 Methodological approaches

In this thesis numerous methods were used to explore the replacement decision problem at the different decision dimensions i.e., at individual cow, herd, and policy level. The exploratory analyses consisted of a survival analysis (Chapter 2), cross-sectional association study (Chapter 3) and descriptive study of survey data (Chapter 4). In addition, a stochastic bioeconomic modelling framework was developed to perform the simulation studies in Chapters 5 and 6. The methods used in Chapters 2, 5 and 6 are discussed in more detail below.

The survival analysis (Chapter 2) was performed using an accelerated failure time model. This modelling strategy was dissimilar to the models used in previous studies with similar aims such as those by Alvåsen et al. (2012), Gussmann et al. (2019) and, Rilanto et al. (2020). These studies used either Cox-proportional hazards or non-parametric survival analysis techniques. The reason for this deviation from earlier applied techniques was that each survival interval in Chapter 2 corresponded to the duration between two test-dates for MPR data of CRV. The previous studies used calving intervals as a basis for survival time. By using the test-date intervals instead, I reduced the time lag between the decision to cull a cow and the point at which the culling is reflected in the data since the test-date interval is considerably shorter (1-4 months) than calving interval (~ 13-14 months). This made it possible to study lifetime survival of cows instead of per parity survival and its association with time-varying factors that are recorded on the same interval.

In Chapter 5, a combined model comprising of cow-level optimization and herd simulation was developed to explore the impact of heifer supply on replacement of dairy cows. The optimization module used in the study was a straightforward cow-level replacement decision optimization, an approach used in many studies from the 1970s until the 2010s. The premise of using dynamic programming and Markov decision processes to economically optimize replacement decisions was purported by multiple bodies of work such starting from early 1970s (Smith, 1973; Stewart et al., 1978, 1977) and improved upon through the next two decades (see theses of van Arendonk, 1985 and, Kristensen, 1993). More complex models in the later years, including multi-level mathematical architecture with added elements of stochasticity in health and diseases, were developed based on this groundwork (for example, see Demeter et al., 2011; Cha et al., 2014).

I revisited these time-tested techniques to explore what management might look like in dairy farming where the goal is not only maximization of economic gains but also to make dairy farming more sustainable. Considering that the agri-environmental policies like phosphate rights system affect the structure of the dairy farm, the replacement strategies of the farmers need to be at herd level rather than at individual cow level. So, by combining cow-level optimization of replacement decisions with herd-level simulation, I could gain insights in the herd level effects of input-driven scenarios such as replacement heifer supply. This circumvented the issue of formulating an objective function for optimal replacement decisions on a herd-level thereby adding a lot of complexity to the optimization model. Previous efforts in this direction, for example, by Ben-Ari and Gal (1986), de Vries (2005), Kristensen (1992) or, Yates and Rehman (1998) have remained largely theoretical. Cabrera (2010) used linear programming to formulate the replacement problem on herd level. To my knowledge, there have been no new developments in solving the cattle replacement problem on a herd-level.

In Chapter 6, the model developed in Chapter 5 was adapted to study the impact of heifer rearing strategies on economics and environmental burden of dairy farms. This chapter demonstrated that it might be possible to study the trade-off between economic gains and environmental burden of dairy farming by investigating different management strategies. More comprehensively, such trade-off can be studied rigorously by an attempt to optimize the replacement decisions by including phosphate production in the objective function of an optimization model. This is possible since there is an economic value attached to the phosphate rights in terms of its lease value (see Chapter 6 for details) which can be added as costs of milk production in an objective function. However, this will not be possible in case of nitrate production or GHG emissions which are yet to be regulated under Dutch agricultural policies. On the other hand, a multi-objective optimization (MOO) wherein the maximization of economic gains and minimization of environmental burdens are both objectives can be a possibility. For instance, Breen et al. (2019) developed a multi-objective optimization of economic gains and environmental emissions for land use, machinery, and management practices on dairy farms. Another example, Groot et al. (2012) implemented a multi-objective model to combine economic, productive, and environmental performance of an organic mixed-dairy farm in the Netherlands.

MOOs can be deployed to develop optimal replacement decisions which consider the trade-off between economic and the environmental factors at least on individual cow-level. A variable set of solutions can be generated by MOOs when the objectives like economic gains and environmental emissions do not align perfectly. This increases the decision space and options for the dairy farmers when strategizing their dairy cattle replacement and heifer rearing. On the flipside, MOOs are difficult to apply since the weights of each objective need to be considered carefully. In case of environmental emissions, it is important to distinguish between the constraints driven by policies and hard limits versus the other herd level goals of farmers before such techniques are used.

However, given the explosion of computational power and increasing use of machine learning (ML) and artificial intelligence (AI), I am cognizant of the fact that several techniques can replace the classical mathematical models to perform complex optimization that is needed in the case of dairy cow replacement. ML/ AI models can handle the complexity and are computational viable for deployment in the dynamics of dairy management to move the sector towards precision farming using big data (Lokhorst et al., 2019). For example, agent-based ML techniques such as reinforcement learning can be a viable alternative.

Reinforcement Learning (RL) in combination with more sophisticated ML techniques has already been applied successfully in supply chains of material distribution and inventory replacement in other industrial sectors (recent example, Cuartas and Aguilar, 2023; Geevers et al., 2023). Relevant to dairy farming, dairy processing supply chains have also seen a rise in employment of RL-based techniques in decision making over traditional mathematical model (recent example, Huerta-Soto et al., 2023). Compared to traditional mathematical models like dynamic programming, RL is scalable to large problems with computationally higher dimensions since it does not require computing the values of all state-action space. So, RL can be a feasible alternative to study replacement decisions of cows on dairy herd level without increasing the computational burden. Techniques like RL are also dynamic and adaptable to changes thereby making it possible to incorporate certain management styles of farmers and presence of perturbation events (e.g., first year after policy change) in the replacement strategy. Prospectively, another advantage of RL is that it can potentially incorporate MOO by using a population-based approach to make the model more dynamic (for details, see Hayes et al., 2022).

Use of ML can be prescribed in other directions as well. For example, ML is already being used to detect patterns in how farmers make culling decisions (Lopez-Suarez et al., 2018) or to predict the incidences of production diseases such as mastitis and lameness (Cavero et al., 2006; Warner et al., 2020) that can help provide information for making replacement decisions. Van der Heide et al. (2020) compared ML techniques with traditional statistical models to predict survival of cows on the farms. Fenlon et al. (2017) demonstrated that it is possible to use ML to predict the dystocia and pregnancy difficulties for heifers and cows based on life events. Such applications of ML can be incorporated in models for farmers to cull and replace cows to add to the prediction power. However, the efficacy of ML hinges on availability of sufficient and relevant data. The CRV data utilized in this thesis is a good example of large and comprehensive data that can be used to train and deploy ML techniques. However, absence or unavailability of such data to research can make it difficult to develop such a methodological practice.

7.4 Potential Implications

Dutch dairy farming is characterized by closed farming systems with a strong interdependence between heifer rearing and dairy cow replacement strategies. The methodology developed in this thesis (Chapter 5) was uniquely adapted to closed farming systems wherein cattle replacement is considered from a farm-level perspective, while accounting for heifer availability. By combining cow-level optimization with herd simulation, different replacement and heifer rearing strategies can be tested for their viability in the evolving policy climate. Since the agri-environmental policies will continue to develop over time, farmers will frequently need to adjust and adapt their management and structure of their herds. Future policy developments will likely focus on reducing the environmental impact of dairy farms (e.g., by reducing GHG or nitrates emissions) and improving the welfare of dairy cows (e.g., by reducing number of cows per unit area). Such developments will likely place constraints on the herd size or herd structure of dairy farms. The methodology used in this thesis can be applied to study the constraints imposed on the production system by such prospective policy changes. Moreover, it provides insight into the potential of different replacement strategies to achieve the regulated societal and environmental goals while maintaining economic viability. The results in this thesis demonstrate that it is possible to move dairy farming towards increased sustainability in terms of phosphate emission without losing the sight of economic sustainability and productivity.

By using unique national level data, this thesis contributed to the literature with the insights gained in the culling and replacement decisions of dairy farmers across a decade long change in policies (Chapter 2). Replication of such studies could potentially inform research on whether changes in policies disturb the long-term management of dairy farms.

Approaches like national level surveying of dairy farmers in Chapter 4, demonstrated that the rules of thumb farmers use to make culling and replacement decisions have not been updated to adapt to the current and the prospective policy changes. Prospectively, such approaches can be utilized by farm advisors and researchers to understand the perspectives of dairy farmers and for guiding dairy farmers. Farm advisors as well as researchers need to be aware of this gap between the practice and the “modelling world” where rationality is assumed a priori. Since farmers’ behavior and management styles strongly influence how they make decisions (Chapter 4, Beaudeau et al., 1996), general advice is insufficient.

7.5 Conclusion

The main conclusions derived from this thesis are:

1. Farmers make culling and replacement decisions of individual dairy cows based on heuristics and rules of thumb with respect to health, reproduction and production

performance measures that are conserved across time, irrespective of farm performance goals or national policy changes **(Chapters 2, 3 and 4).**

2. There is a potential to change current replacement and heifer rearing strategies within the constraints of the agri-environmental policies without hampering the economic gains from milk production **(Chapters 5 and 6).**

More specifically, this thesis fulfilled the sub-objectives with the following conclusions:

Sub-objective 1: To analyze the relevancy of cow-level risk factors for lifetime survival of Dutch dairy cows representing production, reproduction, and health performances under perturbations due to national policy changes related to the milk quota abolishment of 2015 and the phosphate regulations since 2017.

- Survival of Dutch dairy cows was perturbed by changing agricultural policy such as abolishment of milk quota and introduction of phosphate rights system **(Chapter 2).**
- The association of cow-level risk factors for culling was consistent across the national policy changes from 2009 to 2019 **(Chapter 2).**

Sub-objective 2: To gain insights into the cross-sectional associations between annual performance indicators of Dutch dairy farms and their corresponding magnitudes of (i) overall culling and (ii) primiparous cow culling after the introduction of the herd size restricting phosphate regulation in the Netherlands.

- The introduction of phosphate regulation resulted in an increased outflow of cattle, corresponding culling proportions of primiparous or multiparous cows were not associated with the level of farm performance measured in terms of production, reproduction, or udder health **(Chapter 3).**

Sub-objective 3: To (i) determine the reasons behind the culling of cattle on Dutch dairy farms, (ii) to determine whether Dutch dairy farmers follow specific culling strategies (plan) and (iii) if so, to evaluate whether they intend to change their strategies in the near future.

- From farmers' perspective, their culling strategies align with the most frequent culling reasons such as reproduction, lameness, and udder health of the cows. The perceptions of farmers regarding the main culling reasons and strategies have not changed since the implemented policy changes that have imposed additional production restrictions **(Chapter 4).**
- Farmers have intentions to reduce culling rate of dairy cows on their farms to improve economic gains and longevity of dairy cows **(Chapter 4).**

Sub-objective 4: To study on herd level the economic impact of suboptimal replacement decisions due to a constrained replacement heifer supply while accounting for the interdependency among dairy cows within the herd.

- Severe constraints on heifer supply for replacement resulted in reduced gross margin as well as a reduced herd size due to an increase in involuntary disposal without replacement **(Chapter 5).**
- Excess and variable heifer supply for replacement resulted in slightly reduced gross margin due to sale of excess heifers at a loss **(Chapter 5)**.

Sub-objective 5: To gain insights in the economic consequences of different heifer rearing strategies under the current Dutch phosphate rights policy.

- There is room to improve gross margin of the dairy herds within the policy-based constraints by reconsidering heifer rearing strategies for replacement **(Chapter 6).**

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Summary

The Netherlands is one of the world's leaders in commercial dairy production. Dutch dairy farmers are increasingly challenged by evolving agri-environmental legislations to adapt their farming strategies and become more sustainable. Policy changes, like the abolition of milk quotas and the introduction of the phosphate rights system have had a major impact on the structure and operations of Dutch dairy farms. One of the management measures farmers use to adjust their farming strategies and farm structure within the legally established production framework is culling and replacing dairy cows. Replacement of dairy cows can be defined as the removal of producing dairy cow (culling) and replacing it by a suitable heifer that is expected to perform better than the culled cow. Most dairy farmers in the Netherlands have a closed system wherein, they breed and rear their own replacement stock. Therefore, heifer rearing, and dairy cow replacement strategies are strongly interlinked.

In the past, complex models have been developed to study and support not only replacement decisions but also heifer rearing strategies. However, given the considerable time lag between the decision to keep and rear a female calf to replacement heifer and the decision to replace a dairy cow by this reared heifer, it has been difficult to define optimal strategies at herd level for the replacement problem. Moreover, regardless of the models developed, dairy farmers tend to make replacement decisions based on their intuition while relying on rules of thumb. Given that future farm goals must include further reductions in environmental burden while maintaining economic viability, a revisit of optimal dairy cow replacement strategies by owned reared heifers is sorely needed.

Hence, the aim of this thesis was to (1) gain insights in the factors and reasons for culling and replacement of Dutch dairy cows under changing agri-environmental policies and, (2) to use these insights to explore the consequences of policy constraints on replacement strategies. To achieve these aims, five sub-objectives were formulated as follows:

1. To analyze the relevancy of cow-level risk factors for lifetime survival of Dutch dairy cows representing production, reproduction, and health performances under perturbations due to national policy changes related to the milk quota abolishment of 2015 and the phosphate regulations since 2017.
2. To gain insights into the cross-sectional associations between annual performance indicators of Dutch dairy farms and their corresponding magnitudes of (i) overall culling and (ii) primiparous cow culling after the introduction of the herd size restricting phosphate regulation in the Netherlands.

3. To (i) determine the reasons behind the culling of cattle on Dutch dairy farms, (ii) to determine whether Dutch dairy farmers follow specific culling strategies (plan) and (iii) if so, to evaluate whether they intend to change their strategies in the near future.
4. To study on herd level the economic impact of suboptimal replacement decisions due to a constrained replacement heifer supply while accounting for the interdependency among dairy cows within the herd.
5. To gain insights in the economic consequences of different heifer rearing strategies under the current Dutch phosphate rights policy.

In **Chapter 2**, a survival analysis of Dutch dairy cows was conducted on national level using longitudinal data to analyze cow-level risk factors under perturbations due to national policy changes. The associated cow-level risk factors for culling such as lactation value (relative production level), parity number, rolling average of inseminations over all parities, very high fat-protein ratio (highFPR) and very low fat-protein ratio (lowFPR) in early lactation, test-day somatic cell count, were fitted in the model. Along with these, a factor representing three target policy periods, namely Milk Quota period (MQ), Post-Milk Quota period (PMQ) and Phosphate regulation period (PH) were fitted. The mean survival age for all producing cows was 441 weeks overall. The predicted median survival time for the policy periods MQ, PMQ and PH were 273 weeks, 271 weeks, and 256 weeks, respectively. Risk factors such as lactation value, parity and highFPR, rolling average of inseminations over all parities were positively associated with survival time in all three policy periods. Risk factors such as test-day somatic cell count and lowFPR were negatively associated with survival time in all three policy periods.

In **Chapter 3**, associations between the performance of dairy farms and their corresponding culling rates under the herd size constraint as imposed in 2018 by the new phosphate regulation in the Netherlands were investigated. Using rank correlation and logistic regression, associations between 10 farm performance indicators (from 4 areas of longevity, production, reproduction, and udder health) and 4 culling proportions (for overall and primiparous cow culling). Results showed very low-rank conformity (<12%) between the areas of production, reproduction, and udder health to the culling proportions. Logistic regression model showed that higher farm levels of production and higher percentages of cows with poor udder health were associated with more overall culling but with less primiparous culling. For reproduction indicators, the associations were similar for overall and primiparous culling. However, the odds ratios for indicators were close to 1 indicating only weak associations to culling proportions.

In **Chapter 4**, a national level survey of Dutch dairy farmers was undertaken to determine the culling reasons for dairy cattle and to identify farmers' culling strategies and their intentions regarding the alteration of indicated culling strategies. Results showed that the most frequent culling reasons were related to problems with reproduction, udder, and hoof health. Culling reasons for primiparous and multiparous cows were different. Most respondents indicated that they consider formulating a culling strategy, based on certain rules of thumb regarding the most common reasons for culling. Most farmers also reported that culling decisions on their farms were perceived to be unavoidable, though reproductive culling decisions are primarily voluntary. Most respondents stated that they intended to reduce the culling rate for better economic gain did not intend to alter the amount of replacement stock reared. The applied rules of thumb regarding culling strategies did not seem to have changed since the policy changes in dairy farming.

In **Chapter 5**, a scenario study on economic impact of suboptimal replacement decisions due to a constrained heifer supply was performed. In this study, a single-cow optimization model was combined with dairy herd dynamics simulation. Besides the base scenario of following optimal replacement policy, we simulated three input scenarios of constrained, excess, and variable replacement heifer supply. In the base scenario, optimal replacement policy resulted in an average herd gross margin of €260,000, 17% voluntary replacement rate, and a 14% involuntary disposal rate annually for a herd of 100 cows. Constrained as well as excess heifer supply resulted in lower gross margins of €164,000 and €245,000, respectively. Compared to the base scenario, the constrained heifer supply scenario also resulted in 36% reduction of herd size, an increase in involuntary disposal (17%) and no replacements (0.2%) per year. The variable heifer supply scenario resulted in slightly lower gross margins (€250,000), lower voluntary replacement rate (12%), higher involuntary disposal rate (17%) but did not result in reduction of herd size.

In **Chapter 6**, using the model framework of **Chapter 5**, the economic consequences of environmentally driven agricultural policy such as the Phosphate rights system on replacement heifer rearing strategies were investigated. 12 scenarios signifying variation in (1) availability of replacement heifers and, (2) age at first calving for heifers were designed. Results showed that by reducing the replacement heifer supply or the age at first calving of heifers, the phosphate production on farm can be reduced without having a huge decrease in gross margin. By taking phosphate rights system as an example, we demonstrated that policies pertaining to other environmental emissions can also be studied in a similar way.

Based on all the findings, the main conclusions were:

1. Farmers make culling and replacement decisions of individual dairy cows based on heuristics and rules of thumb with respect to health, reproduction and production

performance measures that are conserved across time, irrespective of farm performance goals or national policy changes **(Chapters 2, 3 and 4)**.

2. There is potential to change current replacement and heifer rearing strategies within the constraints of the agri-environmental policies without hampering the economic gains from milk production **(Chapters 5 and 6)**.

More specifically, each study of the thesis had the following conclusions:

1. Survival of Dutch dairy cows was perturbed by changing agricultural policy such as abolishment of milk quota and introduction of phosphate rights system **(Chapter 2)**.
2. The association of cow-level risk factors for culling was consistent across the national policy changes from 2009 to 2019 **(Chapter 2)**.
3. The introduction of phosphate regulation resulted in an increased outflow of cattle, corresponding culling proportions of primiparous or multiparous cows were not associated with the level of farm performance measured in terms of production, reproduction, or udder health **(Chapter 3)**.
4. From farmers' perspective, their culling strategies align with the most frequent culling reasons such as reproduction, lameness, and udder health of the cows. The perceptions of farmers regarding the main culling reasons and strategies have not changed since the implemented policy changes that have imposed additional production restrictions (**Chapter 4)**.
5. Farmers have intentions to reduce culling rate of dairy cows on their farms to improve economic gains and longevity of dairy cows **(Chapter 4)**.
6. Severe constraints on heifer supply for replacement resulted in reduced gross margin as well as a reduced herd size due to an increase in involuntary disposal without replacement **(Chapter 5).**
7. Excess and variable heifer supply for replacement resulted in slightly reduced gross margin due to sale of excess heifers at a loss **(Chapter 5)**.
8. There is room to improve the gross margin of dairy herds within the policy-based constraints by reconsidering heifer rearing strategies for replacement supply **(Chapter 6)**.

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Glossary of terms

Terms are listed in sequence of appearance in the text.

1. EU: European Union
2. CAP: Common Agricultural Policy
3. NL: the Netherlands
4. CBS: Central Bureau of Statistics
5. CRV: Coöpweatie RundveeVerbetering
6. MINAS: MINerals Accounting System
7. RVO: Rijksdienst Voor Ondernemend
8. GHG: GreenHouse Gases
9. highFPR: very high Fat Protein Ratio
10. lowFPR: very low Fat Protein Ratio
11. MQ: Milk Quota period
12. PMQ: Post-Milk Quota period
13. PH: PHosphate regulation period
14. MPR: Milk Production Registration
15. LV: Lactation Value
16. FPR: Fat Protein Ratios
17. SARA: Sub-Acute Rumen Acidosis
18. SCC: Somatic Cell Count
19. Insem: Rolling average of inseminations over all parities
20. AIC: Akaike Information Criterion
21. AFT: Accelerated Failure Time model
22. TR: Time Ratios
23. HPC: High Performance Computing facility
24. Loglik(model): Log-Likelihood estimate from the model
25. OC: Overall Culling proportion
26. PC: Primiparous Culling over total producing cows
27. PPC: Primiparous Culling over total Primparous cows
28. POC: Primiparous Culling over all Culled producing cows
29. SD: Standard Deviation
30. n_culled: number of culled producing cows
31. n_tot: number of total producing cows
32. primi_culled: number of culled primiparous producing cows

33. n_primi: number of total primiparous cows
34. Age_tot: Age of the dairy herd in days
35. Age_culled: Age of the culled dairy cows in days
36. Life_prodn: Lifetime Production of milk in kilograms
37. FPCM: Fat-Protein Corrected Milk
38. Avg_FPCM: Annual average Fat-Protein Corrected Milk in kilograms
39. Services_per_conception: Number of inseminations per calving
40. AFC: Age at First Calving in days
41. Avg_DIM_first_service: Interval in days in milk (DIM) between last calving and first insemination
42. Calv_Int: Calving Interval
43. Avg_high_scc: Annual percentage of cows having high somatic cell count
44. IQR: Inter-Quartile Range
45. Rho: Spearman's rank correlation coefficient
46. OR: Odds Ratios
47. 95% CI: Confidence Interval between 2.5% and 97.5% of probability distribution
48. WECR: Wageningen Economic Research (institute)
49. BSK: Bedrijfs StandKaard Koe
50. UBN: Unieke Bedrijfs Nummer
51. Royal GD: Gezondheidsdienst voor Dieren
52. ID: IDentification
53. AMS: Automatic Milking System
54. CMS: Conventional Milking System
55. ALVA: AfkalfLeeftijd van VAarzen
56. I&R: Identificatie en Registratie dieren
57. MDP: Markov Decision Process
58. RPO: Retention Pay-Off value
59. MR: Milk Revenue
60. FC: Feed Cost
61. IC: Insemination Cost
62. H: Heifer rearing price
63. CV: Carcass Value
64. CR: Calf Revenue
65. R: expected Rewards
66. GM: Gross Margin of herd in euros (€)
67. e_{ID}: Event of Involuntary Disposal
68. e_{C}: Event of Conception

69. VEM: Voeder Eenheid Melk
70. Q_{milk}: Price of Milk in euros (€)
71. $milk_m$: Monthly milk yield
72. FP: Feed Price
73. BW: Body Weight
74. Mj: Mega-Joules/ 1000 Joules
75. DM: Dry Matter
76. m: Mortality rate of calves over 2 weeks age
77. R/100: Expected maximum replacement rate based on heifer supply
78. MOO: Multi-Objective Optimization
79. ML: Machine learning
80. AI: Artificial Intelligence
81. RL: Reinforcement Learning

About the Author

Pranav Shrikant Kulkarni (born September 25, 1992) was born and raised in Pune, India, a city with a rich tradition of valuing the pursuit of education. Hailing from a family that supported this pursuit wholeheartedly, education and academics have been subjects close to Pranav's heart.

Upon completing his undergraduate studies, Pranav decided to follow this interest in biology and pursue a bachelor's degree in veterinary science & animal husbandry at the Krantisinh Nana Patil College of Veterinary Science, Shirwal - a small rural town close to the city of Pune. An undergraduate research opportunity to study the genotyping of β-casein gene in cow milk spurred his interest in animal genetics- the mathematics in biology. The research subject, the pleasant countryside setting of the veterinary college and the comforting presence of dairy cows all around created in him a fondness for the bovine species that has been a constant throughout his academic journey.

Building upon his interests during his bachelor's degree, Pranav began his master's in animal sciences specializing in Genetics and Biodiversity at Wageningen University of Life Sciences in the Netherlands. Here, living in the vicinity of green pastures surrounded by Dutch cows, he wrote his Masters' thesis on the genetic epidemiology of digital dermatitis in Dutch dairy cattle. Additionally, he worked on modeling density-dependent and frequency-dependent transmission of environment-driven infections.

When an opportunity to continue working on mathematical modeling and culling in dairy cattle presented itself in the form of a PhD position, it was the best next step towards achieving Pranav's goal to be a life-long academic. His PhD project, a joint project between Wageningen University (Business Economics Group) and Utrecht University (Farm Animal Health Group), focused on the replacement and culling policies in Dutch dairy farms in response to governmental policy decisions. During this time, he gained valuable knowledge in subjects like animal health economics, policy effects on farm management and dairy herd operations. As a part of his PhD, Pranav has also presented his work in multiple conferences nationally and internationally. Along with the academic achievements of his master's and PhD degrees, Pranav's time in the Netherlands is full of great experiences and memories.

Going from the canals and pastures of the Netherlands to the sunny beaches and vineyards of California, Pranav is now about to embark on the next part of his journey as a post-doctoral researcher in the One Health institute at the University of California, Davis where his work will be aimed at the development of spatio-temporal models for spillover in zoonotic diseases with a focus on Arenaviruses.

(Written by Dr. Aryayashoda P. Kulkarni; edited by Pranav S. Kulkarni)

Pranav S. Kulkarni

Wageningen School of Social Sciences (WASS)

Completed Training and Supervision Plan

Name of the learning activity	Department/Institute	Year	ECTS*
A) <u>Project related competences</u>			
A1 Managing a research project			
WASS Introduction Course	WASS	2020-2021	1
Writing Research Proposal	BEC, WUR	2020	6
‘Survival Analysis to study replacement strategy of Dutch dairy farmers over 10 years’	SVEPM 2021, Toulouse / Online	2021	1
‘Impact of changes in national agricultural policy on the survival age of Dutch dairy cows ‘	ISVEE 2022, Halifax Canada	2022	1
‘Economic Impact of constrained heifer supply on Dutch dairy herds’	ISESSAH 2023, Helsinki Finland	2023	1
PhD Meetings BEC Group	BEC, WUR	2019-2023	2
A2 Integrating research in the corresponding discipline			
Economic Principles for Veterinary Science	Farm Animal Health – Utrecht University	2019	2.5
Advanced Business Economics BEC 30806	BEC, WUR	2020	6
Machine Learning and Applications in Medicine (Summer School)	Utrecht University/ UMC Utrecht		1.5
Essentials of Modelling	PE&RC & WASS	2023	1.5
B) <u>General research related competences</u>			
B1 Placing research in a broader scientific context			
Gaussian State space models	University of Copenhagen, Denmark	2022	1.5
Bi-weekly Epi Meetings	Epi Group, Utrecht University	2019-2023	2
VEEC Study Day – Fewer Livestock	VEEC	2022	1
Best practices for writing reproducible code	Utrecht University	2020	0.3

Scientific Integrity	WGS	2023	0.6
Introduction to Latex	PE&RC	2021	0.1
B2 Placing research in a societal context			
Organizing Committee: Veterinary Science Day 2023	Utrecht University	2023	2
The Conversation (Media training)	The Conversation Newspaper	2022	0.1
Writing Blogs for Academic Transfer	Academic Transfer	2019-2023	1

C) <u>Career related competences/personal development</u>			
C1 Employing transferable skills in different domains/careers			
Competence Assessment	WGS	2020	0.3
Career Assessment	WGS	2023	0.3
Mobilizing Scientific Network	WGS	2021	1
Effective and Efficient Communication in Academia and Beyond	WGS	2023	0.9
Teaching Assistance QVE 20306	QVE, WUR	2022	0.6
Total			**35.2**

*One credit according to ECTS is on average equivalent to 28 hours of study load

List of Publications

1. Kulkarni, P., Mourits, M., Nielen, M., van den Broek, J., and Steeneveld, W. 2021. Survival analysis of dairy cows in the Netherlands under altering agricultural policy. Prev. Vet. Med., 193:105398. DOI: https://doi.org/10.1016/j.prevetmed.2021.105398
2. Kulkarni P., Mourits M., Nielen M. and Steeneveld W. 2023. Associations between dairy farm performance indicators and culling rates under policy-driven herd size constraints. Front. Vet. Sci. 10:1062891. DOI: https://doi.org/10.3389/fvets.2023.1062891
3. Kulkarni, P.S., Mourits, M.C.M., Slob, J., Veldhuis, A.M.B., Nielen, M., Hogeveen, H., van Schaik, G. and Steeneveld, W., 2023. Dutch dairy farmers' perspectives on culling reasons and strategies. Prev. Vet. Med., p.105997. DOI: https://doi-org /10.1016/j.prevetmed.2023.105997
4. Kulkarni, P. S., Haijema, R., Hogeveen, H. and Steeneveld, W., and Mourits, M.C.M, Economic Impacts of Constrained Replacement Heifer Supply in Dairy Herds. SSRN: https://ssrn.com/abstract=4542707 [Preprint] DOI: http://dx.doi.org/10.2139/ssrn.4542707

Other Publications

1. Shende, T. C., Kulkarni P.S., and Pawar P.C., 2017. "Genotyping of HF crossbred cattle for β-casein genes using PCR-RFLP." Ind. Res. J. Ext. Edu. p105-107.
2. Kulkarni, P.S., Biemans, F., de Jong, M.C. and Bijma, P., 2021. On the origin of the genetic variation in infectious disease prevalence: Genetic analysis of disease status versus infections for Digital Dermatitis in Dutch dairy cattle. J. Ani. Breed. Genet., 138(6), p.629-642. DOI: https://doi.org/10.1111/jbg.12635

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