Economic and environmental sustainability in relation to dairy cow longevity

Ruozhu Han

Propositions

1 Farm economic performance is hardly associated with dairy cow longevity.
(this thesis)

2 Extending dairy cow longevity contributes to sustainable milk production.
(this thesis)

3 Research is essential to validate common beliefs.

4 In selecting a research methodology, suitability is more important than feasibility.

5 Integrating mental support into each PhD program is crucial for the well-being of future researchers.

6 Having a pet, as buddy, improves the quality of life.

Propositions belonging to the thesis, entitled

Economic and environmental sustainability in relation to dairy cow longevity

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Contents

CHAPTER 1

1

General introduction

1.1 Background

World milk production is predicted to grow by 1.6% per year from 2020 to 2029 to meet market demand (OECD-FAO, 2020). However, besides being an important source of nutrition and subsistence, milk production is also an important source of greenhouse gas emissions (GHG). In Europe, it is estimated that the dairy sector is responsible for 30%-40% of the livestock sector's GHG emissions (Lesschen et al., 2011; Weiss et al., 2012), while it is estimated that 14.5% of global human-induced GHG emissions is contributed by livestock production (FAO, 2013; Gerber et al., 2013). Consequently, the environmental pressure of milk production forces stakeholders to consider the trade-offs between environmental and economic aspects of dairy farming.

The three main sources of GHG emissions in dairy production are enteric fermentation, feed production and manure management (Rotz, 2018; Vellinga et al., 2013). Strategies to reduce GHG emissions typically focus on these sources through specialized disciplines such as animal nutrition and animal breeding, feed production, and manure management technology (e.g., De Vries et al., 2012; Ellis et al., 2008; Wall et al., 2010). Besides approaches aimed at nutrition, breeding, feed production and manure management, GHG emissions are also affected by dairy cattle management. One management strategy to mitigate GHG emissions is by increasing dairy cow longevity. With an increased dairy cow longevity, less replacement animals need to be reared which is saving in GHG emissions. Dairy cow longevity is usually defined by the total lifespan of an animal from birth to culling, or by the duration of its productive life from first calving and culling (Vacek et al., 2006). Other measures of longevity are also used, such as average lifetime milk production and culling rate (Schuster et al., 2020).

Extending longevity may also improve the profitability of dairy production (Grandl et al., 2019), as rearing a lower number of replacement animals reduces the costs for replacement animals. Moreover, with an increased longevity, the proportion of multiparous cows within the herd increases, which will lead to a higher average milk production per cow per year, because multiparous animals have a higher milk yield than primiparous cows. Moreover, an increased longevity is perceived by society as a relevant indicator of animal welfare (Bruijnis et al., 2013). Good feeding, housing and health, and circumstances that allow for appropriate behaviour are important aspects that contribute to animal welfare (Welfare Quality®, 2009). A good longevity performance is an indicator of good farm management on those aspects. Currently, the average lifespan of dairy cows is about 5.8 years in the Netherlands (Kulkarni et al., 2023). In practise, the maximum lifespan of dairy cows can reach 11 years under production circumstances (Kulkarni et al., 2023), suggesting opportunities to extend dairy cow longevity.

1.2 Consequences of extending dairy cow longevity

Longevity is an important trait for the profitability of dairy production (Allaire et al., 1992; Pritchard et al., 2013). In the Netherlands, as in most high milk producing countries, a farmer's decision to cull a dairy cow is largely driven by economic considerations (Demeter et al., 2011). A cow will be culled, based on a comparison of the expected performance of the present cow (based on her observed productive performance, reproduction and health status) with the expected future performance of an available replacement animal. Increased dairy cow longevity can reduce the costs of rearing youngstock due to a lower replacement rate, while producing the same amount of output (Brickell et al., 2011; Kelleher et al., 2015; Pritchard et al., 2013). Furthermore, because mature cows produce more milk than young cows, increased longevity can also improve the total milk production of the herd (Allaire et al.,1992; Brickell et al., 2011; Vanraden et al., 1995). Although extending cattle longevity can bring economic benefit, it may also lead to increased milk losses and higher costs. As the longevity of cows increases, the proportion of cows with greater parity in a herd also rises, which can result in a higher likelihood of health issues in the herd and consequently higher costs for disease treatments due to a higher risk of disease. Several studies have indicated a strong association between health disorders and parity (Lean et al., 2023; Lee et al., 2006). Finally, since the number of lactations (parity) increases, the difficulty of conception also increases (Rearte et al., 2018), which can lead to reduced milk production efficiency in older cows.

Extending cattle longevity does not only affect herd profitability, it can also reduce the GHG emissions of dairy farming due to a lower demand for replacement animals (Kok et al., 2017; Lehmann et al., 2014). Rearing replacement animals takes two years, during which heifers consume feed and contribute to GHG emissions, without any production. Moreover, an increased herd milk yield in case of an older herd could mitigate the GHG emissions per unit milk produced (Zehetmeier et al., 2012). At the same time, an older herd implies increased disease incidence rates, which could increase GHG emissions (Mostert, 2018).

It is unknown whether the advantages of increasing the longevity of dairy cows outweigh the disadvantages, either from an economic or environmental perspective. Furthermore, there is a lack of research on the trade-offs between economic and environmental consequences resulting from extending the lifespan of dairy cows.

1.3 Managing dairy cow longevity

Culling of dairy cows is often described as being voluntary or involuntary. Involuntary culling, or unexpected mortality, is not subject to farmer decision making and is difficult to avoid. Given this definition, most of the culling is voluntary and thus subject to farm management. The main reasons for voluntary culling of dairy cows are subfertility, health problems, and low milk production (Dallago et al., 2021; Haine et al., 2017). Specifically, poor fertility, mastitis and claw disorders are the main culling reasons in the Netherlands (Compton et al., 2017; A. De Vries et al., 2020; Zijlstra et al., 2020). Strong associations between reproductive performance and dairy cow longevity have been published (e.g., Charfeddine et al., 2017; Sewalem et al., 2008). Moreover, strong associations between dairy cow health and longevity have been published. For instance regarding mastitis (e.g., Hu et al., 2021; Neerhof et al., 2000) and lameness (e.g.,Bruijnis et al., 2013). Culling decisions are primarily driven by economic considerations based on herd characteristics, including intrinsic cow factors such as milk production level, health status and reproduction status, and extrinsic factors such as the availability of replacement heifers, number of cow-places and milk price (Alvåsen et al., 2018). Although many of the intrinsic and extrinsic factors regarding voluntary culling have been identified, little is known about the impact of herd management practices such as young stock rearing, health management, and reproduction management on dairy cow longevity, and the related GHG emissions and economic efficiency (Smith et al., 2000). In addition, numerous studies have evaluated the economic and/or environmental impact of subfertility and health disorders at individual cow level (e.g., Bell et al., 2010; Mostert, 2018; Zehetmeier et al., 2012). Impact at cow level can differ from the impact at herd level. For instance, at the cow level, the consequence of a cow getting sick is a reduction in milk production and costs for treatment, while at the herd level, it may be a lower availability of newborn calves and a higher demand of replacement cows due to a higher probability of culling. The tradeoffs between economic and environmental consequences at herd level of increasing cow longevity through management are rarely studied. In order to see the potential economic and environmental impact of a change in longevity management, information about the association of dairy management and longevity would be useful.

1.4 Aim

The aim of this thesis is to evaluate the economic and environmental impacts of dairy farm management practices related to dairy cow longevity. Based on this objective the following specific subobjectives have been derived:

- Evaluate the association of herd characteristics with dairy cattle longevity;
- Evaluate the association of dairy cattle longevity with farm gross margin;
- Evaluate the association of dairy cattle longevity with farm level technical inefficiency of milk production;
- Quantify the impact of reproduction management decisions on dairy cow longevity, herd profitability and GHG emissions;
- Quantify the impact of disease prevention management measures on dairy cow longevity, herd profitability and GHG emissions.

1.5 Outline of the thesis

The outline of the thesis is visualised in Figure 1.1. Chapter 2, 3 and 4 are empirical studies to assess the associations of dairy cow longevity with herd performance characteristics and farm economic performance. In Chapter 2, the assessed herd performance characteristics included indicators on herd structure, youngstock rearing, reproductive performance, health status and milk production at herd level, derived from a large data set of Dutch dairy herd performance data. In Chapter 3, the association between dairy cow longevity and gross margin was studied using longitudinal Dutch accounting data combined with herd performance data. Considering the non-monetary costs, such as herd and land size, and the impact of price volatility, the economic performance of dairy farms was measured by estimating the technical inefficiency of the farms in Chapter 4. It displays the inefficiency score of each input of a dairy farm, as well as the association of cattle longevity with farm level input-based technical inefficiency. In order to evaluate the causal impact of herd management on extending dairy cow longevity and the associated economic and environmental consequences, simulation studies were performed in Chapters 5 and 6. Combining the results from previous chapters, reproduction management decisions and disease prevention management were applied to extend dairy cow longevity, and the associated partial net return and GHG emissions per kg milk were quantified. In Chapter 7, the assessed sustainability impacts of dairy farm management practices related to dairy cow longevity are integrated, and trade-offs are discussed.

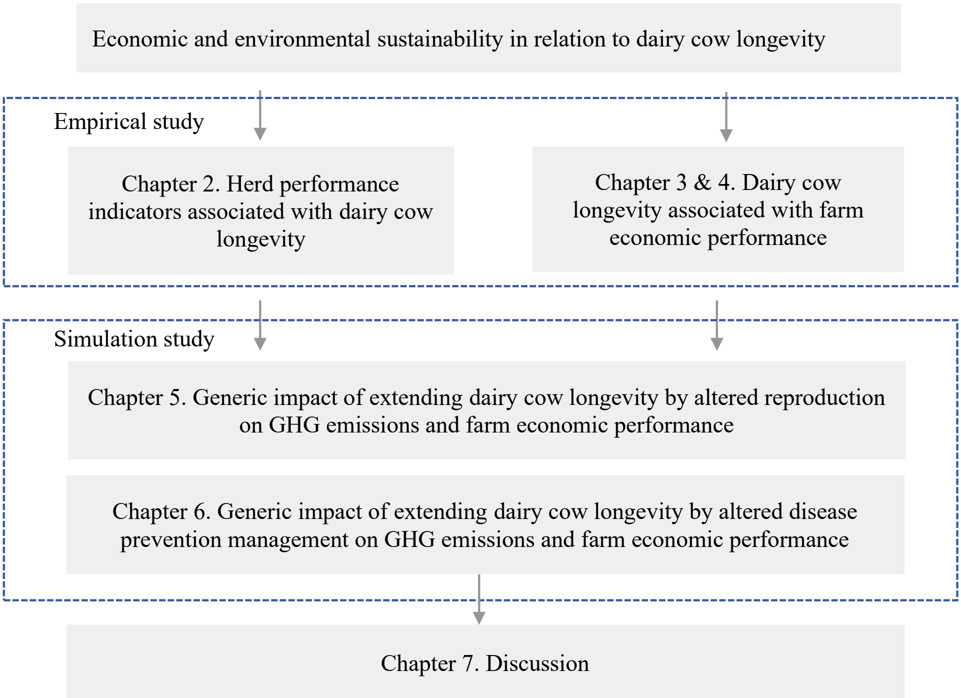

Figure 1.1. Outline of the thesis

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CHAPTER 2

2

The association of herd performance indicators with dairy cow longevity: an empirical study

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2.1 Abstract

The associations between reproductive performance, milk yield and health status with the risk of culling, and thus with a cow's longevity, have been well documented at the individual cow level. Associations at individual cow level may, however, not be valid at herd level due to interrelated herd management aspects and/or policy restrictions. The objective of this study was to explore the association of herd performance indicators with herd-level dairy cow longevity under Dutch production conditions. Longevity was expressed by three different measures, viz. age at culling, lifetime milk production of culled cows and culling rate. The evaluated herd performance indicators included factors on milk production, youngstock rearing, reproduction and health performance as registered on 10 719 Dutch commercial dairy herds during the period 2007-2016. Averaged over herds and the evaluated period, the age of culled milking cows was 2 139 days (5.8 years, SD±298 days), the lifetime milk production of culled cows was 31 238 kg (SD±7,494 kg), and the culling rate was 0.24 (SD±0.08). A mixed linear regression modelling approach was applied to evaluate the association of each of the three longevity measures with the selected herd performance indicators. The results indicated that only four herd performance indictors (herd size, herd expansion, heifer ratio and the proportion of cows with potential subclinical ketosis) shared significant associations with all three longevity variables. Generally, the strength of the associations between each of the evaluated longevity measures and herd performance indicators was only limited. The absence of strong associations between the longevity measures and herd performance indicators reveal that there is potential of extending cattle longevity without affecting the herd performance in terms of milk production, reproduction and health. Moreover, only part of the observed variance in longevity among the herds over time was explained by the herd performance variables, indicating that differences in longevity at herd level may predominantly be determined by other factors, like farmers' attitude and strategic management.

2.2 Introduction

Dairy cattle longevity can be defined as the duration of the life of a dairy cow, reflected by the time from birth until the moment of culling from the herd (Schuster et al., 2020). In the Netherlands, the lifespan of milking dairy cows in a herd is on average about 5.8 years ranging from 4.9 years to 7.1 years (CRV, 2019). This is, however, below the potential natural lifespan of dairy cows. Prolonging dairy cattle longevity is one of the potential options to contribute to more sustainable milk production, from an economic, an environmental as well as a social perspective (Schuster et al., 2020). In the Netherlands, a farmer's decision to cull a dairy cow is largely driven by economic considerations (Demeter et al., 2011), by comparing the expected performance of the present cows (defined by its observed productive performance, reproduction and health status) against the expected future performance of the available replacement animals. As long as a prolonged longevity does not trigger higher risks of reproductive problems, health disorders or both, increased longevity could improve economic efficiency by reducing rearing costs, as fewer replacement heifers are needed, and increasing the average herd production (Olechnowicz et al., 2016).

Dairy production is an important source of greenhouse gas (GHG) emissions (Wolf et al., 2017). An increased longevity could contribute to a more environmental-friendly milk production by reducing the GHG emissions from youngstock rearing. Moreover, an increased longevity is perceived by society as a relevant indicator of animal welfare (Bruijnis et al., 2013). Low culling rates, especially low mortality rates, indicate that a herd keeps a large group of existing cows alive and has the ability to maintain expected production. Up till now, culling decisions were purely regarded as the responsibility of the farmer. However, because of the increased general interest in environment (i.e., GHG emissions) and animal welfare (i.e., the moral concerns regarding premature culling of dairy cows), there is an increased societal interest for a prolonged dairy cattle longevity. To align with these societal interests, Dutch dairy processing companies and farmers' associations actively advocate prolongation of cattle longevity (Galama et al., 2020).

Longevity can be expressed in several ways. Besides average lifespan or average age at culling, other measures are used to express longevity, like average lifetime milk production and culling rate (Schuster et al., 2020). Unlike age at culling, lifetime milk production not only depends on the average lifespan, but also on milk production intensity. Therefore, lifetime milk production measured as the kg of milk produced by the cow during its lifespan embodies a more economic and environmental perspective on longevity (Pritchard et al., 2013). As indicated earlier, animal welfare is often assessed by society on the basis of the proportion of culled cows in the herd, making the culling rate a relevant longevity feature from a societal perspective.

A considerable number of studies have been carried out on the risk factors that are associated with culling or longevity on cow level. In these studies, poor fertility and health disorders, especially the occurrence of mastitis, have been indicated as the most important risk factors to cow survival (e.g., Bell et al., 2011). Significant associations between reproductive traits and functional longevity on cow level have been demonstrated by Pfeiffer et al (2015) and Sewalem et al (2005). In addition, significant impacts of low productivity on the risk of an individual cow to be culled have been verified as well (Compton et al., 2017). These associations at individual cow level may, however, differ at herd level; partially because of interrelated herd management aspects (e.g. young stock rearing) (Haine et al., 2017) and herd size restrictions imposed by policy regulations like milk quota before 2015 or phosphate restrictions after 2018 (Schuster et al., 2020). For instance, a cow with a relatively low production has a higher probability of being culled in comparison to a high productive cow within the same herd, while a herd with a relatively low average milk production may not have a higher culling rate than a herd with a high average milk production. Scientific literature on the association of herd performance indicators with herd-level longevity performance is lacking. Only a few studies so far have explored the association of longevity with herd performance indicators such as herd size, herd turnover rate, and milk yield by the use of empirical data (e.g., Adamczyk et al., 2017; Alvåsen et al., 2014). More extensive insights at herd level are needed when targeting farmer and policy maker towards an increase in dairy cow longevity.

The objective of this study was to explore the association of herd performance indicators with different herd-level dairy cow longevity aspects (age at culling, lifetime milk production and culling rate) using Dutch production conditions. The herd performance indicators included factors on milk production, youngstock rearing, reproduction and health performance as derived from Dutch dairy herd data registered during the period 2007-2016.

2.3 Materials and methods

Available data

Data over the period 2007-2017 were provided by the Dutch Cooperative Cattle Improvement Organization CRV BV (CRV, Arnhem, the Netherlands) with consent of their associated farmers. To prevent researchers to see any information about individual farmers, a separate, independent, company (iDTS, the Netherlands) did anonymize the data so that data could not be traced back to individual farmers. A contract between the data provider, the data anonymizing company and the authors' university (Wageningen University) ensures the correct management procedures of herd data. The data included information on 20 796 dairy herds (mainly Holstein-Friesian), representing approximately 80 percent of all dairy herds in the Netherlands. The dataset contained herd data regarding longevity features, reproduction performance, milk production performance and health status. Information on herd longevity features were available as annual averages for the production year (September-August). Reproduction performance features were registered by annual calendar year averages (January - December). Data on herd milk production performance were routinely collected on several occasions per year (i.e., test days with intervals of 3-9 wks). These milk production data were averaged over the multiple test days in one calendar year to obtain a yearly herd average. The information on the herd health status was derived from individual cow level data and averaged per calendar year at herd level. From the overall database, 19 variables were selected for further data editing and analyzes based on their expected relation with longevity (Bell et al., 2010; Jankowska et al., 2014). An overview of the selected variables is displayed in Table 2.1.

This observational study uses anonymized dairy herd management data that is originally collected, stored and processed by CRV according to their privacy statement on the use of personal data. Within this statement dairy farmers are informed about the purposes for which the collected data could be used (like research) and under what conditions and about their consent and rights to object in this respect. As the data had been anonymized by a third independent party prior to access and analysis, and the study did not pose any potential risks to individual dairy farmers or their privacy, no additional consent was requested for the use of the data in this study.

Table 2.1. Descriptive statistics on the selected herd performance indicators, indicating the distribution of herd averaged values across herds and years (2007- 2016).

Variables	Description	Records, N	Mean	SD	Percentile _5[5]	Percentile _95[5]
Longevity						
Age culled cows	Age of culled milking cows (days)	107 176	2 139	298	1 719	2 674
Life. prod. culled cows	Lifetime milk production of culled milking cows (kg)	107 177	31 238	7 495	20 344	44 465
Culling rate [1]	Annual rate of culled milking cows over number of milking cows	107 168	0.24	0.08	0.12	0.38
Herd structure						
Herd size	Number of milking cows <=50 (Small)	12 034	43	5	34	50
	51-100 (Medium)	62 680	74	14	53	97
	101-200 (Large)	29 413	129	24	102	181
	>200 (Very large)	3 063	267	90	203	432
Herd expansion [1]	Rate of herd size change relative to herd size of 2007	107 190	1.15	0.25	0.91	1.61
Youngstock						
Heifer ratio [1]	Ratio of first calving heifers over number of milking cows	107 176	0.24	0.06	0.14	0.34
Birth first AI	Interval between birth and first AI (days)	88 912	491	54	433	588
Calve born first AI youngstock [2]	Percentage of calves born after the first AI of youngstock	104 870	52.48	18.15	22.22	81.82
N AI success youngstock [2,3]	Number of AIs until conception per head of pregnant youngstock	98 429	1.8	0.4	1.1	2.6

N AI youngstock [2]	Number of AIs per head of inseminated youngstock	103 558	1.9	0.5	1.1	2.8
Age first calving	Age at the first calving(days)	105 731	792	48	733	881
Reproduction						
CI [3]	Calving interval (days)	105 427	415	26	380	462
Calving first AI [3]	Interval from calving to first AI (days)	103 980	99	24	72	140
Calve born first AI [4]	Percentage of calves born after the first AI after calving	106 070	49.73	15.27	26.39	73.40
N AI success [2,4]	Number of AIs until conception per head of pregnant dairy cow	98 633	1.8	0.4	1.2	2.5
N AI [2,4]	Number of inseminations per dairy cow	104 298	2.0	0.5	1.2	2.8
Health status						
High SCC	Percentage of primiparous cows with SSC over 150,000 cells/ml and multiparous cows with SCC over 200,000 cells/ml over average number of milking cows	102 301	19.49	7.13	9.12	32.20
Newhigh SCC	Percentage of new cows in high SCC	102 300	8.89	2.85	4.87	13.54
SCC	Number of somatic cells per ml of milk *1,000 (cells/ml)	102 205	202	63	112	318
Suspect subclinical ketosis	Ratio of suspected cows with subclinical ketosis over average number of milking cows	107 190	0.04	0.02	0.01	0.07
Milk production						
FPCM305 [1]	Fat protein corrected milk production within 305 days of lactation (kg)	106 665	9 093	900	7 534	10 527

[1] Derived indicators, computed by variables registered by CRV
[2-4] Removed indicator due to P-value of univariate analysis<0.25 in model of age of culled milking cows, lifetime milk production of culled milking cows and culling rate, respectively.
[5] The value of variable in 5 or 95 percentile.

2

Data editing

The study focused on commercial Dutch dairy herds, which remained in production throughout the evaluated period of 2007-2017. Until 2017, 20 591 herds met the condition of successive farming. Due to the lack of data after 2017 to prove continued farming thereafter, the data entries from 2017 were excluded from database. To classify a herd as a commercially viable dairy herd, a herd had to adhere to four conditions. Firstly, they had to have at least 6 and not more than 17 test days per calendar year (excluding 7 857 herds). Secondly, the number of milking cows within a herd should not have been less than 30 in each calendar year (excluding 1 167 herds). Thirdly, the herd-level average milk production per 305 days must have been over 6 000 kg per calendar year (excluding 359 herds). Finally, herds should have had an annual culling rate between 0.1 and 0.5 for 8 out of the 10 calendar years (excluding 431 herds). The final dataset on herd performance consisted of 10 719 herds over the years 2007-2016.

Subsequently, data entries reflecting biological unrealistic values were removed from the database. Nine entries were removed because of annual culling rates ≥1. From the herd reproduction performance data, 143 entries were removed due to average calving intervals (CI) on herd level < 310 days or > 600 days. Also, entries indicating a herd average interval between calving to first artificial insemination (AI) of milking cows < 30 days or > 365 days were removed (142 entries). Twenty entries with an average age at first calving < 500 days or > 1 500 days were removed. Entries indicating the ratio of number of the first calving heifer over the milking cow ≥1 were removed (14 entries), Lastly, one entry was removed because of an annual percentage of new cows with a high somatic cell count (SCC) in a herd ≥100%.

Cattle longevity variables.

Three annually (production year) averaged cattle longevity variables were selected: age of culled milking cows (days), lifetime milk production of culled milking cows (kg), and culling rate. The number of culled cows represented all dairy cows, after first calving, removed from the milking herd for slaughter, salvage or death within a production year, following the definition used by Fetrow et al (2006). Animals sold for production purposes to other dairy farms were excluded from this number. The annual average culling rate was computed by dividing the number of culled milking cows by the number of milking cows in the same production year.

Herd size variables.

The herd size was represented by the number of milking cows within a herd on the end of August which was stratified into 4 groups, representing small, medium, large and very large sized herds. The stratification thresholds for these categories were 50, 100, 200 cows, respectively. To account for herd expansion during the evaluated period, a herd expansion ratio was derived by relating the sizes of a herd through time to its reference herd size of 2007.

Young stock variables.

The young stock performance indicator heifer ratio was derived by dividing the number of first calving heifers by the number of milking cows in a production year. Reproduction performance of young stock was presented by the annual averaged herd data on the interval between birth to first AI, percentage of calves born after the first AI, number of AIs until conception, number of AIs and age at first calving.

Reproduction variables.

The herd reproduction performance of milking cows was reflected by the annual averaged herd data on CI, interval between calving to first AI, percentage of calves born after the first AI, number of AIs until conception and number of AIs.

Health variables.

Data that reflected the herd health status in relation to subclinical mastitis included average SCC, the annual percentage of cows with a high SCC and the annual percentage of new cows with a high SCC in a herd. SCC over 150 000 cells/ml for primiparous cows and over 200 000 cells/ml for multiparous cows have been used to define high SCC counts. These thresholds are used in the Netherlands as a standard to reflect subclinical mastitis (De Vliegher et al., 2004; Huijps et al., 2009). The percentage of cows with a high SCC and new cows with a high SCC were collected on each test day and averaged over all test days within a calendar year.

To get insight in the metabolic status of a herd, the fat protein ratio during the first 100 DIM was used as an indicator, where a ratio > 1.5 was regarded as an indication of the occurrence of subclinical ketosis (Van Soest et al., 2019). Given this ratio per cow per test day, the herd ratio of cows with a high fat protein ratio was determined. The average ratio of suspected cows with subclinical ketosis within a herd was calculated as an average over all test days within one calendar year.

Milk Production variable.

Based on the 305-day milk (kg), fat (%) and protein (%) production, the fat and protein corrected milk production in 305 days (FPCM305) was determined as follows (Yan et al., 2011):

$$\mathrm{FPCM305(kg)} = \mathrm{milk\ prod305days(kg)} * (0.337 + 0.116 * \mathrm{Fat\ content\ 305\ days\ (\%)} + 0.06 * \mathrm{Protein\ content\ 305\ days(\%)})$$

Data analyses

A mixed linear regression model was applied to analyze the association of herd performance indicators with the three herd-level longevity variables, i.e., age of culled milking cows, lifetime milk production of culled milking cows and annual culling rate. Herd as random effect was included in the linear mixed model to capture any other unobserved herd heterogeneity, such as specific herd management. To correct for repeated measurements, a covariance structure was adopted based on the Akaike information criterion (AIC). Competing covariance structures (i.e., independent, compound symmetry, first-order autoregressive and unstructured) were tested for their fit and the structure with the lowest AIC, the unstructured covariance structure, was regarded to give the best fit and chosen for the final modelling. A year variable was forced into all models to capture potential time effects (e.g., milk price changes). Explanatory variables were selected based on the following five steps: (1) a linear relationship check between each pair of explanatory variable and longevity variable; (2) continuous variable's normality distribution check; (3) univariate analysis; (4) collinearity screening; and (5) stepwise regression. All data manipulations and modelling were performed in R (Team, 2018).

Linear relationship check.

Continuous variable normality check and univariate analysis. The linearity of the relationship between the selected explanatory variables and longevity variables was visually inspected by creating boxplots. Histograms and descriptive statistics were used to scrutinize the distribution of continuous variables and to assist any further categorization or transformation. As a result, seven skewed variables were log transformed to be more normally distributed and to stabilize the variance, including the variable of herd expansion, percentage of new cows with high SCC in a herd, CI, interval between calving to first AI, interval between birth to first AI, number of AIs until conception and age at first calving. For all potential explanatory values, a univariate analysis with each of the three longevity variables was carried out. Variables with a P-value <0.25 were kept for the final multivariable modelling process (Mickey et al., 1989).

Consequently, five, three and three variables were removed from the age and lifetime milk production of culled milking cows and culling rate models, respectively (see Table 2.1).

(Multi)collinearity.

For the remaining variables, potential collinearity was identified by examining the Pearson correlation coefficients, where a correlation coefficient larger than or equal to 0.8 was used to determine collinearity. In addition, independent variables with a variance inflation factor of more than or equal to 10 were considered as variables causing serious multicollinearity problems (James et al., 2013). For this reason, two potential explanatory variables were removed from all three longevity models: i.e., average SCC and average percentage of new cows with high SCC (highly correlated with average percentage of cows with high SCC). Moreover, in the model for lifetime milk production of culled milking cows, the variable average number of AIs of cows until conception was omitted (highly correlated with average number of AIs of cows). In the model on culling rate, the variable average number of young stock AIs until conception (highly correlated with average number of young stock AIs) was excluded.

Stepwise regression.

The herd indictors were tested using a backward stepwise selection procedure. This procedure continued until the marginal change in the Bayesian information criterion (BIC) between selection steps increased rapidly.

In order to compare the explanatory value of the regressed performance indicators on longevity, the continuous explanatory variables were, subsequently, transformed by centering and scaling to obtain insight in the change in estimated longevity value resulting from one standard deviation increase of in explanatory variable value.

2.4 Results

Longevity descriptive statistics

Averaged over the 10 719 herds and the 10-yrs period, the age of culled milking cows in a herd was 2 139 days (5.8 years, SD±298 days) (Table 2.1). The lifetime milk production of culled milking cows in a herd was 31 238 kg (SD±7,494 kg), and the culling rate in a herd was 0.24 (SD±0.08). The three defined longevity variables had a right-skewed distribution. Although the annually averaged age and lifetime milk production of culled milking cows did not alter much throughout the evaluated 10 years, the variance around these two average variables decreased over the years. This is in contrast to the variance of the annual culling rate, which showed no tendency of change over time. (Table 2.2).

Cattle longevity varied with herd size (Table 2.2). Average age of culled milking cows decreased with increasing herd size (trend coefficient $P<0.001$); the average age at culling in the smallest sized herds (<50 cows) was 130 days higher than in the largest sized herds (>201 cows). Average lifetime milk production of culled milking cows reached a plateau for herds having a medium herd size (51~100 cows). The very large herd size (>201 cows) had the lowest average lifetime milk production of 30 127 kg. Moreover, the standard deviation of these two longevity variables decreased from small (<50 cows) to very large (>201 cows) herds. The average culling rate in a herd slightly varied among herd sizes from 0.24 to 0.26. Although the variance of average culling rate decreased with increasing herd size, the variance in the smallest sized group was extremely larger than in the other herd sized groups.

Table 2.2. Herd averages on age of culled milking cows (days), lifetime milk production of culled cows (kg) and culling rate with SD by year and herd size.

	Age culled cows (days)		Lifetime production culled cows (kg)		Culling rate	
	Mean	SD	Mean	SD	Mean	SD
Year						
2007	2 146	318	30 523	7 952	0.22	0.09
2008	2 171	319	31 286	7 970	0.21	0.08
2009	2 160	303	31 229	7 492	0.26	0.09
2010	2 141	296	31 125	7 327	0.25	0.09
2011	2 119	286	30 938	7 226	0.26	0.09
2012	2 121	298	31 205	7 448	0.24	0.08
2013	2 130	296	31 338	7 569	0.22	0.07
2014	2 138	289	31 562	7 315	0.25	0.08
2015	2 131	292	31 493	7 371	0.23	0.08
2016	2 135	280	31 683	7 169	0.24	0.08
Herd size [1,2]						
Small	2 191	370	31 107	9 025	0.26	0.26
Medium	2 149	304	31 395	7 657	0.24	0.08
Large	2 105	252	31 074	6 536	0.23	0.07
Very large	2 061	212	30 127	5 822	0.24	0.07

[1] Herd size was stratified by small, medium, large and very large based on the number of milking cows >= 50 (2269 herds), 51-100 (8515 herds), 101-200 (5003 herds) and >=201 cows (682 herds), respectively.
[2] The significant associations (p<0.001) tested by simple linear regression.

Modelling results

In the three final mixed linear regression models, 8,11 and 8 herd performance indicators were significantly ($P<0.001$) associated with age of culled milking cows, lifetime milk production of culled cows and culling rate, respectively. Results of the three regression models are displayed in Table 2.3. The models only captured part of the variance that was observed among the herds over times as indicated by the relatively low marginal and conditional R^2. The marginal R^2 were 0.03, 0.08 and 0.23 in the model of culled milking cows, lifetime milk production of culled cows and culling rate. In addition, the conditional R^2 were 0.40, 0.40 and 0.49 respectively. Table 2.4 presents the coefficients based on the centered and scaled continuous variables. The regression results indicated that only four herd performance indictors shared a significant association with all three longevity variables. These indicators were herd size, herd expansion, heifer ratio and the proportion of cows with potential subclinical ketosis in a herd. The relevance of these herd performance indicators varied among the longevity variables as described below.

Herd performance indicators associated with age of culled milking cows.

Age of culled milking cows in the very large (>201 cows), large size (101~200 cows) or medium size (51~100 cows) were successively significantly less than of small herds (<50 cows). The difference was 53, 35 and 18 days less, respectively. Additionally, herd expansion, heifer ratio, age at first calving, CI, ratio of number of suspected cows with subclinical ketosis and FPCM305 were also significantly ($P<0.01$) associated with age of culled milking cows. Heifer ratio had the strongest association with herd longevity. An increase in heifer ratio by one standard deviation (0.06) was associated with a decrease of 27 days in age of culled milking cows.

Herd performance indictors associated with lifetime milk production of culled cows.

Compared with the model for age of culled milking cows, more reproduction performance indicators were included as significant explanatory variables ($P<0.01$) in the lifetime milk production model, such as number of AIs until conception, interval between birth and first AI (Table 2.4). Among all the significant herd indicators ($P<0.01$), lifetime milk production of culled cows was most sensitive for changes of FPCM305 and heifer ratio. One standard deviation (900 kg) increase of FPCM305 was associated with an increase of 1 846 kg in lifetime milk production. One standard deviation in heifer ratio (0.06) was associated with a reduction in lifetime milk production of culled cows by 576 kg (Table 2.4).

Herd performance indicators associated with culling rate.

In the culling rate model, herd expansion was the most important associated variable: one standard deviation increase in herd expansion (0.25) was associated with a decrease of culling rate by 0.04 (Table 2.4). Besides herd expansion, culling rate was strongly associated with herd size. In reference to the smallest sized herds, culling rate was lower in the medium to large herds, but higher in the very large sized herds. In addition, compared to the other herd sizes, smaller herds had a relatively large standard deviation in culling rate, indicating a larger heterogeneity among the herds in this herd size category. Although the coefficients of association between health indicators (i.e., the percentage of cows with high SCC and the ratio of cows with potential ketosis) and culling rate were relatively small, they reflected significant explanatory variables ($P<0.01$).

Table 2.3. Results of the mixed linear regression models on the association of age and lifetime milk production of culled milking cows and culling rate with herd performance indicators.

		Age culled cows (days)			Lifetime production culled cows (kg)			Culling rate		
		Regression coefficient	SE	*P*-value	Regression coefficient	SE	*P*-value	Regression coefficient	SE	*P*-value
Intercept		-55.41	194.20	0.78	40 787.57	4054.22	<0.001	0.4519	0.037	<0.001
Year	2007 [1]	Ref.			Ref.			Ref.		
	2008	29.94	3.76	<0.001	908.57	91.39	<0.001	-0.0028	0.001	0.005
	2009	26.35	3.82	<0.001	860.13	93.84	<0.001	0.0482	0.001	<0.001
	2010	13.65	3.86	0.04	603.47	94.95	<0.001	0.0481	0.001	<0.001
	2011	-9.67	3.91	0.01	341.67	96.10	<0.001	0.0630	0.001	<0.001
	2012	1.64	3.96	0.68	949.91	97.53	<0.001	0.0450	0.001	<0.001
	2013	7.09	4.08	0.08	1 137.81	100.51	<0.001	0.0357	0.001	<0.001
	2014	21.52	4.10	<0.001	1 337.70	100.80	<0.001	0.0726	0.001	<0.001
	2015	15.83	4.29	<0.001	1 146.31	105.38	<0.001	0.0581	0.001	<0.001
	2016	36.07	4.48	<0.001	1 303.78	110.48	<0.001	0.0830	0.001	<0.001
Herd size [3]	Small [1]	Ref.			Ref.			Ref.		
	Medium	-17.96	4.25	<0.001	-42.04	104.07	0.69	-0.0176	0.001	<0.001
	Large	-35.15	5.32	<0.001	-365.30	129.57	0.005	-0.0126	0.001	<0.001
	Very large	-52.62	9.89	<0.001	-1 050.12	240.97	<0.001	0.0181	0.003	<0.001
Herd expansion log [2]		-55.09	8.51	<0.001	-818.57	207.46	<0.001	-0.2203	0.002	<0.001
Heifer ratio		-433.05	14.66	<0.001	-9 242.08	361.47	<0.001	0.1269	0.004	<0.001
Birth first AI log (days) [2]					-1 458.69	350.24	<0.001			
Calve born first AI youngstock(%)								-0.0001	0.000	<0.001
N AI youngstock					-142.51	70.47	0.04			
Age first calving log (days) [2]		208.91	24.31	<0.001	-2 828.13	649.08	<0.001			
CI_log (days) [2]		179.73	21.82	<0.001				-0.0433	0.006	<0.001
Calve born first AI (%)					8.55	3.08	0.01			

N AI				517.14	116.73	<0.001			
High SCC (%)							0.0008	0.000	<0.001
Suspect subclinical ketosis	-273.29	61.89	<0.001	-15 173.35	1 520.62	<0.001	0.0984	0.017	<0.001
FPCM305 (kg) [4]	-0.02	0.00	<0.001	2.13	0.05	<0.001			

[1] This group was used as reference category in the regression analyzes

[2] Indictors were log transformed

[3] Herd size was stratified by small, medium, large and very large based on the number of milking cows >= 50, 51-100, 101-200 and >=201 cows respectively

[4] FPCM305 = the average fat and protein corrected milk production in 305 days within a herd

Table 2.4. The estimated association of continuous herd performance indicators on age and lifetime milk production of culled milking cows and culling rate. The coefficients of the continuous variables indicate the change in longevity variables resulting from a SD increase in mean values.

			Age culled cows (days)		Lifetime production culled cows (kg)		Culling rate	
	Mean	SD	Regression coefficient	SE	Regression coefficient	SE	Regression coefficient	SE
Estimated value [1]			2141.81	5.11	30858.10	124.63	0.206	0.0014
Herd expansion log	1.15	0.25	-10.03	1.55	-149.01	37.77	-0.040	0.0004
Heifer ratio	0.24	0.06	-26.53	0.90	-566.14	22.14	0.008	0.0002
Birth first AI log (days)	491	54			-142.28	34.16		
Calve born first AI youngstock(%)	52.48	18.15					-0.002	0.0003
N AI youngstock	1.9	0.5			-67.43	33.34		
Age first calving log (days)	792	48	11.45	1.33	-155.00	35.57		
CI log (days)	415	26	10.30	1.25			-0.002	0.0003
Calve born first AI (%)	49.73	15.27			104.55	37.69		
N AI	2.0	0.5			213.79	48.26		
High SCC(%)	19.49	7.13					0.005	0.0004
Suspect subclinical ketosis	0.04	0.02	-5.15	1.17	-285.80	28.64	0.002	0.0003
FPCM305(kg) [2]	9 093	900	-15.01	1.56	1 846.12	38.58		

[1] Estimated value based on the reference levels of the categorical indicators and the mean values of continuous indicators. Categorical indicators (year and herd size) displayed the same value of Table 2.3.

[2] FPCM305 = the average fat and protein corrected milk production in 305 days within a herd

2.5 Discussion

This study is based on census data from 10 719 commercial dairy herds in the Netherlands from the years 2007 to 2016 to explore the association of herd performance indicators with herd-level cattle longevity.

Due to changes in dairy farm management strategies associated with the milk quota abolishment in 2015, changes in average cattle longevity were expected over time. The three studied cattle longevity variables, however, remained relatively stable over the evaluated years. For instance, the annually averaged age of culled cows and lifetime milk production for years 2007 to 2016 ranged from 2 119 to 2 160 days and 30 523 to 31 683 kg, respectively (Table 2.2). The annually averaged culling rate (based on cows culled for slaughter) ranged from 0.21 to 0.26 (Table 2.2) over the evaluated years and was close to the previously described culling rate in the Netherlands of 0.25 (Nor et al., 2014). Interestingly, the distributions of the three longevity variables were right-skewed, which indicates that there is a proportion of herds with a considerably higher cattle longevity. For instance, the average age of culled milking cows in a herd was 2 139 days, while the 95 percentile equaled 2 674 days, indicating a difference of almost 1.5 years (Table 2.1).

The regression results revealed that only four herd performance indicators were significantly associated with all three cattle longevity variables, i.e., heifer ratio, herd expansion, herd size and potential subclinical ketosis. It may not be surprising that heifer ratio is the most strongly associated with all three studied longevity variables (Table 2.4). The heifer ratio represents the relative number of replacement youngstock reared on a farm. In the Netherlands, most dairy farms rear their own replacement youngstock. The existence of abundant dairy heifers often results in shorter productive lifespans in herds of fixed sizes (De Vries, 2020). Culled cows are generally replaced by young stock to sustain or expand herd size. Considering the time lag between the decision on rearing a calve as a replacement heifer and the actual replacement of a dairy cow by this heifer, it is important for dairy farmers to plan the number of heifer calves to be reared as replacement animals. Herd expansion can be managed either by rearing more young stock, culling less cows, buying additional cows or a combination of these. Therefore, it is not surprising that in our models herd expansion was also associated with longevity. Similar to previous research (Raboisson et al., 2011), we found a negative association between herd size and longevity. The association between herd size and longevity may be caused by less personal attention and/or a higher level of physiologic stress from increased mechanization with increasing herd size (Raboisson et al., 2011). In addition, infectious disease may also lead to more culling in larger herds (Mõtus et al., 2021). The percentage of cows that had potential subclinical ketosis was also associated with all longevity variables. Beside the direct impact of subclinical ketosis on culling risk, this health disorder is also known to be able to trigger other health problems such as displaced abomasum, cystic ovaries and mastitis (Berge et al., 2014), which may lead to earlier culling (Steeneveld et al., 2020) and consequently lower longevity.

The significance of the associations between the remaining herd performance indicators varied with different longevity variables. However, the strength of these associations were generally weak. Remarkable to notice is the opposite association of age at first calving with age at culling (positive) and lifetime milk production(negative). Our data showed that one SD increase in first calving age (48 days) was associated with an increase in age of culling of only 11.5 days, indicating a reduction in production lifespan. Since lifetime milk production is subjected by length of production lifespan and production intensity, the lifetime milk production will be reduced in the case of an increased calving age and an unaltered production intensity, explaining the negative association.

Low milk production, poor reproduction performance and occurrence of health disorders (peripartum health disorders, metabolic disorders, udder disorders) are commonly regarded as risk factors for culling of individual cows within a herd (Sewalem et al., 2005). It is tempting to extrapolate the individual cow risk factors to the herd level. However, from a herd level perspective, the association of milk production level only strongly contributes to lifetime milk production. The associations with age of culling and culling rate are only mild or even insignificant, which contradict the often propagated public belief that intense milk production leads to short longevity and high culling rates. Similar reasoning can be carried out for the reproductive performance. A failure to conceive is a reason for individual cow culling (Fodor et al., 2020). When, as a management measure, farmers cull cows relatively quickly due to a failure to conceive, this will lead – on herd level - to a shorter CI. Many cow-level studies indicate strong correlations between CI and survival rate of cows (Ozsvari et al., 2020). Within in this study, the comparable associations of CI with the longevity features were mild at a herd level. One standard deviation increase in CI (26 days) was associated with a 10 days higher age of culled milking cows and a 0.002 lower culling rate only. In addition, since one standard deviation of CI (26 days) captures one insemination cycle in the Netherlands, the first association (higher age of culled milking cows) can be deduced from a notion that a higher tolerance for failure of conception or late first insemination may lead to less culling. Since CI excludes the group of animal that not get conception, herd reproduction performance can be better reflected by pregnancy rate. However, Information on pregnancy rate was lacking. In order to overcome this gap, other variables were selected as well, such as number of AI. Interestingly, other reproduction variables only displayed significant association with lifetime milk production of culled milking cows. Regarding the association of cattle health with longevity, the percentage of cows with high SCC in a herd, reflecting subclinical mastitis problems, was only significantly associated with a higher culling rate, although very weakly(small impact). Usually clinical mastitis is seen as the most important udder health parameter leading to removal of cows from the herd (Cha et al., 2013). However, due to the lack of data, the relevance of this health disorder could not be studied.

Although a large observational cohort of Dutch commercial dairy farms was available for this study, the results revealed only limited associations between each of the evaluated longevity measures and herd performance indicators. Combined with the right-skewed distribution of each of the evaluated longevity measures, this finding indicates that there is potential for extending herd longevity without affecting the performance of the herd. Moreover, the relatively low marginal and conditional R^2 of the regression models disclose that only part of the observed variance in longevity among the herds over times was explained by the herd performance variables. This indicates that differences in longevity at herd level may be predominantly determined by other factors, like farmers' attitude and management style (Olechnowicz et al., 2016).

2.6 Conclusion

In the Netherlands, the average longevity of dairy cattle at herd level, represented by age of culled milking cows, lifetime milk production and culling rate remained relatively constant over the years 2007 to 2016, although variance between herds was substantial. Four herd performance indicators (herd size, herd expansion, heifer ratio and suspects to subclinical ketosis) were associated with all longevity aspects. However, the relevance of the herd performance indicators differed among the longevity variables, although most associations were rather weak. The absence of strong associations between herd performance and each herd-level longevity variables indicate that there is potential for extending herd longevity without affecting herd performance in terms of milk production, reproduction and health.

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CHAPTER 3

An empirical analysis on the longevity of dairy cows in relation to economic herd performance

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3.1 Abstract

Several studies have stated the various effects of an increased dairy cow longevity on economic herd performance, but empirical studies are lacking. This study aimed to investigate the association between longevity of dairy cows and the economic performance of dairy herds based on longitudinal Dutch accounting data.

Herd and farm accounting data (n= 855 herds) over the years 2007-2016 were analysed. Herd data contained yearly averages on longevity features, herd size and several production variables. Longevity was defined as the age of cows at culling and by lifetime milk production of culled cows. Farm accounting data contained yearly averages on revenues, fixed and variable costs of the herds, by which gross margins were defined. Data was analysed using generalized linear mixed modelling, with gross margin as dependent variable. The independent variables consisted of average age of culled cows, average lifetime production of culled cows, year, herd size, herd intensity (milk production per ha), herd expansion rate, soil type, milking system, successor availability, total full-time equivalent, heifer ratio (% of heifers per cow) and use of outsourced heifer rearing. Herd was included as a random effect to account for the heterogeneity among herds.

Descriptive statistics showed that the average age of culled cows was 5.87 (STD=0.78) years and the average lifetime milk production of culled cows was 31.87 (STD=7.56) tons per cow with an average herd size of 89 cows (STD=38.85). The average age of culled cows was stable over the 10 years (variation between 5.79 - 5.90 years). The gross margin was on average €24.80/100 kg milk (STD=4.67), with the lowest value in year 2009 and the highest value in year 2013. Gross margin was not significantly associated with age of culled cows and lifetime milk production of culled cows.

Variance in longevity between herds was large (STD=0.78 years) but herds with a higher longevity did not perform economically better nor worse than herds resulting in lower longevity. This indicates that, within current practice, there is potential for improving longevity in order to meet society's concerns on animal welfare and environmental pollution, without affecting the economic performance of the herd.

3.2 Introduction

Longevity of a dairy cow can be defined as the total lifespan of a cow or as the length of productive life (Schuster et al., 2020). The productive lifespan of average dairy cows in industrialized countries varies from less than 3 years (Pinedo et al., 2014) to at least 4.5 year (Kerslake et al., 2018). These cows calve for the first time at approximately 2 years of age, which brings their total lifespan from birth to departure from the herd between 4.5 and 6.5 years. The average total lifespan of dairy cows in the Netherlands in 2018 was 5.5 years (CRV, 2019), while the natural lifespan of dairy cattle is approximately 20 years (Nowak & Walker, 1999). Hence, cows are culled well before the end of their natural lifespan, which is common for animals in dairy livestock production. The decision to cull a cow is primarily driven by economic considerations as made by the farmer. Therefore, dairy replacement management decisions largely determine the average productive lifespan of dairy cattle (De Vries, 2020). Decisions to cull and replace a dairy cow are driven by the cow's level of production, reproduction and health in comparison to the other cows in the herd and the available replacement animals. In the Netherlands, the main culling reasons in 2011 were poor fertility, mastitis and claw disorders (Zijlstra et al., 2013).

When cows have a prolonged longevity less replacement is needed, and therefore total rearing costs will be lower and rearing costs are spread out over a longer productive life. In the Netherlands, rearing costs of a heifer are on average between €1,423 and €1,715 per heifer (Mohd Nor et al., 2012), reflecting one of the highest dairy production costs. Moreover, a higher longevity will result in more cows in higher parities, and thus in a higher proportion of cows in higher producing age groups, and thus a higher average milk production of the herd. Under milk quota circumstances a higher herd production does have little value, but the farmer then has the option to reduce the herd size due to a higher milk production per cow. A higher longevity might, however, also result in disadvantages, such as increased health and reproduction problems and a reduction in genetic improvement (De Vries, 2017).

Besides economic consequences, an increase in longevity will also have environmental and social consequences. Cows with an increased longevity produce less methane per kg of milk (Grandl et al., 2019), improve environmental sustainability (Overton et al., 2020) and indicate good animal welfare on the farm (Barkema et al., 2015). Impacts on the environment and animal welfare have become increasingly important in public debate.

As stated in several studies (e.g., De Vries et al., 2020; Schuster et al., 2020) a higher longevity can result in less rearing costs and increased returns from a higher lifetime milk production. Empirical studies that support these expectations are, however, lacking. So, it is not yet known from practice, whether farms with a higher longevity perform economically better than farms with a lower longevity of the cows.

The aim of this research is to investigate the association between longevity of dairy cows and the economic performance of dairy herds based on available Dutch accounting data.

3.3 Materials and Method

Data

Anonymized yearly herd level data was obtained from a Dutch accounting agency (Flynth, Arnhem, the Netherlands). The data represented 2,809 herds with 30,170 yearly records from 2007-2016. The accounting dataset contained information on economic performance indicated by revenues (e.g., milk revenues) and fixed and variable costs (e.g., feed costs and veterinary costs), as well as on general herd characteristics (e.g., soil type, number of full-time employees). Economic data was expressed in absolute values and in ratios per 100kg milk produced per year.

The annual farm accountancy data of these 2,809 herds were subsequently merged with herd performance data derived from the Cattle Improvement Cooperative (CRV, Arnhem, the Netherlands). These data included herd information on herd size, longevity features (e.g., age of the cows in days and number of production days of the cows) and production, such as 305-day milk production and 305-day percentage fat and protein. For 2,105 herds CRV herd performance data was available

Data management

Only data from commercial dairy herds were selected for further analysis. A commercial Dutch dairy farm was defined as a herd with more than 30 cows and an average 305-day milk production above 4,000kg per cow. It was argued that the amount of labor needed to manage at least 30 cows indicates a commercial way of farming. Moreover, by using 30 cows, non-commercial farms like hobby herds and petting farms were excluded. Furthermore, herds with missing values on important variables (e.g., 305-day milk production, age at culling, lifetime milk production of culled cows and number of heifers) were removed (Figure 3.1). Subsequently, organic herds (n=22 herds) and a herd with an unexplainable high milk revenue (n=1 herd) were excluded, because on all these herds milk revenues were distinct higher than on conventional herds. Also, herds producing dairy products (e.g., cheese, yoghurt) (n=30 herds), with non-dairy revenues higher than €1.00/ 100kg milk (n=68 herds) or with an extreme heifer ratio (<=0.08; >=0.5) (n=12 herds) were excluded. Heifer ratio was calculated by the number of heifers that have calved divided by the average number of milking cows annually. It was argued that these herds may had other business activities than only dairy production, like cow trading, crop production, or running a farm shop. Since the longevity performance of herds can be better analysed based on data of several years only farms with continuous data of 10 years were selected. As a consequence, farms that quitted farming or changed accounting agency during the evaluated period were excluded from further analysis. The final balanced dataset contained information on 855 commercial dairy herds with 10 years of consecutive observations (Figure 3.1).

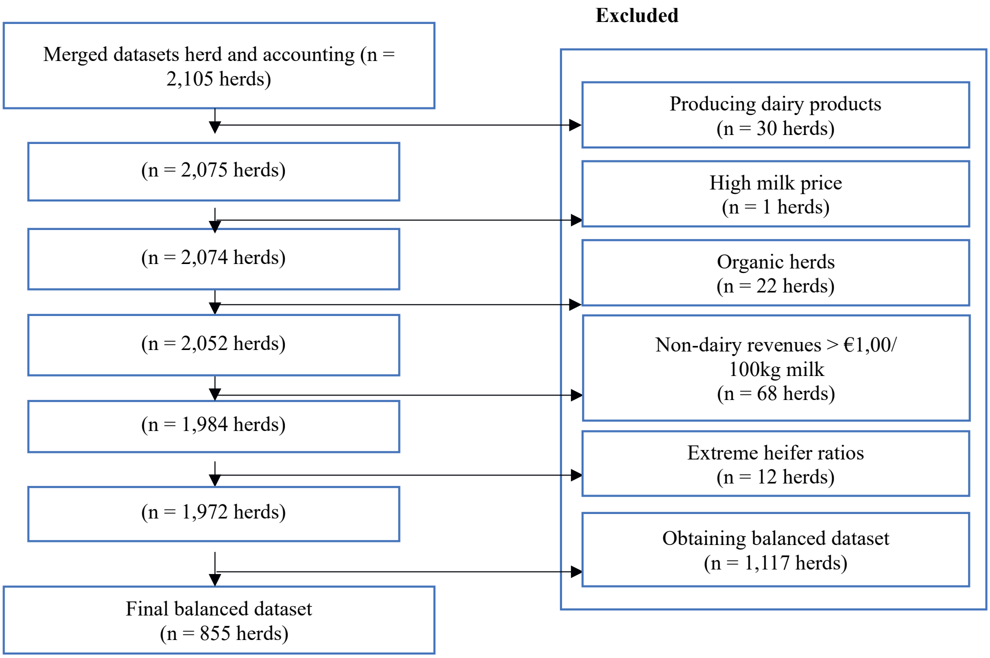

Figure 3.1. Data editing steps, starting with the merged dataset till the final dataset containing 855 herds.

The average age and lifetime milk production of culled cows were chosen to reflect the longevity features of the herd. Other selected variables in the data were selected based on an expected association with gross margin. The selected variables were herd size, use of outsourced young stock rearing (yes/no), number of full-time employees, land area, whether the farmer has a successor (yes/no), soil type (sand vs non-sand), milking system (conventional vs automatic milking system), total herd milk production and number of cows per ha. Soil type was selected as Dutch farms producing on different soil types (especially clay versus sand) differ in milk revenues and costs for purchasing feed (Evers et al., 2008). The variable having a successor was selected as it was expected that farmers with a successor make different management decisions than those without a successor, hence, resulting in different gross margins. In addition, the variables herd expansion, production intensity and heifer ratio were calculated. Herd expansion reflected the ratio of herd size changes on the basis of reference year 2007. Production intensity indicated the annual average milk production in tons per hectare. To analyse the economic performance of herds, the gross margin for dairy production was calculated as the total revenues minus the total variable costs and was expressed in euros per 100kg milk produced (Figure 3.2).

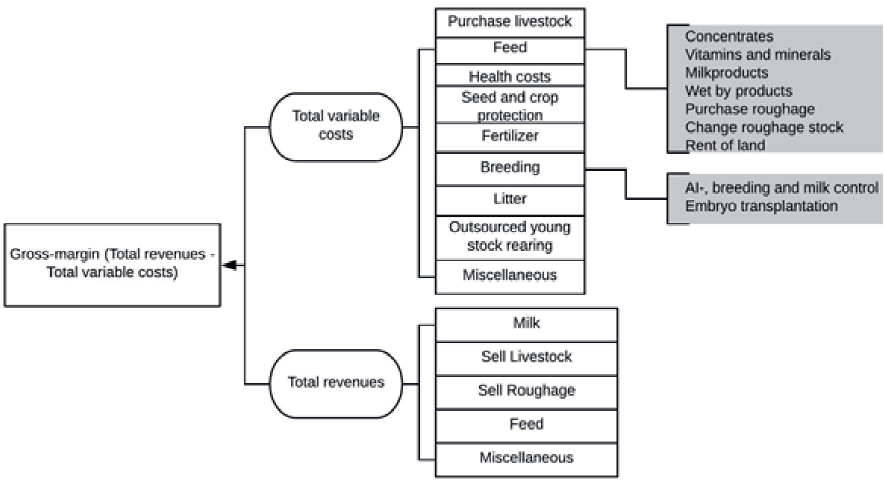

Figure 3.2. Overview of revenues and costs accounted for in the gross margin of the herds for dairy production. Examples of miscellaneous costs are costs related to water, electricity and manure disposal. Examples of miscellaneous revenues are subsidies and rental of barn space. Feed revenues include, for instance, the sales of silage.

Data analysis

The linearity of the relationships between the selected variables and gross margin were visually inspected by creating boxplots. In order to avoid multicollinearity, a Pearson correlation coefficient above 0.6 between continuous independent variables was used to remove the strongly correlated variables. Consequently, the total ha of the farm (highly correlated with herd size) and the average number of cows per ha (highly correlated with average tons of milk production per ha) were removed from further analysis. Two generalized linear mixed models (GLMM) were developed to analyse the association of dairy cow longevity (measured either by age or by lifetime milk production of culled cow) with economic performance of herds. The dependent variable of these models was the gross margin of the herd, reflecting the economic performance. The independent variables consisted of age or lifetime milk production of culled cows (hence 2 models) in combination with the independent variables soil type, milking system, whether a successor was available, whether young stock was outsourced, number of full-time employee, heifer ratio, herd expansion, herd size and herd intensity. A year variable was forced into both models to account for potential year effects (e.g., milk price changes). Moreover, to capture the unobserved herd related heterogeneity, such as management strategy, a herd variable was entered into the models as a random effect. To account for the covariance among the consecutive gross margin measurements within herds, competing covariance structures (i.e., independent, compound symmetry, first-order autoregressive, first-order autoregressive moving average and unstructured) were tested for their fit. Based on the Akaike information criterion, the unstructured covariance structure resulted in the best model fit and was eventually used in the presented models.

3.4 Results

Descriptive statistics

Over the evaluated period of 2007 to 2016, the average age of culled cows was equal to 5.87 years. Meanwhile, the average lifetime milk production of culled cows was 31.87 tons per cow. The standard deviations (STD) of the longevity variables between farms, were larger than the average STD within farms. The STD of age of culled cows between farms was 0.78 years, while the average STD within farms was equal to 0.59 years. For the lifetime milk production, the STD between farms was 7.56 tons, while the average STD within farms was 5.37 tons. The average herd size over the evaluated period was almost 89 cows (Table 3.1) and increased from, on average, 76 cows in 2007 to, on average, 103 cows in 2016.

Average total variable costs were €14.54/100kg milk, while the average total revenues equalled €39.34/100kg milk. The average gross margin over the evaluated period was €24.8/100kg milk (Table 3.2).

Table 3.1. Descriptive statistics on continuous variables over herds and years (n=855 herds).

	Description (unit)	Mean	STD	5% percentile	95% percentile
Age culled cows	Age of culled cows (years)	5.87	0.78	4.75	7.24
Lifetime milk production	Lifetime milk production of culled cows (tons)	31.87	7.56	20.73	45.16
Total FTE	Total number of full-time employees	1.88	0.72	1	3
Heifer ratio	Number of calved heifers per average cow present in the herd	0.24	0.06	0.15	0.33
Herd size	Number of cows present in the herd	88.87	38.85	44	161
Herd expansion	Herd size change from 2007-2016 in relation to base year 2007	1.15	0.23	0.92	1.57
Herd intensity	Milk production per ha (tons)	15.84	4.46	9.97	23.63

Table 3.2. Descriptive statistics on variable costs, revenues and gross margin (in €/ 100 kg milk) over herds and years (n=855 herds).

		Mean	STD
Variable costs	Feed	8.95	2.43
	Purchase livestock	0.47	1.47
	Fertilizer	1.04	0.37
	Seed and crop protection	0.56	0.30
	Health	0.98	0.41
	Breeding	0.95	0.31
	Outsourced young stock rearing	0.17	0.67
	Litter	0.46	0.35
	Miscellaneous[1]	0.96	0.38
	Total	14.54	1.99
Revenues	Milk	36.24	4.70
	Sell livestock	2.96	1.65
	Sell roughage	0.13	0.43
	Feed[2]	0.0001	0.01
	Miscellaneous[3]	0.01	0.05
	Total	39.34	5.15
Gross margin	Total revenues – total variable costs	24.80	4.67

[1] E.g., water, electricity and manure disposal.
[2] Selling of silage
[3] E.g., subsidies and rental of barn space.

The descriptive statistics on age of culled cows, lifetime milk production of culled cows, and gross margin for different categories of the categorical variables year, soil type, milking system, having a successor and making use of outsourced youngstock rearing are presented in Table 3.3. The average age of culled cows was rather constant over the years (variation between 5.79 - 5.90 years). A slight increase in average lifetime milk production of culled cows was displayed throughout the evaluated period (30.82 - 32.65 tons) . Among the categorical variables, such as soil type, milking system, whether having a successor and whether young stock rearing was outsourced, there were almost no differences in average age of culled cows and average lifetime milk production of culled cows . The average gross margin varied substantial between years, with the lowest value realized in 2009 (€18.48/ 100 kg milk), and the highest value in 2013 (€29.90/ 100 kg milk) . The average gross margin tended to be higher in farms with sandy soil and farms with a conventional milking system, compared to farms with non-sandy soil and an automatic milking system, respectively. In addition, herds outsourcing their young stock rearing had a lower average gross margin (€22.92/ 100 kg milk) than herds not outsourcing young stock rearing (€25.02/ 100 kg milk).

Table 3.3. The number of observations, mean and standard deviation (STD) of average longevity variables (age and lifetime milk production of culled cows) and gross margin per categorical variable.

		N obs	Age of culled cows (year)		Lifetime milk production of culled cows (tons)		Gross margin (€/100 kg milk)	
			Mean	STD	Mean	STD	Mean	STD
Year [1]	2007		5.87	0.84	30.82	7.72	26.58	2.56
	2008		5.94	0.83	31.74	7.80	25.13	3.06
	2009		5.89	0.76	31.59	7.11	18.48	2.65
	2010		5.86	0.75	31.74	7.49	25.20	2.59
	2011		5.79	0.77	31.43	7.68	28.00	2.87
	2012		5.78	0.73	31.60	7.39	24.98	2.96
	2013		5.90	0.84	32.48	7.97	29.29	3.14
	2014		5.89	0.74	32.45	7.32	29.09	3.38
	2015		5.86	0.78	32.24	7.55	21.28	3.47
	2016		5.89	0.73	32.65	7.32	20.01	3.26
Soil type	Sandy soil	6,067	5.86	0.79	31.77	7.51	24.95	4.67
	Other soil	2,483	5.88	0.76	32.14	7.65	24.44	4.64
Milking system	Conventional	7,023	5.89	0.79	31.91	7.70	24.90	4.61
	Automatic	1,527	5.74	0.70	31.71	6.88	24.37	4.92
Successor	No	5,410	5.87	0.79	31.66	7.43	24.84	4.69
	Yes	3,140	5.85	0.77	32.24	7.75	24.74	4.64
Outsourcing young stock rearing	No	7,674	5.86	0.78	31.73	7.56	25.02	4.62
	Yes	876	5.90	0.75	33.16	7.44	22.92	4.67

[1] In comparison to the other categorical variables, each year category consists of only one herd measurement

Regression analysis

Table 3.4 presents the results of the developed GLMM to study the association between longevity (age of culled cows and lifetime milk production of culled cows) and economic herd performance (gross margin). Overall, the results did not demonstrate any significant association between the longevity variables and gross margin. Of the evaluated independent variables soil type, milking system, use of outsourced heifer rearing, heifer ratio and herd intensity were significantly associated with gross margin. The strength of these associations was comparable among the two models. The use of outsourced youngstock rearing was associated with on average a €1.02/100 kg milk lower gross margins compared to the use of only own youngstock rearing. In addition, herds on sandy soils were associated with a €0.56/100 kg milk higher gross margins than herds on non-sandy soils, while the use of an automatic milking system was associated with €0.52/100 kg milk lower gross margins than on farms with a conventional milking system. One ton of milk production increase per ha was associated with an decrease in gross margin by €0.13/100 kg milk. An increase in heifer ratio of 0.1 (hence, having 10% more calved heifers in relation to milking cows) was associated with an increase in gross margin by €0.08/100 kg milk.

The marginal R^2 (variance explained by fixed effects) and the conditional R^2 (variance explained by entire model) of the model on age of culled cows were 0.60 and 0.80, respectively. The same values were found for the model on lifetime milk production of culled cows.

Table 3.4. Results of the generalized linear mixed models on association between longevity (age of culled cows and lifetime milk production of culled cows) and gross margin (in €/100 kg milk).

		Age of culled cows		Lifetime milk production of culled cows	
		Estimate	P-value	Estimate	P-value
Intercept		28.690	<0.0001	28.770	<0.0001
Year	2007	Ref.[1]		Ref.[1]	
	2008	-1.356	<0.0001	-1.352	<0.0001
	2009	-7.959	<0.0001	-7.955	<0.0001
	2010	-1.196	<0.0001	-1.190	<0.0001
	2011	1.640	<0.0001	1.645	<0.0001
	2012	-1.386	<0.0001	-1.380	<0.0001
	2013	3.044	<0.0001	3.054	<0.0001
	2014	2.881	<0.0001	2.891	<0.0001
	2015	-4.825	<0.0001	-4.816	<0.0001
	2016	-5.989	<0.0001	-5.978	<0.0001
Age culled cows (years)		-0.017	0.5920		
Lifetime milk production (tons)				-0.006	0.0915
Soil type	Sandy soil	Ref.[1]		Ref.[1]	
	Other soil	-0.564	0.0004	-0.561	0.0004
Milking system	Conventional	Ref.[1]		Ref.[1]	
	Automatic	-0.519	<0.0001	-0.518	<0.0001
Successor	No	Ref.[1]		Ref.[1]	
	Yes	-0.070	0.4165	-0.068	0.4302
Outsourcing young stock rearing	No	Ref.[1]		Ref.[1]	
	Yes	-1.023	<0.0001	-1.020	<0.0001
Total full-time employee		-0.025	0.6860	-0.024	0.7064
Heifer ratio		0.823	0.0241	0.805	0.0273
Herd expansion		-0.041	0.8614	-0.040	0.8631
Herd size		0.001	0.7666	0.001	0.7997
Herd intensity (tons milk/ha)		-0.129	<0.0001	-0.128	<0.0001

[1] This category is used as reference category in the regression analysis

3.5 Discussion

The average age of culled cows was rather constant over the evaluated period (variation between 5.79 - 5.90 years). Corresponding averaged STD of 0.78 years, however, indicated distinct differences in culling age between herds. Similarly, averaged observed variance in lifetime milk production (STD 7.56 tons) indicated relevant differences between herds, while the average annual lifetime milk production of culled cows only slightly varied around a value of 31.9 tons of milk. Hence on herd population level, longevity did not alter much during the evaluated years 2007-2016. The gross margin was on average €24.80/100 kg milk (STD=4.67). It might be possible that a very small proportion of this gross margin was due to non-dairy production. This will, however, be a neglectable small proportion as dairy herds with distinct other business activities were excluded.

Modelling results indicated that longevity (age and lifetime milk production of culled cows) was not significantly associated with the gross margin of commercial Dutch dairy herds. Herds with higher longevity did not have a significantly higher nor lower gross margin than herds with a lower longevity. Although it is frequently reported that a higher longevity will have positive economic consequences because of less young stock rearing and a higher average milk production (e.g., De Vries et al., 2020; Schuster et al., 2020), this was not observed in the observational data used in the current study. Negative effects of a higher longevity, like the reduction in livestock sales due to a reduction in the removal of dairy cows or increased health and/or reproduction costs (Beaudeau et al., 2000; Nor et al., 2014), might have levelled out potential positive consequences. Moreover, this balance between positive and negative effects between years might have been influenced by differences in price levels as well as by management changes triggered by policy alterations (e.g., abolishment milk quota). The effects of longevity on specific costs or revenues (e.g., health costs, livestock sales) can be investigated in the future.

The independent variable year was strongly associated with the gross margin, which was largely caused by the differences in milk price between the years. Since the milk price in the Netherlands was lowest in 2009 and highest in 2013 (respectively, €27.51/100 kg milk and €43.04/100 kg milk) (Wageningen University and Research, 2020), it was to be expected that the year 2009 was associated with the lowest gross margin, and the year 2013 with the highest gross margin (Table 3.3). Moreover, the years 2013-2015 (period in which farmers already anticipated on the abolishment of the milk quota system in 2015) can be considered as years where farmers might have made different strategic management decisions (e.g., building new barns, rearing more or less youngstock, and culling more or less cows) than in the more stable (quota restricted) years before that period, resulting in some year specific influences. To account for any specific effects between longevity and year that might have affected the gross margin, interaction terms have been tested but these turned out to be insignificant (data not shown).

It remains, however, inherent to field data that results are influenced by external changes, such as national agricultural policies and changes in price levels. Moreover, the gross margin is only a partial measure of farm profitability. Farm assets such as the modernity of the farm buildings and farm machinery, the quality and amount of land and the amount of own labour. Hence, the fixed costs are not taken into account. It is difficult to work with economic measures such as net profit because in accountancy data, the value of these assets is not well known. In the future, other methods, such as the use of an efficiency analysis (Oude Lansink, 2002; Steeneveld et al., 2012), where the farm's relative efficiency in terms of producing milk given a certain amount of resources is evaluated may provide a more complete economic view of the association between cow longevity and farm performance. On the other hand, because most of the fixed costs are linked to farm structure which cannot be changed in the short run, gross margin does provide a good indication of the short term profitability of a farm.

The independent variables milking system, use of outsourced heifer rearing, herd intensity, soil type and heifer ratio were not significantly associated with the gross margin (Table 3.4). Herds with an automatic milking system had on average a lower economic performance than herds with a conventional milking system, which was an expected association based on earlier findings of Bijl et al. (2007) and Steeneveld et al. (2012). Making use of outsourced young stock rearing was also associated with a lower gross margin than the use of own young stock rearing. This was expected as outsourced young stock rearing means that all costs (feed, housing and labour) are represented as a variable costs in the gross margin. While with own young stock rearing, only the feed costs (approximately one-third of the total costs of young stock rearing; Mohd Nor et al., 2012) are represented in the variable costs and housing and labour are fixed costs. More intensive farms (defined as more kg milk per hectare) were associated with a lower gross margin, most probably due to higher purchasing feed costs than less intensive farms. Also farms on non-sandy soil were associated with a lower gross margin due to lower milk revenues than on sandy soil (data not shown). Heifer ratio was positively associated with gross margin, indicating that farms that had more calved heifers per milking cow had a higher gross margin in comparison with farms that have less calved heifers per milking cow. This was to some extent an unexpected association as generally the amount of young stock is reflected in the heifer ratio. A higher heifer ratio, hence more young stock, would, in theory, lead to more variable costs and hence a lower gross margin. This assumption is, however, only valid in a stable farm production system, which was not the case during the evaluated period. Triggered by the abolishment of the milk quota in 2015, farmers already anticipated in the preceding years 2013-2014 by increasing their young stock rearing resulting in higher rearing costs, while the revenues resulting from this accelerated heifer rearing were not obtained until 2 years later. Due to this rearing time lag the increase in youngstock rearing was not direct captured by the heifer ratio. Hence, increased rearing costs were related to unaltered heifer ratios, while the additional revenues as a result of the increased rearing were related to higher ratios.

Longevity of dairy cows has been mostly evaluated in terms of culling of individual cows, as longevity is determined by the moment of the cows' departure from the herd for voluntary or involuntary reasons. Culling reasons and risk factors for culling are intensively studied worldwide (e.g., Gröhn et al., 2005; Rilanto et al., 2020; Sewalem et al., 2008). Also studies on optimization of culling decisions and costs of culling (DeLorenzo et al., 1992; Demeter et al., 2011; Kristensen, 1989) are performed. Empirical analysis on the economic consequences of a higher longevity or a lower culling rate are however lacking. Only De Vries (2020) and De Vries & Marcondes (2020) discussed the economic consequences of a higher longevity at the herd level and stressed lower replacement costs and a higher lifetime milk production. It was, however, also mentioned that a higher longevity is not necessarily profitable per cow per year, since the facilities are the most limiting factor (De Vries et al., 2020). Our study is the first study that analysed the economic consequences of longevity in an empirical way, and the Dutch commercial farm economics was taken into account by using farm accounting data. The gross margin was expressed per 100 kg milk per year as under Dutch milk quota circumstances (until 2015) kg of milk was the most limiting factor.

De Vries & Marcondes (2020) argued that it is conceivable that society will start to demand a higher longevity that is more in line with the natural life expectancy, given that health problems are major drivers of culling at a young age. According to the Farm Animal Welfare council (2009) an increase in longevity of 2 years would be desirable. However, forcefully increasing longevity to such an extent, without adjustments on health management will, however, have negative effects, such as increasing incidences of diseases. Therefore, additional costs for changes in health management and housing (access to pasture, improving cow comfort) will be needed to improve longevity in a structural way De Vries (2020). Although observational studies, due to a lack of experimental control, have disadvantages in interpretation, the data in this study may help the dairy sector in their decisions regarding in setting their ambitions regarding longevity.

In conclusion, longevity (age at culling, lifetime milk production of culled cows) was not statistical significantly associated with the gross margin of Dutch dairy herds, based on observational longevity and accounting data. Variance in longevity between herds was large but results demonstrated that herds with a higher longevity did not perform economically better nor worse than herds resulting in lower longevity. This indicates that within current practice there is potential for improving longevity in order to meet society’s concerns on animal welfare and environmental pollution without affecting the economic performance of the herd.

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CHAPTER 4

4

The association of dairy cattle longevity with farm level technical inefficiency

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4.1 Abstract

Prolonging dairy cattle longevity is regarded as one of the options to contribute to a more sustainable milk production. Cattle longevity is a direct result from culling decisions, which is primarily driven by economic considerations. As a consequence, at the herd level, cattle longevity can have effects on the efficiency of dairy production. This study investigates the technical inefficiency of dairy input, and its association with cattle longevity under Dutch commercial dairy production conditions, using a two-stage data envelopment analysis (DEA) approach. First, the technical inefficiency of capital, labor, land, seed & crop protection expenses, veterinary services, livestock purchase & services, feed purchase, miscellanea, livestock units and total input on total farm revenues was computed using DEA. Secondly, a bootstrap truncated regression analysis was applied to identify the association of cattle longevity with the evaluated input-specific and total input scores for technical inefficiency. Data were compiled from performance and accountancy records of 1,037 commercial Dutch dairy herds over the period of 2007 to 2014. In general, Dutch dairy farms displayed a relatively good overall technical efficiency, represented by an average inefficiency score of 0.09. The economic benefit of extending cattle longevity was evidenced by the negative association of cattle longevity with total input inefficiency. Of the evaluated inputs, the utilization of livestock units and feed was most efficient, with inefficiency scores below 0.26. This contrasts with the poor input efficiency of capital and livestock purchase & services with inefficiency scores around 0.52. Although the strength of the evaluated associations was generally low, the regression results illustrated that, except for labor, the age of culled cows was significantly negatively associated ($P < 0.05$) with each of the input inefficiencies. This contrasts with the significant associations of input inefficiencies with lifetime milk production, which were mostly positive. Since lifetime milk production is driven by length of cattle lifespan in combination with production level of the cows, the reverse direction of the associations with the two longevity indices illustrates that prolonging cattle longevity can improve efficiency performance of a dairy farm as long as the milk yield per cow remains unchanged.

4.2 Introduction

Longevity of a dairy herd is reflected by the average age at which cows in the herd are culled (Alvåsen et al., 2018; Schuster et al., 2020). In the Netherlands, the average age of culled dairy cows is 5.9 years (CRV, 2019; Van Pelt et al., 2015). This average age of culling is far below the potential natural lifespan of dairy cows (De Vries, 2013). Therefore, increased longevity is perceived by society as a relevant indicator of animal welfare (Bruijnis et al., 2013). Moreover, prolonging dairy cattle longevity is one of the potential options to contribute to a more sustainable milk production (Alvåsen et al., 2018; Schuster et al., 2020), by reducing GHG emissions from youngstock rearing (Grandl et al., 2019).

Within a commercial dairy herd, cattle longevity directly results from culling decision, which are primarily driven by economic considerations, by comparing the expected performance of present cows with the expected future performance of the available replacement cows. In the last two decades, technical efficiency has been widely used to measure the economic performance of dairy farms (e.g., Oude Lansink et al., 2015; Skevas et al., 2018). Unlike accounting analysis (Vredenberg et al., 2021), technical efficiency analysis is able to consider monetary as well as non-monetary inputs and outputs such as herd and land size and minimizes the impact of price volatility on farm's inputs and outputs (Timothy J. Coelli et al., 2005). A farm is technical efficient if it produces a maximum output (total farm revenues) with a minimum amount of inputs, such as labor, feed and equipment. Dairy farmers have greater autonomy to adjust the expenses on inputs rather than on output. Therefore, it is crucial for a dairy farm to promote the efficiency of inputs expenses. One of the options to adjust expenses on inputs is to prolong the longevity of dairy cattle, because that reduces the need for young stock and, therefore, reduces the need for inputs. To date, only a limited number of studies have been conducted on the association of prolonged cattle longevity on farm efficiency (e.g., Ali, 2021; Kovács et al., 2011). More specifically, insights on the association between longevity and the efficiency of input specific use (e.g., the use of feed and labor) are lacking. The association of a prolonged cattle longevity with a farm's technical efficiency is expected to vary with the type of input resource used. As increased longevity could reduce costs associated with the rearing of replacement heifers and increase average herd milk production due to an increase in higher producing age groups (Lush et al., 1950; Vredenberg et al., 2021), but at the same time could also result in increased health and reproduction problems (Hu et al., 2021). In the total input technical score of a dairy farm, these potential opposing impacts might cancel each other out. These trade-offs between positive and negative impacts of longevity on farm efficiency make it difficult to advise farmers in their cattle longevity management. Insight in the association between dairy farm longevity and input-specific technical efficiency is, therefore, useful.

The objectives of this study was therefore (i) to measure the total input and input-specific technical inefficiency of dairy farms and (ii) to explore the association of cattle longevity with technical inefficiency under Dutch production conditions.

4.3 Materials and Methods

To achieve the indicated objectives, data envelopment analysis (DEA) was employed to measure technical inefficiency scores of specified inputs used to produce milk, followed by a bootstrap truncated regression model to identify the association of cattle longevity with input-specific technical inefficiencies. Data for this study were compiled from annual performance and accountancy records on Dutch commercial dairy herds during the period of 2007-2014.

Methodology

Input-Specific DEA model

DEA is a non-parametric method to estimate the relative efficiency of decision-making units (DMUs; in this study farms). Unlike parametric methods, DEA is able to estimate efficiency with minimal prior assumptions about the production technology by which inputs are converted to an output. The production technology is, represented by the input requirement set of each DMU by comparing the level of inputs and outputs (Boussofiane et al., 1991; Charnes et al., 1997). The best levels of inputs and outputs among those DMUs are located on the so-called efficient frontier. In this study, we consider i (i=1,...,N) farms (or DMUs), employing a number of variable and quasi-fixed inputs (X)[1] to produce a single output Y. Under the assumption that returns to scale are variable (VRS)[2], the production technology T is characterized by the input requirement set:

$$\mathrm{T}(y) = \{(x, y)\}$$

(1)

or non-parametrically as

$$\mathrm{T}(y) = \{(x\colon \mathrm{Y}'\lambda \geq y_i, \mathrm{X}'\lambda \leq x_i, \mathrm{L}'\lambda = 1, \lambda \geq 0\}$$

(2)

with all quantities being non-negative. Y denotes the (N*1) vector of output and y_i the output level of farm i. X denotes the matrix of inputs and x_i the vector of inputs for farm i. λ denotes the vector of farm-weights which indicates the observations to which a given farm is compared to. L denotes the vector of farms.

Following the definition of the production technology, a directional distance function was applied to determine the potential reduction of the amount of a specific input to achieve the same amount of output and using the same quantity of other inputs (Oude Lansink, 2002; Oude Lansink et al., 2004). The directional distance function, representing the inefficiency scores, measures the amount that a given individual farm observation can be projected in the direction g_x until it reaches the efficiency frontier (Chambers et al., 1998). Within this function, g_x denotes the directional vector associated with each input X. This input oriented method satisfies the condition that a farmer has limited capacity to increase the amount of milk production under a milk quota regimen, as was the case in the Netherlands during the reflected period of 2007-2014. To simplify the interpretation, inefficiency scores (θ) were calculated by a relative comparison of the actual performance score with the efficiency performance score using the following directional distance function:

[1] Under the assumption that farmers can adjust quasi-fixed inputs in the long run, the quasi-fixed inputs, in this study, are also regarded as variable inputs.

[2] VRS permits constant but also increasing and decreasing returns to scale at different scale sizes (Thanassoulis, 2001).

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$$\vec{D}(x, y;\ g_x) = \max\{\theta\ |(x - \theta g_x) \in T(y)\}$$

(3)

The inefficiency term (θ) is a vector for each farm concerning the separate inputs respectively. Under the condition of VRS, this linear programming problem can be formulated as follows:

$$\vec{D}(x, y; g_x|\text{VRS}) = \max \theta$$

(4)

Subject to

$$\sum_{i=1}^{N} \lambda_i Y \geq y_i \tag{5}$$

$$\sum_{i=1}^{N} \lambda_i X \leq x_i - \theta g_x \tag{6}$$

$$\sum_{i=1}^{N} \lambda_i = 1 \tag{7}$$

$$\lambda_i \geq 0 \tag{8}$$

The inefficiency scores (θ) range from 0 to 1, where a value of 0 represents a fully efficient farmer, located on the efficient frontier. In order to capture the different farm conditions across time with our multi-dimensional data, the linear programming calculations were carried out for each year separately to account for annual differences in the production conditions. Consequently, the inefficiency scores (θ) were obtained for each input and each year.

Truncated bootstrap regression

To associate longevity with the inefficiency scores (θ), bootstrap truncated regression modelling was applied by which farm characteristics were regressed onto farm inefficiency scores. This regression modelling was computed separately for total input and each input-specific inefficiency score. The formal model looks as follows:

$$\theta = \alpha I + \gamma T + \beta Z + \varepsilon \tag{9}$$

Where θ is the vector of inefficiency scores across all years of farmers with $\theta > 0$ obtained for each input derived from the input-specific DEA model. I is a vector of ones with length N, and α denotes the parameter for the intercept. T denotes the year-dummies that were included to correct for the differences in the inefficiency frontier between the different years and γ denotes the corresponding vector of parameters. Z denotes the matrix of farm characteristics (Table 4.2), among which we find cows' longevity, and β denotes the vector of parameters for these data. ε denotes the error term.

Since the input-specific inefficiency score for a farm was defined relative to the frontier representing the best practice, estimated DEA inefficiency scores are serially correlated. As this violates the basic assumption of independence within sample values, the direct use of the estimated scores in a regression analysis to evaluate differences in efficiency among farmers in relation to longevity could result in invalid interpretations. In order to overcome this difficulty, a single truncated bootstrap regression (Simar et al., 2007) was applied. Estimated inefficiency scores θ derived from the input-specific DEA model were used to reckon β and estimate σ_ε by the method of maximum likelihood in truncated regression. In order to obtain a set of bootstrap estimates $(\beta^*, \sigma_\varepsilon{}^*)$, the next three steps were looped over 2,000 times. Firstly, the error term ε_i was assumed to be an N $(0, \sigma_\varepsilon{}^2)$ distribution with left-truncation at (0- βZ). Secondly, for each $i = 1,...,N$, θ_i^* was estimated by $\theta_i^* = \alpha I_i + \gamma T_i + \beta Z_i + \varepsilon_i$. Lastly, the estimated $(\beta^*, \sigma_\varepsilon{}^*)$ was obtained by estimating the truncated regression of θ_i^* on Z_i. In each iteration, truncated regression model above is computed. Consequently 2,000 coefficient estimates were obtained. The mean of these estimates was used as the final coefficient estimate and the distribution of them was used to conclude on the statistical significance at different confidence levels.

Available Data

Annual farm accountancy data provided by a Dutch accounting agency (Flynth, Arnhem, the Netherlands) was merged with herd characteristics data derived from the Cattle Improvement Cooperative (CRV, Arnhem, the Netherlands) with consent of their associated farmers. Data was anonymized so that we could not trace it back to individual farmers. A contract between the data providers and the university guaranteed proper data management procedures. The

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resulting dataset consisted of comprehensive data with information on 2,362 herds over the period 2007 to 2014. The economic performance of the herds was indicated by accountancy data on total revenues, quasi-fixed costs and variable costs. The data on herd characteristics covered information on cattle longevity, production intensity, herd size and general farm characteristics (e.g., heifer ratio).

Data Editing

To ensure that the analysis was representative of commercial dairy milk production circumstances, farms included in the analysis needed to adhere to the following five conditions: continuous farming throughout all evaluated years, > 75% of the total revenue stems from milk sales, no by-product revenue from milk processing (e.g., farmhouse cheese production), no organic farming, and a dairy herd size ≥30 cows. After enforcing these conditions, 7,782 herd-year observations from 1,036 herds with complete information were kept for further analysis.

One output and nine input sources were defined for the technical efficiency analyses. Output (Y) was reflected by the indicated total farm revenue (€), which was deflated by a Tornqvist index based on the reference year of 2010. Total farm revenue was an aggregate of milk revenue, meat revenue and revenue generated from feed sales. The selected inputs X_i $(i = 1, \ldots .9)$ included i) capital as reflected by the balance sheet values collected in a consistent manner by the accounting firm (Flynth) for farm buildings and machinery, ii) labor including family and hired labor as indicated by the number of full-time employees (**FTE**), iii) land as measured by the area used for production, iv) seed & crop protection expenses, indicating expenses of seed and crop protection and fertilizer; v) veterinary services, containing the expenses for veterinary services, artificial insemination, breeding and control, AI breeding & milk production recording and embryo transplantation; vi) livestock purchase & services, containing expenses for young cattle rearing carried out by third parties, livestock purchases and expense of work by third parties. As most of Dutch dairy farm rear their own youngstock, the majority of the costs within this category is from work by third parties; vii) feed, reflecting expenses of all feed purchases, being mainly concentrates purchase; viii) miscellanea comprising expenses for litter and other remaining variable costs, and lastly, ix) livestock units containing information on the number of cattle kept. Livestock units were calculated based on the livestock reference units as applied by EUROSTAT[3]. All monetary expenses were expressed in Euro and were deflated using individual price indices obtained from EUROSTAT. The descriptive statistics of the selected inputs and output variables are displayed in Table 4.1.

Table 4.1. Descriptive statistics of the selected DEA variables based on the herd data (n=7782) from 2007 to 2014

Variables	Mean	SD	Percentile_5	Percentile_95
Inputs				
capital (€)	384,709	343,745	65,700	1,037,666
labor (FTE)	1.88	0.73	1.00	3.00
land (ha)	51	26	25	93
seed & crop protection expenses (€)	12,038	6,654	4,640	23,844
veterinary service (€)	20,575	9,760	9,056	38,507
livestock purchase & services (€)	23,531	17,560	5,606	52,247
feed (€)	66,550	42,611	23,418	142,976
miscellanea (€)	10,249	5,966	3,312	21,709
livestock units	127	67	60	231
Output				
revenue (€)	302,193	167,868	132,661	573,205

Cattle longevity is the factor of interest in the second stage of the modelling. Two annually (over the production year) averaged indices were selected to measure cattle longevity: age of culled milking cows (year) (Z_1) and lifetime milk production of culled cows (ton) (Z_2). According to the definition used by Fetrow et al., (2006), the number of culled cows represented milking cows after first calving that were removed from the dairy herd for slaughter, salvage or death within a production year. Animals sold for production purposes to other dairy farms were excluded from this number. Besides cattle longevity, five covariates were selected as explanatory variables based on an expected association with longevity and farm technical inefficiency. These covariates included production intensity (Z_3), herd expansion (Z_4), heifer ratio (Z_5) and successor availability (yes/no) (Z_6). Since Dutch farms producing on different

[3] livestock units = number of milking cows + 0.7 * number of youngstock > 1 year old + 0.4 * number of youngstock $\leq$ 1 year old

soil types (especially clay vs. sand) differ in milk revenues and costs for purchasing feed (Vredenberg et al., 2021), soil type (sand/others) (Z_7) was also taking into consideration. Production intensity, herd expansion and heifer ratio were derived from the registered data. Production intensity indicated the annual average milk production in tons per hectare. Herd expansion reflected the ratio of herd size change relative to the reference year 2007. In addition, the heifer ratio was calculated by dividing the number of first calving heifers by the number of milking cows in a given production year. The descriptive statistics of the selected covariates are presented in Table 4.2.

Table 4.2. Descriptive statistics of the selected covariates in the bootstrap truncated regression based on the herd data from 2007 to 2014 (n=7782)

Variables		Mean	SD	Min	Max
age of culled cows (year)		5.9	0.8	4.7	7.4
lifetime milk production (ton)		31.5	7.7	20.2	45.0
production intensity (ton/ha)		15.2	4.2	9.6	22.3
herd expansion ratio		1.1	0.2	1.0	1.4
heifer ratio		0.23	0.06	0.13	0.33
		N obs			
successor	no	4,880			
	yes	2,902			
soil type	Sandy soil	5,439			
	Other soil	2,343			

4.4 Results

Total input and input-specific technical inefficiencies

The annual average inefficiency scores for each of the individual input sources as well as for total inputs are displayed in Table 4.3. The generic inefficiency performance of each input is arrayed by its corresponding mean value (Table 4.1) and distribution of inefficiency score across years (Figure 4.1). In general, total input is rather efficiently used as indicated by the average technical inefficiency over the evaluated period of 0.09 (where 0 denotes the best achievable efficiency). This means that, on average, farmers can decrease the use of overall inputs by only 9% to produce the same amount of output (total farm revenues). Inefficiency scores of the specific inputs are higher and vary substantially among each other. The utilization of livestock units and feed are the most efficient. Their mean inefficiency scores indicate that, on average, by employing the same quantity of other inputs, the same output can be achieved by decreasing the use of livestock by 16% or feed by 26%. On the other hand, the inputs of capital and livestock purchase & services can, on average, be reduced with 52% and 53%, respectively, to achieve the same amount of output, indicating a less efficient use of these inputs.

Table 4.3. Average annual inefficiency scores for capital, labor, land, seed & crop protection expenses, veterinary services, livestock purchase & services, feed, miscellanea, livestock units and total inputs.

	2007	2008	2009	2010	2011	2012	2013	2014	Mean[1]
capital	0.45	0.51	0.54	0.55	0.54	0.53	0.50	0.54	0.52
labor	0.29	0.34	0.32	0.30	0.30	0.29	0.29	0.33	0.31
land	0.24	0.28	0.34	0.29	0.26	0.28	0.28	0.27	0.28
seed & crop protection expenses	0.36	0.41	0.46	0.41	0.35	0.36	0.35	0.38	0.39
veterinary services	0.33	0.36	0.40	0.39	0.37	0.34	0.35	0.38	0.37
livestock purchase & services	0.49	0.57	0.57	0.53	0.53	0.55	0.49	0.52	0.53
feed	0.21	0.24	0.36	0.29	0.27	0.26	0.22	0.25	0.26
miscellanea	0.39	0.47	0.45	0.45	0.42	0.43	0.38	0.42	0.43
livestock units	0.14	0.17	0.17	0.16	0.18	0.17	0.15	0.17	0.16
total input	0.07	0.09	0.10	0.09	0.09	0.09	0.08	0.09	0.09

[1] Mean value of each input-specific inefficiency score over evaluated period (2007-2014)

In order to present the distribution of input-based efficiency performance, a density plot was used to show the probability density function of each input inefficiency score over the evaluated period (Figure 4.1). Since input inefficiency scores within the population of evaluated farmers display a bimodal distribution, the degree of the bimodal spread of values is not observed when solely looking at the mean inefficiency score. The peaks of a density plot helps to display where the modes of the population are situated along the inefficiency interval (Figure 4.1). As a sizable number of farms lay on the efficient frontier for the individual inputs, all density curves show a peak at 0. However, the different input-specific inefficiencies vary considerably in the distribution for values larger than 0 (i.e., more inefficient farms). For example, the second mode for the inefficiency scores for livestock units lays around 0.24, whereas, this value for capital and livestock purchase & services lays around 0.87. This means that farmers are relatively comparable in their managerial performance per livestock unit, but that for other inputs, such as capital, the sample can be differentiated into farms that are very efficient and farms that are less efficient.

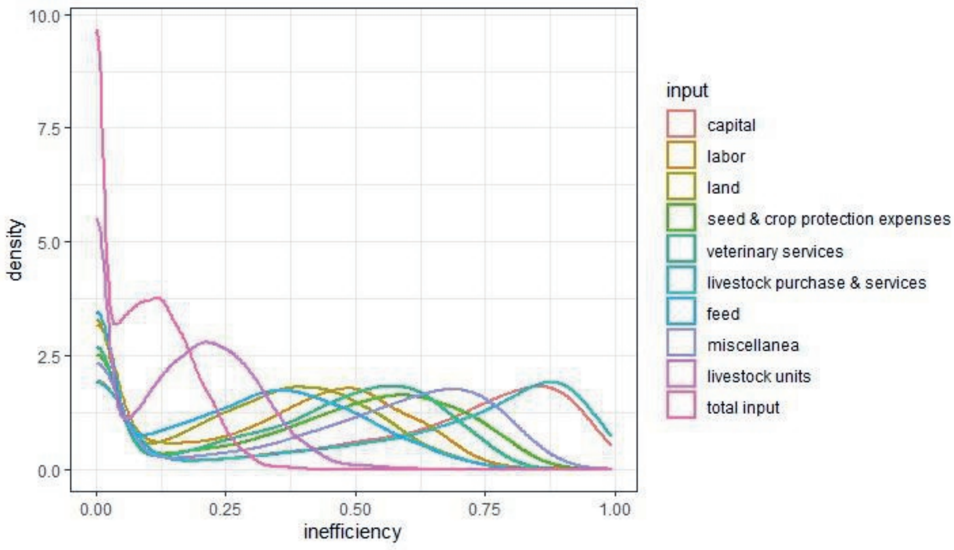

Figure 4.1. Density plot reflecting the inefficiency score distribution of the individual input factors and overall input over years

Determinants of technical inefficiency

The results of the bootstrap truncated regression analysis are depicted in Tables 4.4 and 4.5 corresponding to the models including culled cows age or lifetime milk production as longevity feature. In order to compare the goodness-of-fit of each models, the tables also provide Akaike information criterion (AIC).

Except for the input labor, age of culled cows is significantly negatively ($P< 0.05$) associated with total input inefficiency and each of the input inefficiencies. However, the association is rather weak as indicated by the small values of the coefficients (ranging between -0.004 to -0.014). For example, the coefficient of age of culled cows on feed inefficiency is -0.007. It indicates that one year increase in the age of culled cows is associated with a decrease in the inefficiency of feed input by 0.007. Although the degree of association is very small, the results reveal that cattle longevity is associated with slightly better total input and input specific efficiency.

Similarly, the coefficient of the covariate production intensity displays significant ($P<0.01$) negative relationships with each input inefficiency score, ranging from -0.003 to -0.022.

In addition, heifer ratio is positively associated ($P<0.1$) with total input and most of the input specific inefficiencies, except for labor, land and livestock units. Herd expansion is only negatively associated with seed & crop protection expenses, miscellanea and feed inefficiency. Interestingly, for farms with a successor, the coefficients illustrate positive associations with total input and each of the input inefficiencies compared to farms without successor. In addition, farms with another type of soil other than sand undermine the utilization of agriculture area (positive association).

In the models regarding lifetime milk production as longevity index, lifetime milk production was significantly ($P <0.05$) associated with the inefficiency of labor, land, veterinary service, livestock units and total input. While the technical efficiency of total input was negatively associated with lifetime milk production, most of the significant input specific inefficiencies (labor, land, veterinary service) disclosed a positive relationships with lifetime milk production, except for the input livestock units. The association of other covariates (availability of successor, soil type, production intensity, herd expansion, heifer ratio) with each of the inputs inefficiency displayed similar results as in the model expressing longevity by the age of culled cow index.

Table 4.4. Results of bootstrap truncated regression models on technical inefficiency for, respectively, capital, labor, land, seed & crop protection expenses, veterinary services, livestock purchase & services, feed, miscellanea, livestock units and total input with age of culled cows as longevity feature.

		capital		labor		land		seed & crop protection expenses		veterinary services		livestock purchase & services		feed		miscellanea		livestock units		Total input	
age culled cows (year)		-0.010	**	-0.004		-0.010	***	-0.009	***	-0.005	*	-0.010	***	-0.007	**	-0.014	***	-0.005	***	-0.005	***
successor	no[1]																				
	yes	0.014	**	0.105	***	0.026	***	0.020	***	0.013	***	0.043	***	0.011	***	0.013	**	0.006	**	0.015	***
soil	sand[1]																				
	others	-0.002		-0.035	***	0.032	***	-0.030	***	-0.014	***	-0.017	***	-0.001		-0.008		-0.006	**	-0.004	**
production intensity		-0.005	***	-0.003	***	-0.022	***	-0.012	***	-0.010	***	-0.010	***	-0.012	***	-0.012	***	-0.012	***	-0.009	***
herd expansion		0.0002		0.035	**	0.010		-0.043	***	-0.006		0.057	***	-0.054	***	-0.029	*	0.044	***	0.015	**
heifer ratio		0.121	**	0.037		0.049		0.148	***	0.118	***	0.116	**	0.095	**	0.107	**	0.001		0.026	
AIC		-1237		-7008		-4303		-3788		-4589		-1091		-6168		-3325		-11458		-17011	

***P < 0.01; **P < 0.05; *P < 0.10

[1] This group was used as reference category in the regression analysis

Table 4.5. The results of bootstrap truncated regression models on technical inefficiency for, respectively, capital, labor, land, seed & crop protection expenses, veterinary services, livestock purchase & services, feed, miscellanea, livestock units and total input with lifetime milk production as longevity feature.

		capital	labor	land	seed & crop protection expenses	veterinary services	livestock purchase & services	feed	miscellanea	livestock units	Total input
lifetime prod (ton)		-0.0001	0.0011 ***	0.0005 *	0.0004	0.0013 ***	-0.0005	-0.0002	0.0003	-0.0027 ***	-0.0006 ***
successor	no[1]										
	yes	0.014 **	0.105 ***	0.026 ***	0.020 ***	0.012 ***	0.043 ***	0.011 ***	0.013 **	0.007 ***	0.015 ***
soil	sand[1]										
	others	-0.003	-0.036 ***	0.032 ***	-0.031 ***	-0.015 ***	-0.017 ***	-0.001	-0.009	-0.005	-0.004 *
production intensity		-0.004 ***	-0.004 ***	-0.022 ***	-0.012 ***	-0.010 ***	-0.010 ***	-0.012 ***	-0.012 ***	-0.010 ***	-0.009 ***
herd expansion		0.0002	0.038 **	0.012	-0.041 ***	-0.002	0.055 ***	-0.055 ***	-0.028	0.035 ***	0.013 *
heifer ratio		0.154 ***	0.069	0.091 ***	0.184 ***	0.156 ***	0.139 ***	0.113 ***	0.160 ***	-0.029	0.031
AIC		-1230	-6994	-4310	-3782	-4603	-1086	-6163	-3306	-11617	-17015

***P < 0.01; **P < 0.05; *P < 0.10

[1] This group was used as reference category in the regression analysis

4.5 Discussion

Over the last decade, several studies have explored the overall technical efficiency performance of Dutch dairy farms (e.g., Kovács et al., 2011; Steeneveld et al., 2012). These studies indicated that Dutch dairy farms, in general, perform rather efficient in overall input usage which is similar as the inefficiency score of total input around 0.09 obtained from this study. However, inputs of a farm are comprised of several components, such as feed and health expenses, which are managed differently by farmers. Hence, the impact of prolonging cattle longevity can be different due to different inputs inefficiency. Since the overall technical efficiency performance of a dairy farm is not simply the summation of inputs specific efficiency performance, the utilization level of these individual inputs can hardly be derived from the overall technical efficiency performance, and vice versa. In this study, the combination of elaborate databases including the accountancy and longevity performance of commercial Dutch dairy farm provided a possibility to get insight into the technical efficiency of each input and determinants of input-based inefficiency.

Capital and livestock purchases & services had the highest technical inefficiency scores. In the density plots of inefficiency score distribution, a strong bimodal nature of those two inputs reveals that two different populations of farmers may underly the analysis. That means the farms are either very efficient or very inefficient in relation to capital and livestock purchases & services expenses. The covariates availability of a successor and heifer ratio could partially explain the inefficiency of capital and livestock purchase & services expenses given the regression results in the second stage of our research. Firstly, a farm with a potential successor aims to continue the business and/or may have a stronger educational background, which is more likely to result in innovative investments to better cope with future changes in the production condition (Mohd Suhaimi et al., 2017). Therefore, innovative investments in buildings and equipment could explain the difference in input inefficiencies between farms with and without a successor. Additional data exploration also reveals that the average capital differs among these two groups. Secondly, introduction of heifers to replace the culled cows involve large costs (Mohd Nor et al., 2015), contributing around 20% to the overall expenditure on a dairy farm (Heinrichs, 1996). Farmers only start to earn back these costs when the net revenues realized from the milk production by the replacement animal cover the costs accrued during the rearing period. Previous research highlights that the costs of rearing a replacement heifer are not recovered until their second lactation (Archer et al., 2013). Consequently, farms with a higher heifer ratio use most inputs less efficient, i.e. capital, veterinary service, livestock purchase & services and miscellanea expenses.

After capital and livestock purchases & services, the input variable miscellanea (expenditures for litter, electricity, water, etc), had the highest inefficiency score. This variable, however, represents, only a small amount (7%) of the total variable expenses (Table 4.1). From an efficiency point of view, the use of these inputs can be significantly improved, although the absolute effect on net returns will be limited. In contrast, the cost of feed, on average, accounts for 50% of total variable expenses (Table 4.1) which displayed the highest efficiency performance after livestock units utilization.

When using a regression model to analyze observational data, such as a truncated bootstrap regression, causality may be implied while not supported by the underlying data generating process. Although the analysis is based on the hypothesis that longevity affects input inefficiency, input inefficiency itself could potentially affect longevity (higher input inefficiency could lead to earlier culling), suggesting the presence of reverse causality. Reverse causality could harm the quality of the results of the regression model, indicating a limitation of the approach used.

The main results from the second stage truncated bootstrap regression indicate the benefit of extending cattle longevity for the economic performance of a dairy farm, as shown by the negative associations of total inefficiency scores with the two independent longevity indices. With regard to the input specific associations with longevity , the average age at culling was negatively associated with all input-specific inefficiencies. Although coefficients of those associations are small, these results do illustrate the potential benefit of extending the age of culling in improving the farm input efficiency performance. In contrast, the associations of average lifetime milk production with input-specific inefficiencies were mostly positive. Average lifetime milk production only showed a negative association with the inefficient utilisation of livestock units. Since lifetime milk production is driven by two elements, i.e.

lifespan (culling age) and production level of an individual cow, the opposing associations of input-based inefficiency scores with age at culling and lifetime production indicate that increasing age at culling could improve farm efficiency performance as long as the milk yield at cow level remains unchanged. The positive associations of lifetime milk production with veterinary services and labor inefficiency could be related to higher risk of health disorders caused by higher milk yields per cow. At the cow level, numerous studies have proven a strong association of high milk yield with health and fertility disorders, resulting in increased risk of culling (Armengol et al., 2018; Horváth et al., 2017; Pinedo et al., 2010). Since the results of the regression model do not indicate a negative impact on veterinary service and labor efficiency performance by extending the average culled cow age, the negative impact of extending lifetime milk production on veterinary service and labor efficiency could be mainly due to the stronger association with the milk production level of individual cows.

The negative association of livestock units with both longevity indices illustrates that extending lifespan of a dairy cow or increasing lifetime milk production per cow can achieve better livestock units efficiency. Since the variable livestock units represents cows from two age groups, viz. youngstock (before 1st calving) and milking cows, the negative associations are mainly based on the milk production of the group of dairy cows. With an increased culling age, the relative contribution of the number of dairy cows to the total number of livestock units on a farm increases, leading to a higher total milk production on the farm. In the case of the extended lifetime production, the increase in livestock unit performance directly results from an increased milk production per cow.

Cattle longevity is often seen as one of the possibilities to reduce the environmental footprint of dairy production (Alvåsen et al., 2018; Schuster et al., 2020). The results of this study show that it is possible for a farm to work with a longer longevity without negative economic consequences and even some potential positive economic consequences.

4.6 Conclusion

Despite, the relatively good overall technical efficiency of Dutch dairy farms, the efficiency performance varied for different inputs. Capital and livestock purchase & services expenses displayed poor efficiency performance. Overall technical inefficiency was negatively associated with longevity illustrating the potential economic benefit of extending cattle longevity. For associations of longevity with each input-based inefficiency score, except for score of labor, age of culled cows was significantly negatively associated with each of the input inefficiencies. In contrast, the significant associations of input inefficiencies with lifetime milk production were mostly positive. Since lifetime milk production is driven by length of cattle lifespan and individual cow production intensity, this reverse direction of associations of inefficiency scores with two longevity indices indicated that extending the cow age at culling may lead to improved economic performance of dairy farms as long as the milk yield at cow level remains unchanged.

4.6 References

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CHAPTER 5

5

Effects of extending dairy cow longevity by adjusted reproduction management decisions on partial net return and greenhouse gas emissions: A dynamic stochastic herd simulation study

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This chapter is submitted

5.1 Abstract

Prolonging dairy cattle longevity is regarded as one of the options to contribute to a more sustainable milk production. Since subfertility is one of the main reasons for culling, this study investigates how adjustments in reproduction management affect partial net return at herd level and greenhouse gas emissions per unit of milk, using a dynamic stochastic simulation model. The effects of reproduction decisions that extend cattle longevity on milk yield, calving interval and conception rate were derived from actual performance of commercial dairy cows over multiple lactations. The model simulated lactations, calving and health status events of individual cows for herds of 100 cows. Evaluated scenarios differed in the maximum number of consecutive artificial insemination (AI) attempts (4, 5 or 6 services), or the production threshold at which subfertile cows are culled (20, 15, or 10 kg milk per day). Annual partial net return was computed from revenues from sold milk, calves and culled cows, and the costs from feed consumption, rearing replacement heifers, AI services and treatment for clinical mastitis and lameness. Greenhouse gas emissions were computed using a life cycle approach. Average age at culling increased with an increased maximum number of AI services. The change was larger when going from a maximum of 4 to 5 AI attempts (108 days) than from a maximum of 5 to 6 attempts (47 days). Similarly, the average age of culled cows increased from 1,968 to 2,040 and 2,132 days when the subfertility culling standard decreased from 20, to 15 and 10 kg milk per day, respectively. Average annual partial net return increased from €165,850 at a maximum of 4 AIs to €167,670 at a maximum of 6 AIs, and increased from €161,210 at a subfertility culling threshold of 10 kg/day to €168,190 at a threshold of 20 kg/day. Greenhouse gas emissions decreased with an increased maximum number of AIs from 0.926 to 0.915 kg CO_2 equivalents per kg fat-and-protein-corrected milk (FPCM) at maximum 4 or 6 AIs respectively, while they increased from 0.926 kg at a threshold of subfertility culling of 20 kg/day to 0.928 kg CO_2 equivalents per kg FPCM at a threshold of 10 kg/day. Although lower subfertility culling standards has the potential to extend cattle longevity more than increasing the maximum number of AI services, only the latter benefits a farm's partial net return, while mitigating greenhouse gas emissions.

5.2 Introduction

On commercial dairy farms, subfertility is one of the primary reasons for culling cows, in addition to health disorders and low milk production (Dallago et al., 2021; Zijlstra et al., 2020). Farmers' reproduction management involves decisions rules on the maximum number of artificial insemination (**AI**) attempts to get cows pregnant, as well as the production threshold below which cows that did not conceive after those maximum AI attempts are culled. Easing these reproduction management decision rules, will reduce culling for subfertility reasons and prolong the lactation period of subfertile cows, thereby increasing the average age at culling.

The average lifespan of a dairy cow in the Netherlands is around 5.8 years, with a range of 4.9 to 7.1 years across farms (Han et al., 2022), considerably shorter than the natural lifespan of dairy cows of approximately 20 years (De Vries et al., 2020). Prolonging the lifespan of dairy cattle could contribute to more sustainable milk production, from an economic, an environmental as well as a social perspective (Han et al., 2022; Schuster et al., 2020).

Extending cattle longevity through changes in reproductive decisions will inevitably affect farm profitability and greenhouse gas (**GHG**) emissions. A lower culling rate will reduce the demand for replacement heifers, reducing the associated rearing costs and GHG emissions. In addition, the milk yield of a herd might increase when longevity increases. Reduced subfertility culling increases the proportion of multiparous cows in a herd. Multiparous cows usually produce more milk than primiparous cows (Neave et al., 2017; Walter et al., 2022), resulting in a lower GHG emission per kg milk produced. However, the yield increase due to more multiparous cows may not offset the amount of milk loss due to higher disease risk for older cows. In addition, more AIs will directly increase AI costs, while a higher disease risk for older cows may increase both treatment costs and milk losses. The trade-offs between positive and negative impacts of extending longevity on farm economic and environmental performance make it difficult to advise on optimal longevity.

The objective of this paper is to explore the effect of extending cattle longevity by assessing how different reproduction management decisions affect technical and economic results at herd level, and GHG emissions per unit of milk, using a dynamic stochastic simulation model.

5.3 Materials and Methods

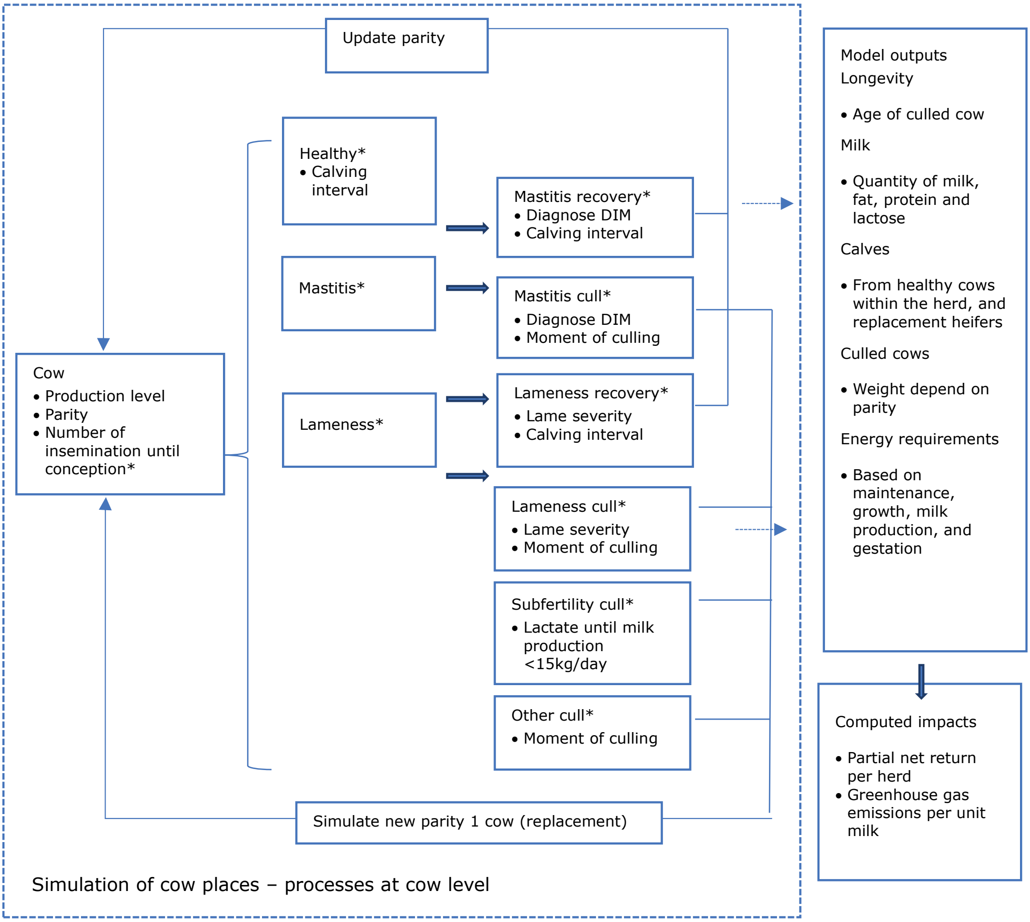

Figure 5.1. Schematic representation of the simulation model reflecting the processes at cow level per cow place. Stochastics events are marked with an asterisk.

This study used an adapted version of the bio-economic simulation model by Kok et al. (2017), developed to stochastically simulate Dutch dairy herds of 100 cows to evaluate the impact of varying dry period lengths. This model simulated individual lactations and calving intervals, while accounting for culling, either for fertility reasons or for other reasons (i.e. general culling). Model output was defined by partial cash flow and GHG emissions per herd per unit of fat-protein-corrected milk (FPCM). To compute GHG emissions from 'cradle to farm gate', a life cycle approach was applied, which also accounts for the production of meat from surplus calves and culled cows, assuming that it substituted other meat on the basis of edible product, thus avoiding additional GHG emissions from meat production elsewhere.

To evaluate the economic and environmental impact of alternative reproduction management strategies, the herd simulation model of Kok et al. (2017) was modified. First, reproduction performance of a dairy farm including the timing and success of AI and the resulting calving interval were taken into account. Second, disease categories were added to account for the impact of clinical mastitis and lameness and the probability of disease was adjusted for time present in the herd. Third, lactation curve parameters were updated, and milk production losses and discarded milk due to lameness and clinical mastitis were accounted for. Fourth, the model parameters associated with the growth of first and second parity cows were modified to account for the increase in lactation length. Fifth, costs for AI and treatments for clinical mastitis or lameness were added (see Figure 5.1).

The adapted herd simulation model was used to evaluate the impact of strategies defined by alternative reproduction management decision rules. In the default scenario, cows were inseminated a maximum of 4 times before being considered for subfertility culling. These subfertile cows were culled when their milk yield dropped below a threshold of 15 kg/day. This default scenario was set to reflect typical reproduction management practices in Dutch dairy herds (Rutten et al., 2014). Alternative strategies were set by either increasing the maximum number of consecutive AI attempts per cow to 5 or 6 times, or modifying the subfertility culling threshold to either 10 or 20 kg milk per day. A sensitivity analysis was conducted to evaluate the impact of variations in average milk production on financial performance of the herd, GHG emissions and longevity, and the impact of changes in replacement heifer costs and milk prices on the financial performance of the herd. The model was run for 500 herds of 100 cow places for each reproduction management strategy. Results are presented from year 7 when cattle longevity estimates reach model equilibrium for adjusted reproduction management strategies. Details on the model updates and simulations are provided in the following sections.

Herd simulation model modification

Reproduction

For each cow, the model randomly assigned a number of AIs (1-6) until conception at the start of each lactation, based on the proportion of cows getting successful AI per parity (Table 5.1) (Inchaisri et al., 2011). Subsequently, the length of the calving interval was determined by days between calving until conception and an assumed 280 days gestation period (Nogalski et al., 2011) (Table 5.1). Parity differences were estimated based on the mean proportion of successful AIs from parity 1 as reference, and the relative differences in probability of successful AI between parities(Inchaisri et al., 2011).

Table 5.1. The proportion of conception per consecutive number of AIs per parity and corresponding calving interval (CI) based on Inchaisri et al. (2011).

Number of	Parity 1–3	Parity 4	Parity 5+	CI (days)
1	0.45	0.44	0.41	363
2	0.23	0.23	0.23	398
3	0.13	0.13	0.14	439
4	0.07	0.07	0.08	476
5	0.04	0.04	0.04	510
6	0.02	0.02	0.03	544
Not	0.06	0.07	0.07	

Health status

At the start of each lactation, each cow was stochastically assigned to one of seven health events that could occur during the lactation (Figure 5.1): staying healthy, recovering from clinical mastitis, recovering from lameness, being culled because of clinical mastitis, being culled because of lameness, being culled because of subfertility, or being culled for other reasons (‘other culling’). Clinical mastitis was defined as an intramammary infection causing visibly abnormal milk (e.g., colour, fibrin clots), and lameness was defined as a case of poor locomotion (suboptimal mobility score 4 or 5 on a scale of 5). A culled cow was replaced by a heifer that was assumed to calve and enter the herd the following day. The probability of a cow remaining healthy was adjusted for the length of the CI. The incidence rate of clinical mastitis varied with parity and stage of lactation (before or after 100 days in milk (DIM)). To capture the distribution of mastitis incidence within lactation, 60% of clinical mastitis cases were assumed to occur before 100 DIM and 40% between 101 to 307 DIM, based on the interval between calving to dry period from first successful AI. It was used to avoid mastitis occurring after the end of lactation. The moment of mastitis occurrence within these lactation periods was determined using a uniform distribution. Only cows with mastitis in the first 100 DIM were culled for clinical mastitis 90 days after diagnosis. The probability of cows being culled due to clinical mastitis in each parity is stated in Table 5.2.

Similar to mastitis, the incidence rate of lameness varied with parity. It was calculated based on the odds ratio between multiparous and primiparous cows and the incidence rate in parity 1 (Alban, 1995; Enting et al., 1997)(Table 5.2). Since the severity of lameness leads to varying degrees of milk loss, 80% of lameness cases was assumed to be mild and 20% to be severe (Randall et al., 2018). The probability of cows being culled due to lameness in each parity is stated in Table 5.2. The timing of culling due to lameness was determined using the data from the study of Edwardes et al. (2022).

The probability of culling due to subfertility varied with parity and the defined maximum number of AIs (Tables 5.1 and 5.2). In addition, more AIs until conception resulted in a longer calving interval. Cows were assigned to subfertility culling when they did not become pregnant within the maximum number of AIs and when their milk production dropped below the defined subfertility culling .

In order to meet an overall cull rate in each parity, 'other culling' remained in the model besides culling for subfertility, clinical mastitis, and lameness. Its probability varied across parities to meet the overall culling rate of 30% in Dutch dairy farms (Table 5.2). 'Other culling' occurred at a certain fraction of completion of a cow's assigned CI, drawn from a distribution with a positive skew and a median fraction of 0.17 (beta distribution with parameter a=1.3, b=5 (Rutten et al., 2014)).

Table 5.2. Incidence rates of clinical mastitis and lameness and proportion of cows culled due to clinical mastitis, lameness or other reasons, and overall culling rate in each parity based on the default reproduction management decision rules of maximal 4 AIs and a subfertility culling production threshold of 15 kg/day.

	parity 1	parity 2	parity 3	parity 4	parity 5+	Source
Clinical mastitis incidence	0.20	0.23	0.31	0.34	0.40	Lean et al. 2023
Lameness incidence	0.25	0.19	0.21	0.35	0.35	Alban 1995, Enting et al. 1997
Lameness cull	0.02	0.02	0.03	0.05	0.06	Edwardes et al. 2022; Zijlstra et al. 2020
Mastitis cull	0.01	0.03	0.04	0.05	0.08	
Other cull	0.05	0.06	0.09	0.14	0.22	
Subfertility cull (max N_AI4)	0.12	0.12	0.12	0.13	0.14	Inchaisri et al. 2011
Overall cull[1]	0.19	0.23	0.28	0.37	0.50	

[1] Including culls for subfertility based on maximal 4 AIs (default), clinical mastitis, lameness and other cull reasons.

Milk production

Lactation curves were updated based on milk production recording data of 50 randomly selected Dutch herds collected by the Dutch Cooperative Cattle Improvement Organization CRV BV (CRV, 2017). Individual milk production (MP) in kg of cow i in parity j at each day in milk (DIM) was calculated as:

$$MP_{ij} = a_{ij} + b_{ij} * DIM + c_{ij} * exp(-k_{ij} * DIM) + RPL_i + ADY_j$$

where RPL_i is the relative production level of cow i; ADY is the average daily 305-d yield in kg milk of a cow in parity j; a, b , c, and k model the shape lactation curve (Wilmink, 1987) (Table 5.3). In order to reflect the natural variation in milk production from about 80% to 120% of the average milk production, RPL was defined from a normal distribution with a mean of 0 and standard deviation of 0.1. Average milk protein, fat and lactose contents were calculated per parity class and used to parameterise the milk composition of the simulated lactation curves (Table 5.3). Milk yield was computed per cow per time step, using the integral of the milk production function.

Clinical mastitis was assumed to result in a yield reduction of 5% for the remaining lactation period from diagnosis until dry-off or culling day (Seegers et al., 2003). Moreover, milk was assumed to be discarded for 6 days following the diagnosis due to assumed treatment with antibiotics. Mild lameness was associated with a milk yield loss of 1.6% in total lactation yield, and severe lameness was associated with a milk yield loss of up to 6%, compared to the average yield in that lactation (O'Connor et al., 2023).

Table 5.3. Model inputs for individual lactation curves per parity

parity	ADY[1](kg)	a	b	c	k	Fat (%)	Protein (%)	Lactose (%)
1	23.5	25.75	-0.01468	-18.92	0.157	4.48	3.55	4.62
2	26.6	30.03	-0.02248	-25.01	0.2612	4.50	3.59	4.53
3	28.6	33.01	-0.02885	-28.85	0.2557	4.51	3.51	4.48
4	29.3	34.08	-0.0312	-32.15	0.2467	4.51	3.51	4.48
5+	28.5	32.4	-0.0256	-31.9	0.2718	4.51	3.51	4.48

[1]ADY is the average daily 305-d milk yield; parameters a, b, c and k of the Wilmink lactation curves; and fat, protein and lactose content of the milk per parity class.

Energy requirement

Maintenance, milk production, gestation, and growth were included in the calculation of energy requirements (Kok et al. 2017, 2019). Subsequently, these requirements were used to compute feed intake of dairy cows.

Partial net return

In accordance with a metric describing the economic performance of the simulated dairy farm from Kok et al. (2017), partial net return was estimated based on the modelled revenue from sold milk, calves and slaughter culled cows, and the costs from replacement heifer, feed, AI and treatment for clinical mastitis and lameness per case. The cost inputs were updated from Kok et al. (2017) and are displayed in Table 5.4.

$$
\begin{aligned}
&\text{Partial net return} \\
&= \text{revenues (milk, calves and slaughter culled cows)} \\
&- \text{costs (replacement heifer, feed, AI, treatment cost of clinical mastitis and lameness)}
\end{aligned}
$$

Table 5.4. Parameters used to compute partial net return based on years 2019–2021

	Value (€)	source
Milk revenue (per 100kg solids)[a]		FrieslandCampina, 2022
Protein	580.5	
Fat	290.3	
Lactose	58.0	
Calves revenue (per animal)		Wageningen Economic Research, 2022
Female	21.2	
Male	68.0	
Slaughter value culled cows (per kg meat)[b]	2.2	
Replacement heifer (per animal)	1078	KWIN 2022–2023
Feed cost (per t DM)		KWIN 2022–2023
Summer ration	159	
Winter ration	192	
Artificial insemination (per time)	35	KWIN 2022-2023
Treatment cost (per case)		
Clinical mastitis	35	Lam et al., 2013
Mild lameness	0	Edwardes et al., 2022; O'Connor et al., 2023
Severe lameness	38	

[a] This results in €35.56 per 100 kg milk given average solids content (3.47% protein, 4.41% fat and 4.51% lactose).
[b] Assumed dressing percentage 60% (KWIN)

Annual partial net returns were computed per herd for different reproduction management decision rules. The revenues consisted of revenues obtained from milk production, surplus calves and culled cows. Milk revenues were based on the Dutch payment system based on milk solids value (10:5:1 ratio of protein : fat : lactose) using the average Dutch prices from 2019–2021 (Table 5.4).

To estimate the revenues for surplus calf sales, it was assumed that 50% of the calves born was male and 50% was female. The number of female calves kept annually to be reared as a replacement heifer equalled 113.4% of the number of culled cows, to account for a 13.4% calf mortality rate during the rearing period. Female calves not needed for replacement as well as all male calves were sold at 2 weeks of age, adjusted for 10% mortality.

The weight of slaughtered cows was estimated by assuming a dressing percentage of 60%. Calf values as well as slaughter value (Table 5.1) were based on the yearly values of 2019–2021 (Table 5.4).

Costs consisted of rearing costs of replacement heifers, feed costs and costs for AI and for clinical mastitis and lameness treatment. Replacement heifer costs were based on the average market value of full grown heifers over the period 2019–2021, while feed costs were calculated from Dutch feed prices per feed stuff during that same time period (Kok et al., 2019).

The cost of AI included both the price of semen and the costs of the AI procedure (KWIN, 2022). Each case of clinical mastitis was assumed to be treated with antibiotics. The applied treatment costs were derived from Dutch survey results from 2009 (Lam et al., 2013). For the treatment of lameness, this study differentiates between mild and severe cases: the treatment costs for mild lameness are negligible and for severe cases, it was based on a weighted average treatment cost of multiple claw disorders. It was estimated by combining the cost for each type of claw disorder by its mean annual prevalence. These included sole ulcer and digital dermatitis, two of the most expensive disorders to treat (Edwardes et al., 2022; O'Connor et al., 2023).

Sensitivity analysis

Milk revenue is the paramount component of farm partial net return. Variation in milk production could directly lead to changes in partial net return of a farm and affects GHG emission and culling decisions. Besides milk yield, the milk price is directly associated with milk revenue. One of the benefits of extending cattle longevity is the reduced demand for replacement heifers. Rearing these heifers comes at a cost, and while variable costs can fluctuate in the short term, fixed costs may undergo changes over a longer period. Therefore, a sensitivity analysis was conducted to capture the variation of those factors by evaluating the impact of production level, replacement heifer price or milk price on the model's results.

The default average daily milk production within one lactation was 25.75 kg per day. To examine the effect of production level on the model's results, the lactation curve was shifted up or down by 3 kg/day (Han et al., 2022). The effect of price variation on the economic performance of a dairy farm was estimated by analysing the highest and lowest prices of milk between 2019 and 2021 and replacement heifers costs were varied by including and excluding own rearing labor and barn costs (FrieslandCampina, 2022).

5.4 Results

The technical, economic and environmental results per herd of 100 cow places for all reproduction management strategies are presented in Table 5.5. The reproduction management strategies evaluated include increasing the number of AIs for all cows from 4 to 6 times or using a different subfertility culling threshold, i.e. when milk production drops below 10, 15 or 20 kg/day.

In the default scenario, based on a maximum of 4 attempts of AI and a milk yield drop below 15 kg as subfertility culling threshold, the average age at culling is 2,040 days or about 5.6 years. With an increase in the maximum number of AIs, all technical variables except for the culling rate show an upward trend. The impact is larger when shifting from a maximum of 4 to 5 AIs (108-day increase in age at culling) than from 5 to 6 AIs (47-day increase). Decreasing the threshold for subfertility culling from a milk yield of 20 to 10 kg/day decreases all evaluated technical results except for the age of the culled cows.

The increase of partial net return resulting from the increase in maximum number of AIs is illustrated in Figure 5.2, and a similar effect is shown for altered thresholds of subfertility culling. Table 5.5 provides further insight into the effect of the various reproduction management decisions on components of the partial net return. While revenues from milk and calves increase with 0.7% and 5.7% respectively, with an increase of maximum number of AIs from 4 to 6, meat revenues decrease with 11%. All costs, except for replacement costs, are also higher with an increased maximum number of AIs, resulting in an overall increase in partial net return of 1.0%. With less stringent subfertility culling standards, all components of partial net return decrease, resulting in an overall decrease in partial net return of 4.0%. Within the strategy of increasing maximum number of AI, replacement costs are most strongly affected. As for changes in the subfertility culling threshold, milk revenues show the most prominent alterations among other economic components.

With increased maximum number of AIs, the CO_2-equivalents per kg FPCM decreased from 0.926 to 0.915 (Table 5.5). In terms of the environmental consequences, there is no difference in GHG emissions per kg milk when the subfertility culling standard is increased from 15 to 20 kg/day (Table 5.5).

Figure 5.2. Impact of maximum number of AIs on partial cash flow (A) or on greenhouse gas emissions (B)

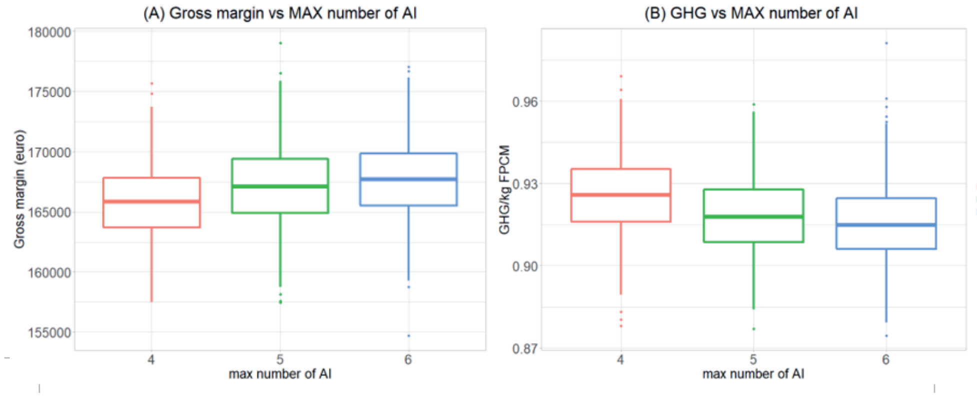

Table 5.5. Technical, economic and environmental simulation results per herd per year for herds with a maximum of 4, 5 or 6 artificial insemination attempts per pregnancy (n = 500 herds per max number of AIs) with default subfertility culling standard (15 kg/day) and average milk production levels.

	Max number of AI			Subfertility culling standard		
	4	5	6	<20 kg/d	<15 kg/d	<10 kg/d
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Technical indicators						
Number of calves	98 (5)	100 (5)	101 (5)	105 (5)	98 (5)	92 (6)
Age of culled cow (days)	2 040 (161)	2 148 (169)	2 195 (172)	1 968 (143)	2 040 (161)	2 132 (165)
FPCM delivered (kg/cow)	8 616 (105)	8 656 (111)	8 682 (110)	8 745 (99)	8 616 (105)	8 393 (131)
Cull rate	0.28 (0.05)	0.25 (0.05)	0.25 (0.05)	0.3 (0.05)	0.28 (0.05)	0.26 (0.05)
Mastitis incidence rate	31 (2.93)	31.4 (2.97)	31.4 (3.08)	32 (3.15)	31 (2.93)	30 (3.09)
Lameness incidence rate	30.3 (3.13)	30.2 (3.04)	30.4 (2.97)	31.3 (3.18)	30.3 (3.13)	29.1 (3.12)
Economic indicators						
(10^3 euros)						
Partial net return	165.83 (3.11)	167.11 (3.28)	167.65 (3.22)	168.17 (2.88)	165.83 (3.11)	161.19 (3.64)
Milk revenues	291.45 (3.53)	292.73 (3.71)	293.55 (3.7)	295.8 (3.33)	291.45 (3.53)	283.89 (4.39)
Meat revenues	23.51 (4.07)	21.5 (3.95)	20.84 (4.09)	24.76 (3.99)	23.51 (4.07)	21.74 (3.91)
Calf revenues	3.33 (0.18)	3.45 (0.16)	3.52 (0.17)	3.57 (0.15)	3.33 (0.18)	3.14 (0.19)
Feed costs	113.1 (0.92)	113.57 (0.96)	113.84 (0.96)	114.37 (0.85)	113.1 (0.92)	111.06 (1.18)
Replacement costs	30.08 (5.24)	27.47 (5.08)	26.62 (5.25)	31.87 (5.18)	30.08 (5.24)	27.77 (5.03)
AI cost	7.65 (0.66)	7.87 (0.68)	8.11 (0.71)	8.03 (0.65)	7.65 (0.66)	7.21 (0.66)
Mastitis treatment cost	1.05 (0.16)	1.08 (0.16)	1.1 (0.17)	1.09 (0.17)	1.05 (0.16)	0.99 (0.16)
Lameness treatment cost	0.58 (0.14)	0.58 (0.14)	0.59 (0.14)	0.59 (0.14)	0.58 (0.14)	0.55 (0.13)
Environmental indicator						
CO_2-eq (kg /FPCM)	0.926 (0.014)	0.918 (0.014)	0.915 (0.014)	0.926 (0.013)	0.926 (0.014)	0.928 (0.015)

Sensitivity analysis

A lower milk yield leads to earlier culling, lower partial net returns and higher GHG emissions. Similarly, a higher milk yield leads to later culling, higher partial net returns and lower GHG emissions. The absolute mean changes in comparison to the default settings are presented in Table 5.6.

Lower milk yields mitigated the effects of reproduction management changes on partial net returns (Table 5.6). In contrast, higher milk production levels increased the effect. With altered milk production levels, increasing the maximum number of AI times from 4 to 5 resulted in smaller differences in greenhouse gas (GHG) emissions and the age of culled cows, compared to the comparable max AI strategies in the default scenario. The partial net return increased when the replacement heifer price decreased, but decreased with a decreased milk price. When considering the maximum price for replacement heifers and for milk, the difference of partial net return increased for each additional AI services.

Table 5.6. Absolute mean changes compared to the default scenario in average partial net return (€/herd per year), GHG emission (kg FPCM) and age at culling (days) for a variation in milk production level of one standard deviation (SD). A minimum and maximum (min, max) price of replacement heifer and milk given a reproduction strategy based on a maximum of 4, 5 and 6 inseminations (n=500 herds).

	Partial net return (€/herd per year)			GHG (kg FPCM)			age of culled cows (days)		
Max number of AIs	4	5	6	4	5	6	4	5	6
Reference[1]	165 828	167 112	167 649	0.926	0.918	0.915	2 040	2 148	2 195
Production level, -SD	-23 523	-24 372	-24 551	0.045	0.046	0.045	-44	-58	-30
Production level, +SD	22 985	23 003	23 543	-0.037	-0.034	-0.034	75	30	22
Replacement heifer price, min	6 055	5 529	5 359						
Replacement heifer price, max	-13 645	-12 460	-12 075						
Milk price, min	-29 724	-29 854	-29 937						
Milk price, max	60 650	60 916	61 085						

[1] Refers to the default setting of a subfertility culling standard of 15 kg per day.

5.5 Discussion

This study aimed to explore how extending longevity of dairy cows by changing reproduction management decision rules (more AI attempts or lowering yield threshold for subfertility culling) affects partial net return at herd level and GHG emissions per unit milk. We developed a dynamic stochastic simulation model that simulates individual lactations in herds with 100 cow places, while accounting for culling for subfertility, mastitis, lameness or other reasons (i.e. general culling). The effects of longevity (increase in age) on the probability of disease were also taken into consideration.

In the default scenario with a maximum of 4 inseminations and a minimum milk production of 15 kg/day as a subfertility culling threshold, the average age of culled cows is 5.6 years, in line with the average of 5.8 years reported for Dutch dairy farms (Han et al., 2022). Comparing this default scenario with a situation allowing for more AI services (from maximum 4 to maximum 6), cattle longevity increased with 155 days. The age at culling increased with 164 days when the subfertility culling rules were changed from 20 kg/day milk production to 10 kg/day. More insemination rounds directly resulted in a longer CI for cows that conceived in the fifth or sixth round. At herd level, less fertility culling due to more AIs contributed to more cows having a next lactation, but also to a lower need for replacement animals. More AI attempts resulted in a higher farm partial net return and lower GHG emissions per unit FPCM. However, decreasing the subfertility culling threshold from 20 to 10 kg/day resulted in a decrease in farm partial net return, while increasing GHG emissions.

Considering the technical results under the strategy of increasing the maximum number of AIs, the number of calves increased. An increase in AIs reduced the number of cows that are not pregnant. For instance, the proportion of non-pregnant cows was 4% lower in parity 1 if the maximum number of inseminations increased from 4 to 5. Cows that are not pregnant get a relatively long lactation until they are culled when milk production drops below 15 kg/day. This lactation is longer than the calving interval of a cow that becomes pregnant from the fourth, fifth or sixth round of AI. That means the next calf is born earlier than the calf of the heifer that would have replaced the nonpregnant cow. Delivered FPCM increased with more AI due to the higher proportion of multiparous cows in a herd, which generally leads to higher milk production (Bokkers et al., 2014). Apparently, this increase in number of multiparous cows compensated for the longer average lactation length, which generally results in a lower milk yields per day of calving interval.

Under the strategy of easing the subfertility culling threshold, the number of calves decreased. A lower threshold leads to a longer lactation period for subfertile cows, prolonging the time until they are eventually replaced by a calving heifer. The long lactations at a lower milk production also explain the decrease in herd FPCM production in this scenario. A cow in late lactation produces less milk than a cow in early lactation, but with a higher fat and protein content (Panthi et al., 2017). This increase in milk content was not taken into account in this model, which could have resulted in a small underestimation of milk yield in late lactation, especially for the least stringent subfertility culling threshold.

Considering the economic results; the average replacement cost was affected most by a change in reproduction management. Replacement costs decreased by 3,460 euros per year when the maximum number of AIs increased from 4 to 6 times, due to a lower demand for replacement animals. In addition, the decreased culling rate resulted in less meat production from culled cows, which is the second largest reduction in economic components. Costs for AI, mastitis and lameness treatment increased with an increased maximum number of insemination rounds, as more cows entered the next lactation. In combination with a higher probability of disease in higher parities, the disease-related costs increased with more rounds of AI. Secondly, in this study, the probability of health disorders per lactation was adjusted for the lactation interval (or calving interval). Longer intervals lead to a higher probability of disease, therefore higher treatment cost and production losses. However the partial net return increased from €165,830 to €167,110 with an increased maximum number of AIs from 4 to 6 times, compensating for any economic losses.

Under the strategy of easing the subfertility culling threshold, milk revenues substantially decreased. The average lactation length of 1,878 days on average with a threshold of 20 kg/day is substantially lower than the 2,358 days with a threshold of 10 kg/day. Replacing cows with lower yields earlier avoids the low production levels at the end of lactation. The same reasoning also applies to the cost of AI, mastitis and lameness treatments that all decrease with a lower subfertility culling threshold. A less stringent subfertility culling threshold means a lower frequency of cow replacement, i.e. fewer heifers enter the herd in the same period. Since AI services are required for each new lactation and heifers face the full risk of disease development, the cost of AI and other treatments at the herd level reduces when the replacement frequency decreases.

The estimated GHG emissions per unit milk decreased by 0.9% when the maximum number of inseminations increased from 4 to 5 times, and by 1.2% when it increased to 6 times. This is caused by an increased milk production and lower annual cull rate, which reduce the GHG emissions from rearing replacement heifers. Under the strategy of easing the subfertility culling threshold, a lower threshold leads to higher GHG emissions. Specifically, the lowest threshold of 10 kg/day results in the highest CO_2-eq of 0.928 kg. In contrast, more stringent culling thresholds lead to a better environmental performance, which indicates the benefit in terms of milk yield outweighed the earlier culling.

For all results, the impact of increasing the maximum number of AI rounds from 4 to 5 is larger than for the increase from 5 to 6 times. This means there is a decreasing marginal effect of adapting reproduction management. For instance, the age at culling increases by 108 days when changing from 4 to 5 inseminations, but only by 47 days when changing the maximum number of inseminations from 5 to 6. This is because the proportion of cows conceiving drops for each insemination attempt. Approx. 4% of all primiparous cows conceives at the 5^{th} AI attempt, but only 2% at the 6^{th} attempt (Table 5.1).

In the sensitivity analysis, milk production levels had the largest impact on partial net return compared with GHG emissions and age at culling. The impact on GHG emissions was larger at lower production levels than at higher production levels, which is similar as the impact on age of culled cows. Cows with low milk yields will be replaced earlier than cows with high yields. Among the effect of price changes on partial net return, milk price has the greatest impact on partial net return. This is in line with the fact that milk revenue is the largest component in partial net return.

Higher milk production levels, a higher price of replacement heifers and higher milk price all increase the effect of increasing the maximum number of AI services on partial net return. However, higher production levels mitigate the effect on GHG emissions. Quantifying GHG emissions per unit of milk produced means that both the emissions themselves and the milk production levels affect the GHG emissions measure. Higher milk production does not only increase milk yield but also reduces the demand for replacement heifers. This is because it takes longer for more productive cows to reach the subfertility culling threshold. It is the same reason as why the age at culling is more strongly affected with higher milk production levels.

In this study, increasing longevity by increasing the maximum number of AIs reduces GHG emissions and improved partial net return. In contrast, lowering the yield threshold for subfertility culling leads to both a worse economic and worse environmental performance. Instead of easing the subfertility culling threshold, an increase in AI attempts can improve the sustainability of dairy farming from an economic, environmental and welfare perspective.

5.6 Conclusion

The study shows that cattle longevity can be extended by up to 5.5 months by altering reproduction management decision rules in terms of the maximum number of AI services or the subfertility culling production thresholds. Although lower subfertility culling thresholds has the potential to extend cattle longevity more than increasing the maximum number of AI services, only the latter benefits a farm's partial net return, while mitigating greenhouse gas emissions.

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CHAPTER 6

Effects of extending cattle longevity by disease prevention management measures on partial net return and greenhouse gas emissions

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This chapter is submitted

6.1 Abstract

Extending cattle longevity is seen as an option to achieve a better dairy farm economic and environmental performance. However, extending dairy cow longevity may lead to higher risks of health disorders. Health disorders reduce milk production, increase culling rate, and reduce cattle longevity, and therefore lead to additional labour, disease treatments and rearing of replacement heifers. Disease prevention is a crucial prerequisite for sustainably extending the cattle longevity. In particular, clinical mastitis and lameness are two of the most prevalent and expensive diseases. Therefore, simulations were conducted to evaluate the effect of increased cattle longevity on the technical and economic performance of a herd by applying preventive measures for clinical mastitis (7 measures) and lameness (5 measures). The incidence rate of clinical mastitis or lameness was updated in relation to the expected effectiveness of the evaluated preventive measure, using information from literatures. The results indicated that introducing disease prevention measures increased the age of culled cows by a maximum of 57 days, whereas the maximum decrease in GHG emissions resulting from the implementation of a disease prevention measure was 0.007 kg CO_2-eq per kg FPCM. Moreover, the majority of disease prevention measures resulted in a net decrease due to additional costs outweighed the increase in partial net return.

6.2 Introduction

Longevity of a herd is reflected by the average lifespan or age at which cows are culled. The average lifespan of a dairy cow in the Netherlands is around 5.8 years, with a range of 4.9 to 7.1 years across farms (Han et al., 2022). This is considerably shorter than the natural lifespan of dairy cows of 20 years. Extending cattle longevity is seen as an option to achieve a better dairy farm economic and environmental performance (Dallago et al., 2021; De Vries, 2020). Moreover, an increased longevity is perceived by society as a relevant indicator of animal welfare (De Vries et al., 2020).

However, extending dairy cow longevity may lead to higher risks of health disorders (Juarez et al., 2003; Lam, 2008). Within a commercial dairy farm, besides reproduction problems, health disorders are one of the main reasons for culling. Health disorders reduce milk production, increase culling rate, and reduce cattle longevity, and therefore lead to additional labour, disease treatments and rearing of replacement heifers. Clinical mastitis and lameness are two of the most prevalent and expensive diseases. In Europe, up to 30% of cows in a herd may suffer from mastitis (van den Borne et al., 2010), while around 25% of dairy cows may experience lameness (Amory et al., 2006; Edwardes et al., 2022; van den Borne et al., 2022). Clinical mastitis can lead to an reduction of approximately 5% in annual milk production of an affected cow. It also elevates the culling rate by 1.5-5% and decreases the conception rate, with estimated failure costs of about \$131 per cow per year at herd level (Hogeveen et al., 2019). Lameness can decrease milk production by 270 to 574 kg per cow per lactation, while also negatively impacting reproduction performance, including an extension in days open or calving interval, and increasing the risk of culling. The estimated failure cost of cows with sub-optimal mobility is approximately €122 per cow per year (Edwardes et al., 2022).

Disease prevention is a crucial prerequisite for sustainably extending the cattle longevity. Many preventive measures are possible to limit the incidence of production diseases such as mastitis and lameness. Preventing these diseases will not only reduce the economic losses to the farmer, but will also reduce GHG emissions per unit of milk produced (Mostert et al., 2018; Mostert et al., 2018). This is largely due to the fact that fewer replacements animals are needed. Rearing replacement animals takes two years, during which heifers consume feed and contribute to

GHG emissions, without any production. However, implementing preventive measures requires additional costs for e.g. labour, expenditures and/or investments. Therefore the objectives of this paper are (i) to quantify the extension of cattle longevity by applying disease prevention measures and (ii) to explore the effect of extending cattle longevity by applying disease prevention measures on technical and economic results at herd level, and GHG emissions per unit of milk, using a dynamic stochastic simulation model.

6.3 Materials and methods

Herd simulation model

This study used the model developed by Han et al. (Chapter 5). This model is designed to stochastically simulate Dutch dairy herds of 100 cows with extended cattle longevity through different reproduction management decisions. The model simulates lactations, and calving and health status events of individual cows within a herd. Annual partial net return is computed from revenues from sold milk, calves and culled cows, and the costs from feed consumption, rearing replacement heifers, AI services and treatment for clinical mastitis and lameness. Greenhouse gas emissions are computed using a life cycle approach, which also accounts for the production of meat from surplus calves and culled cows, assuming that it substituted other meat on the basis of edible product, thus avoiding additional GHG emissions from meat production elsewhere. Evaluated scenarios differed in the maximum number of artificial inseminations (AI) per lactation cycle (4, 5 or 6), or the moment of culling of subfertile cows (when milk production dropped below 20, 15, or 10 kg/d) (Chapter 5).

In this study, the analysis was conducted to evaluate the effect of increased cattle longevity on the technical and economic performance of a herd by applying preventive measures for clinical mastitis and lameness. The incidence rate of clinical mastitis or/ and lameness were updated in relation to the evaluated preventive measures. The reference scenario used in this study was based on a maximum of 4 AI services per lactation cycle given the default subfertility culling standard of 15 kg/day and average milk production levels. In this reference scenario, the proportion of cows getting clinical mastitis or lameness, on average, was 31% and 30.3% respectively (see Chapter 5).

Disease prevention management measures

Selection

Several measures to prevent clinical mastitis or lameness have been presented in the studies from Hogeveen et al (2011) and Bruijnis et al (2013). Some of these measures described are no longer relevant for further consideration, because they have already been massively applied in current farming practices. That means their impact is assumed to be reflected by the default scenario. Other measures were not feasible to include in the current modelling study because they resulted in combined effects. For instance, a measure related to the optimization of feed rations will not only have an impact on the disease occurrence. Consequently, seven clinical mastitis measures and five lameness measures were selected from these studies to prevent clinical mastitis or lameness, respectively, with one measure (floor hygiene) having a preventive effect on both diseases.

Effectiveness

This study recalculated the incidence decrease percentage for mastitis preventive measures based on the work of Hogeveen et al (2011), which originally specified the effect of such measures on an incidence decrease for a 100% environmental problem and as well as a 100% contagious mastitis problem. However, this study did not distinguish between the causes of mastitis. A combination of causes was considered to represent average mastitis situation by accounting for 65% environmental and 35% contagious problems (Hogeveen et al., 2011). The incidence decrease percentages per mastitis measure were weighted accordingly. Bruijnis et al., (2013) assessed the incidence of lameness in a default scenario, as well as the incidence rate resulting from the implementation of various intervention measures separately. To determine the reduction in lameness incidence resulting from the prevention measures in this study, the incidence rate of each measure was compared to the incidence rate under the default situation. The expected efficacy of each of the evaluated preventive measures on incidence reduction as simulated in this study is presented in Table 6.1.

Table 6.1. Description of selected preventive measures based on the applicability of the measure in commercial Dutch dairy farm and feasibility to apply in the simulation model and the relative percentage decrease in the incidence of clinical mastitis and lameness per parity.

Preventive measures[1]	Description	Percentage decrease
Clinical mastitis		
Milk cows with clinical last	All cows with clinical signs are milked last	19
Wash dirty udders during preparation	Dirty udders are washed with water and dried before attaching the cluster	13
Teat disinfection post-milking	All cows are treated with a good teat disinfectant after milking	39
Back-flushing clusters after milking a cow with clinical mastitis	After milking a cow with clinical signs, the cluster is rinsed with hot water before another cows is milked	14
Keep cows standing after milking	After milking, cows are kept standing for at least 30 min	13
Clean cubicles	Clean the stalls twice every day and make sure enough and clean bedding material is present	16
Floor hygiene	Improve hygiene by clean and dry flooring	10
Lameness		
Additional foot trimming	Including an extra foot trimming intervention at drying off	13
Footbath	Improve footbath management by more accurate application and increased frequency	4
Lying surface	Improve lying surface in cubicle by using more bedding material or better mattress	32
Rubber flooring	Apply a rubber floor in the alleys	23
Floor hygiene	Improve hygiene by clean and dry flooring	23

[1] Source: Bruijnis et al (2013); Hogeveen et al (2011)

Costs

For each of the measures, the additional costs were calculated derived from the study of van Soest et al (2016) and Bruijnis et al (2013) (Table 6.2). These additional costs captured all farm inputs that were affected by the alternative prevention management measures. Resources that remained unchanged, such as buildings, were not considered. The additional costs of preventive measures included labour costs, expenditures such as for water and clean gloves, and investment costs related to the use of durable assets such as a fence. Labor costs were updated using labor cost from year 2019-2021 (WUR statistics).

Table 6.2. The estimated costs for preventing lameness or clinical mastitis.

Preventive measures	Additional cost	Unit
Clinical mastitis		
Milk cows with clinical last	1,855	€/herd with 100 cows/year
Wash dirty udders during preparation of udder	490	€/herd with 100 cows/year
Teat disinfection post-milking	4,745	€/herd with 100 cows/year
Back-flushing clusters after milking a cow with clinical mastitis	54.5	€/clinical cases /year
Keep cows standing after milking	912	€/herd with 100 cows/year
Clean cubicles	5,464	€/herd with 100 cows/year
Lameness		
Additional foot trimming	720	€/herd with 100 cows/year
Footbath	4,300	€/herd with 100 cows/year
Lying surface	1,600	€/herd with 100 cows/year
Rubber flooring	3,200	€/herd with 100 cows/year
Clinical mastitis & Lameness		
Floor hygiene	3,310	€/herd with 100 cows/year

Cost-effectiveness

In this study the cost-effectiveness of the preventive measures is evaluated by a marginal analysis. The change in net partial returns for the situation with and without the preventive measure is seen as the economic benefit of the preventive measure. Considering the changes in costs and revenues, the net impact of each preventive measure was determined by subtracting the additional costs from the anticipated rise in partial net revenues. Preventive measures were assumed not to be carried out in the reference scenario and to be implemented completely and correctly in the new situation.

6.4 Results

Applying preventive disease measures increased the average age of culled cows by 3 to 57 days (Table 6.3). All preventive measures resulted in reduced GHG emissions per kg of milk, and an increased partial net return. For all preventive measures, except *Wash dirty udders during preparation of udder*, the net effect of those measures was negative (benefit/cost ratio <1). The additional cost outweighed the increase in partial net return.

Within measures to prevent clinical mastitis, teat disinfection post-milking contributed most to improving age of culled cows, average delivered FPCM and partial net return, and mitigating GHG emissions. Compared with the reference scenario, the application of teat disinfection post-milking increased average age of culled cows by 57 days, and the average delivered FPCM by 74 kg per cow place. This resulted in reduced greenhouse gas emissions of 0.007 kg CO_2-equivalents per kg FPCM and in increased partial returns of €2,420 at a cost of €4,750, giving a net negative effect of €2330 (benefit/cost ratio = 0.51). Within measures to prevent lameness, improving lying surface contributed most to improving age of culled cows, partial net return and mitigating GHG emissions. Compared with the reference scenario, the application of improving lying surface resulted in an increase in average age of culled cows of 45 days, and in an increase in average delivered FPCM of 23 kg per cow. Meanwhile, it contributed to a 0.005 kg CO_2-equivalents per kg FPCM reduction and a €1,140 increase in partial returns of a farm. However, the additional costs were equal to €1,600, indicating a negative net effect (benefit/cost ratio = 0.71).

Table 6.3. Absolute mean change of technical, environmental and economic simulation results per herd per year for each disease prevention measures compared with the reference scenario with a maximum of 4 times AI per lactation cycle with default subfertility culling standard (15 kg/day) and average milk production level, additional cost (10^3 €/ herd) ,net economic effect (10^3 €/ herd) and benefit cost ratio (n = 500 herds).

	Age of culled cow (days)	FPCM delivered (kg/cow)	Cull rate	CO_2-eq (Kg/ kg FPCM)	Partial net return (10^3 €)	Additional cost (10^3 €/ herd)	Net effect (10^3 €/ herd)	Benefit/Cost ratio
Reference	2040 (SD=161)	8616 (SD=105)	0.28 (SD=0.05)	0.926 (SD=0.014)	165.85 (SD=3.11)			
Clinical mastitis								
Milk cows with clinical last	38	22	-0.008	-0.003	0.81	1.86	-1.05	0.44
Wash dirty udders during preparation of udder	22	23	-0.005	-0.003	0.78	0.49	0.29	1.59
Teat disinfection post-milking	57	74	-0.012	-0.007	2.42	4.75	-2.33	0.51
Back-flushing clusters after milking a cow with clinical mastitis	31	18	-0.006	-0.002	0.66	1.71	-1.05	0.39
Keep cows standing after milking	18	28	-0.004	-0.002	0.85	0.91	-0.06	0.93
Clean cubicles	27	31	-0.002	-0.002	0.87	5.46	-4.59	0.16
Clinical mastitis and lameness								
Floor hygiene	28	29	-0.004	-0.002	1.02	3.31	-2.29	0.31
Lameness								
Additional foot trimming	18	-1	-0.006	-0.002	0.26	0.72	-0.46	0.36
Footbath	3	0	-0.005	-0.001	0.14	0.43	-0.29	0.33
Lying surface	45	23	-0.015	-0.005	1.14	1.60	-0.46	0.71
Rubber flooring	26	14	-0.006	-0.002	0.64	3.20	-2.56	0.20

6

6.5 Discussion

This study aimed to quantify the effect of additional preventive measures for production diseases on cattle longevity and the consequences on environmental and economic sustainability. The study was focused on the two most important production diseases: clinical mastitis and lameness, and was carried out with a dynamic stochastic simulation model. This model simulated individual lactations in herds with 100 cow places with lactation curve, calving interval, while accounting for culling for fertility reasons, mastitis, lameness and other reasons (i.e. general culling).

It is clear that a reduction in the incidence of mastitis and/or lameness has a positive impact on age of culled cows, through a lower culling rate. For different preventive measures, this effect differed because of varying effectivity. A consequence of the higher longevity, is the lower demand for replacement heifers and a larger proportion of multiparous cows in the herd. The first aspect saves costs of young stock rearing, while the second aspect leads to a higher milk production per cow per year, since multiparous cows produce more than primiparous cows (Neave et al., 2017; Walter et al., 2022). The impact of measures to prevent clinical mastitis on average milk production was larger than the impact of measures to prevent lameness. This is because the expected effect of mastitis on milk production is larger than the effect of lameness. Moreover, mastitis is responsible for a higher proportion of culling compared to lameness (Dallago et al., 2021; Garvey, 2022). Therefore, decreasing the incidence rate with a similar relative percentage had a larger absolute influence on milk yield in the case of clinical mastitis than in the case of lameness. For instance, the same percentage disease reduction of 13% (Table 6.1) by preventing clinical mastitis through the udder measure of *washing dirty udders during preparation of udder* or by preventing lameness using the measure *additional foot trimming* displayed an average increase of 23 kg delivered FPCM per cow and an average decrease of 1 kg delivered FPCM per cow, respectively. The negative impact on milk production might result from the stochastic feature of simulation study.

The application of disease prevention measures mitigated GHG emissions per unit milk and resulted, except for *Wash dirty udders during preparation of udder,* in a negative economic net effect. GHG emissions per unit milk are determined by the amount of GHG emissions and milk production yield. Reduced disease incidence rates can reduce GHG emissions due to a reduced demand for replacement heifer and an increased milk production at herd level due to a higher proportion of multiparous cows in the herd. Reducing the incidence of disease through prevention measures reduced treatment costs, milk loss or discard, and the cost of replacement heifer. However, the additional costs to implement the prevention measure outweighed in most cases these financial benefits.

Considering the largest relative decrease in the incidence of mastitis by 39% by applying *Teat disinfection post-milking*, the technical, environmental and economic simulation results for this alternative displayed the largest absolute changes compared to the reference scenario. Introducing the measure of *Teat disinfection post-milking* increased the average age of culled cows by 57 days, increased FPCM production by 74 kg per cow per year and increased the partial returns by €2,420 per herd per year, while the GHG emission per kg FPCM decreased by 0.007 kg compared with the reference scenario. However, the net financial effect was a loss in partial net return of €2,330 per year, indicating a benefit / cost ratio of 0.51.

It should be noted that the results demonstrate the impact of disease prevention measures at the average level, assuming a decrease from the default scenario in which, respectively, 31% or 30.3% of cows in a herd experience clinical mastitis or lameness. However, there is a wide variation in disease incidences between Dutch dairy farms (van den Borne et al., 2010). It is conceivable that farms with a higher incidence exhibit larger changes than the average model output. This is because, when considering the same percentage reduction, the absolute reduction in high incidence farm is larger.

Comparing the effect of extending cattle longevity by reproduction management decisions (Chapter 5) or disease prevention measures, the reproduction management decisions had a larger impact on cattle longevity. For instance, introducing disease prevention measures increased the age of culled cows to a maximum of 57 days, whereas the age increase was on average 155 days or 164 days when maximum number of inseminations was increased from 4 to 6 services or the subfertility culling production threshold was decreased from 20 kg/ day to 10 kg/ day. Similarly, the maximum decrease in CO_2-eq kg per kg FPCM resulting from the implementation of disease prevention measure was 0.007 kg per kg FPCM, while a change in number of maximal AI services from 4 to 6 resulted in a decrease of 0.011 CO_2-eq kg per kg FPCM. Moreover, while a relaxation in the maximum number of AI services from 4 to 6 services resulted in an average increase in partial net returns of €1820 per year, the majority of disease prevention measures resulted in a net decrease. Only the measure *Wash dirty udders during preparation* resulted in a net positive increase in returns of €270 per year.

The main contributor in the additional costs related to the implementation of disease prevention measures is labor costs. For instance, €1,655 out of the €1,855 annual additional costs for implementing the measure of *milk cows with clinical mastitis last* are labor costs. While the previous studies of Bruijnis et al., (2013) and van Soest et al., (2016) indicated a positive net effect in applying disease prevention measures (Bruijnis et al., 2013; Hogeveen et al., 2011; van Soest et al., 2016), net effect of most prevention measures in this study were below zero. This difference is particularly attributed to the higher value of labor used in this study; the hourly value of labor increased from €20 per hour in 2012 to €27.2 per hour in year 2021 (KWIN).

6.6 Conclusion

Dairy cow longevity can be extended by up to 57 days by introducing single disease prevention management measures. The application of disease prevention measures positively affect GHG emissions and age of culled cows. However, the net economic effect of those measures is negative.

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CHAPTER 7

General discussion

7.1 Introduction

In the Netherlands, the average longevity of dairy cows in a herd is about 5.8 years, ranging from 4.7 years to 7.3 years (Chapter 2). This is, however, below the potential longevity of dairy cows of 11 years under commercial production circumstances or up to 20 years in their maximum nature lifespan (Kulkarni et al., 2023; De Vries et al., 2020). Extending dairy cow longevity has been considered an option to contribute to more sustainable milk production from an economic, environmental, as well as societal perspective. This is mainly because increased longevity reduces the need for replacement heifers, and increases the average herd production level. In addition, longevity is regarded as one of the animal welfare indicators that reflects good health management practices. However, increased disease incidence due to higher age can also result in milk losses, more discarded milk and higher disease treatment costs. Therefore, the objective of this dissertation is to evaluate the economic and environmental impacts of dairy farm management practices related to dairy cow longevity.

7.2 Synthesis of the results

This dissertation consists of three chapters with an empirical approach, viz. Chapters 2 to 4. Chapter 2 provides the foundation for this dissertation. The absence of strong associations between average herd longevity, expressed as average age at culling, average milk production at culling and culling rate, and herd performance indicators indicated that it is possible to obtain a high cattle longevity without affecting the herd performance in terms of milk production, reproduction and health. The results of Chapter 3 showed that there are opportunities within current practice for improving longevity in order to meet society's concerns on animal welfare and environmental pollution, without affecting the gross margin of the herd. Chapter 4 estimated the total input and input-specific technical inefficiency of dairy farms, and explored the association of cattle longevity with technical inefficiency. Results indicated that extending the average age at culling may lead to improved economic performance of dairy farms as long as the milk yield at cow level (or individual cow production intensity) remains unchanged.

Two chapters, Chapter 5 and 6, of this dissertation were conducted with a bio-economic modelling approach to explore the impact of extending dairy cow longevity on economic and environmental performance of dairy farm. Chapter 5 explored the effect of extending cattle longevity by altering reproduction management decisions on technical and economic results at herd level, and on GHG emissions per unit of milk. Chapter 6 quantified the impacts on technical and economic performance as well as on GHG emission of extending dairy cow longevity by applying disease prevention measures. The simulation results from Chapter 5 and 6 indicated the possibility of extending cattle longevity by altering reproduction or disease prevention management. In addition, the results revealed the economic performance of a dairy farm can benefit from the adjusted reproduction management decision. Furthermore, the environmental consequences were also beneficial when the maximum number of insemination was increased or when additional disease prevention management was introduced. Figure 7.1 visualizes the interrelationships between the research chapters.

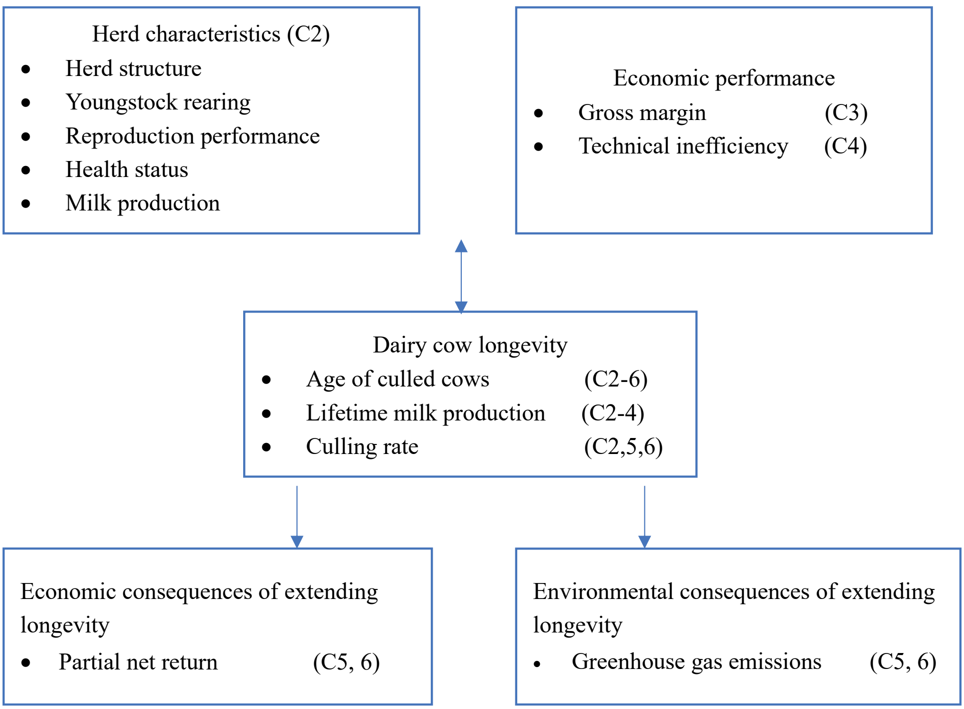

Figure 7.1. Overview of the interrelationships between Chapters (C).

Potential to extend dairy cow longevity

The definition of dairy cow longevity varies with different studies. Common metrics include herd life or productive life, which is the total time a cow remains in the herd from first calving until culling or death (Brickell et al., 2011; Compton et al., 2017). Additionally, other definitions such as stayability or survivability that reflect the proportion of cows surviving to a specific point in time, are also employed as measures of longevity (Oltenacu et al, 2010). Those definitions are commonly applied in cow level studies. In order to reflect economic, environmental and societal sustainable development at herd level, in this dissertation, I used three longevity indictors, namely age of culled cows, lifetime milk production, and culling rate. Age of culled cows measures the time from birth until culling or death, providing insight into the duration of the life of a dairy cow. Unlike age at culling, lifetime milk production not only depends on the average lifespan, but also on milk production intensity. Therefore, lifetime milk production, measured as the kg of milk produced by the cow during her lifespan embodies a more economic and environmental perspective on longevity. As indicated earlier, animal welfare is often assessed by society on the basis of the proportion of culled cows in the herd, making the culling rate a relevant longevity feature from a societal perspective.

The results from Chapter 2 illustrated that the average age of culled cows remained relatively constant at around 2,100 days (approximately 5.8 years) from 2007 to 2016 based on the performance data of 10,719 herds. The variance among herds showed that the average age of culled cows could reach 7.3 years (95 percentile) in practice. In those ’95 percentile’ herds, the longevity was almost 1.5 year longer than in average herds. This finding demonstrated the practical feasibility to obtain high dairy cow longevity under Dutch dairy production circumstances.

The performance data that I used in Chapter 2 were until the year 2016. Since that year, the average dairy cow longevity has increased with 141 days, until 6.1 years in 2022, due to the implementation of phosphate rights legislation in 2018 (CRV, 2022), which restricted the livestock density on a farm (especially of the unproductive youngstock). This is a considerable increase, but there is still ample room for improvement given the insights obtained from Chapter 2.

Despite the considerable difference in longevity between herds and the variation in productive, health and reproductive performance between herds, only part of the observed variance in longevity among the herds over time was explained by these herd performance variables. Factors such as low milk production, poor reproductive performance, and occurrence of health disorders (such as peripartum health disorders, metabolic disorders, and udder disorders) are often considered as reasons for culling individual cows within a herd (Bell et al., 2011; Pfeiffer et al., 2015; Sewalem et al., 2005). However, these clear associations at the individual cow level were not reflected at the herd level. The absence of strong associations between herd performance and each of the herd-level longevity variables indicated that there is potential for extending herd longevity without affecting herd performance in terms of milk production, reproduction and health (Chapter 2).

Gross margin and technical inefficiency were used as indictors to estimate economic performance of a dairy farm. Several studies (e.g., De Vries et al., 2020; Schuster et al., 2020) have stated the various effects of an increased dairy cow longevity on economic herd performance, although empirical studies were lacking. The results of the empirical study based on observational data from Dutch dairy farms, as presented in Chapter 3, showed that it is possible to obtain a higher cattle longevity without affecting farm economic performance (gross margin). The potential opposing economic impacts of a high dairy cow longevity might cancel each other out in the total economic performance of a dairy farm. This balance between positive and negative effects on different inputs might have been influenced by differences in price levels. In order to get insight in the association between dairy farm longevity and input-specific technical inefficiency, a data envelopment analysis was conducted in Chapter 4. Until now, only a limited number of studies have investigated the association between prolonged cattle longevity and farm efficiency (Ali, 2021; Kovács et al., 2011). In particular, there is a lack of research on how longevity may affect the efficiency of specific inputs such as feed and labor. The results of Chapter 4 revealed that the efficiency performance varied for different inputs, although Dutch dairy farms have relatively good overall technical efficiency. Capital and livestock purchase & services expenses displayed poor efficiency performance. In addition, extending the cow age at culling may lead to improved economic performance of dairy farms as long as the milk yield at cow level (or cow production intensity) remains unchanged.

Although association studies based on empirical data can provide valuable insights, they are often unsuitable to establish causation. Studies have indicated that poor fertility and health disorders, especially mastitis and lameness, are the main culling reasons in the Netherlands (Dallago et al., 2021; Haine et al., 2017). However, there is a lack of comprehensive studies investigating the causal effects of improving reproduction and health management on increasing the longevity of dairy cows. Simulation studies in Chapter 5 and 6 were therefore, conducted to bridge this knowledge gap. The results of those chapters showed that by adjusting reproduction management or disease prevention management, dairy cow longevity could be extended by a few months.

The economic and environmental consequences of extending cow longevity

Extending cattle longevity by altering reproduction management decisions or disease prevention management resulted in better economic and environmental performance (Chapter 5 and 6). Two strategies were considered in the reproduction management decisions: changing the maximum number of inseminations per pregnancy and changing the milk production threshold of subfertility culling. Both decisions only require a change in a decision rule. An extended longevity was reached by providing more opportunities for cows to become pregnant. There are no direct costs involved in this management change. Indirect costs consisted of higher insemination costs per pregnancy and higher costs for disease management due to the increased age of the herd. These additional indirect costs were more than compensated by reduced costs for young stock rearing (Chapter 5). The results showed that extending cattle longevity by increasing the maximum number of insemination services improved the economic performance and environmental performance of the simulated dairy farms. While numerous studies have examined the association of milk production with economic or environmental performance (e.g., Capper et al., 2020; Krpálková et al., 2014), there is a notable gap in the literature regarding the trade-off between economic and environmental performance in dairy farms by extending dairy cow longevity.

Only a few studies have evaluated the economic or environmental impact of additional disease prevention measures (e.g., Mostert, 2018). However, most of these studies focus on the effect on individual cow level, which may differ from herd level as health disorders can affect other herd characteristics. For example, a reduction in disease incidence does not only lead directly to lower treatment costs, but also indirectly to higher revenues from calve sales as more calves are born due to a higher proportion of healthy cows. In addition, technical results such as longevity and milk production are rarely quantified in those studies. An analysis was, therefore, conducted in Chapter 6. This study provided insight into the effect of extending dairy cow longevity by introducing additional disease prevention measures at herd level. The results demonstrated that for almost all preventive measures, the net economic effect was negative because the additional expenditures of the disease prevention measures exceeded the increase in partial net return. All preventive measures mitigated GHG emissions. When comparing the impact of management decisions concerning dairy cow reproduction and disease prevention, it can be concluded that adjusting reproduction management has a greater impact on extending cattle longevity, increasing partial net return and reducing GHG emissions than the introduction of additional disease prevention measures.

Despite the findings in Chapter 5 and 6 indicated that increased dairy cow longevity can mitigate GHG emissions in a dairy farm, a higher longevity of dairy cows is leading to a reduction in meat production. This decrease of meat production within the dairy sector can be offset by an increase in meat production from other sectors. Emission intensities, which refer to the amount of emissions produced per unit of product, vary across different commodities. Among these commodities, beef has the highest emission intensity, with approximately 300 kg of CO_2-eq emitted per kilogram of protein produced. Meat and milk from small ruminants follow closely, with emission intensities of 165 kg CO_2-eq/kg and 112 kg CO_2-eq/kg, respectively. Cow milk, chicken products, and pork, on the other hand, exhibit lower global average emission intensities, falling below 100 kg CO_2-eq/kg (FAO, 2013). Consequently, the various alternatives for dairy meat may result in different GHG emissions within the overall livestock sector.

7.3 Reflection on data and methods

Data

For this study, various data sources were used. Chapter 2, 3, and 4 employed herd performance data from CRV (Cattle Improvement Cooperative, Arnhem, the Netherlands). Anonymized farm accountancy data, obtained from a large Dutch accounting agency (Flynth, Arnhem, the Netherlands), was used in Chapter 3 and 4. The combined database, used in Chapter 3 and 4 offered a unique opportunity to combine economic performance of farms in relation to herd performance. Furthermore, Chapter 5 and 6 utilized secondary data from literature and expert interviews to parameterize the bio-economic simulation models (Figure 7.2).

The observational panel data from CRV and Flynth provided a substantial sample over a long continuous period of time. Data from CRV included information on 20,796 dairy herds (mainly Holstein-Friesian) over the period 2007-2017, representing approximately 80 percent of all dairy herds in the Netherlands. The CRV data contained comprehensive herd characteristics data regarding longevity features, reproduction performance, milk production performance and health status. The accountancy data from Flynth represented 2,809 herds with 30,170 yearly records from 2007-2016 containing information on economic performance indicated by revenues (e.g., milk revenues) and fixed and variable costs (e.g., machines, feed costs and veterinary costs), as well as on general farm characteristics (e.g., soil type, number of full-time employees).The performed analyses based on these databases offer a comprehensive picture of the existing association between dairy cow longevity, herd characteristics, and economic performance.

However, the disadvantages of observational data are obvious. Firstly, the selected sample may be biased. For example, farms collaborating with Flynth may have specific characteristics, such as being geographically close to Flynth's headquarters or being more interested in their economic performance. Secondly, pre-collected data restricts the selection of indicators. For instance, although conception rate or oestrus detection rate are more effective indicators of a dairy farm’s reproductive performance than calving interval, the absence of data on these rates necessitates the use of calving interval. Thirdly, the data cleaning process is crucial and timeconsuming. This includes the selection of representative Dutch commercial dairy farms according to specific criteria, dealing with outliers and missing values. Finally, it should be noted that observational data can be used to assess the association between variables, but cannot be used to determine a causal relationship. The relationship between dairy cow longevity and herd characteristics is based on mutual causation. Since the important reasons for culling are based on reproductive performance and disease occurrence, farms with a poor reproductive performance and health may have more culling. On the other hand, by culling decisions, the reproductive and health performance of herds (as represented by key figures) may be better.

Methods

In this dissertation, numerous methods were employed. In the empirical studies, mixed linear regression models (Chapter 2 and 3) and data envelopment analysis (DEA) (Chapter 4) were used. In addition, a dynamic stochastic bio-economic simulation model was built to perform the simulation studies in Chapter 5 and 6 (Figure 7.2).

The association between dairy cow longevity and economic performance of dairy farms was conducted with two methods: mixed linear regression modelling and data envelopment analysis. Linear models are commonly used to assess the associations between variables in observational data (e.g., Adamczyk et al., 2017; Jago et al., 2011; Kulkarni et al., 2023). In the mixed linear model, as built in Chapter 3, economic performance of dairy farms was expressed by the gross margin. The gross margin captures the overall economic performance of a dairy farm by subtracting total variable costs from total revenues the in a herd. Since both the revenues as well as the variable costs are consistently available in the accountancy data of farms, this is an often used metric. However, it not a complete metric. Fixed costs (e.g., labour, buildings and machines) are not taken into account and there are trade-offs between fixed and variable costs. Often, information about the fixed costs, such as availability of labour and land, is available, but it is very difficult to monetarize these costs. Therefore, DEA was conducted in Chapter 4. With DEA, it is possible to consider monetary as well as non-monetary inputs and outputs such as herd and land size and minimizes the impact of price volatility on farm's inputs and outputs. Since the efficiency performance of each input can be different, the overall economic performance can provide limited insight in the efficiency performance of each input. The input specific technical efficiency and its association with longevity were analysed in Chapter 4. To date, only a limited number of studies have been conducted on the association between prolonged cattle longevity and farm efficiency (Luik-Lindsaar et al., 2019). More specifically, insights on the association between longevity and the efficiency of specific input use (e.g., the use of feed and labor) were lacking.

In Chapters 2 to 4, associations between dairy cow longevity and farm performance could be studied, but it was not possible to conclude on causality. In order to study causality empirically, either an intervention study need to be performed or, in observational panel data, large changes in longevity within farms are needed to allow for a difference-in-difference study. An intervention study at the herd level, where some farms extend longevity and other farms serve as control farms, is complicated and very costly. An intervention study on longevity would need a long period to collect data. The intervention study, therefore, would likely exceed the duration of a PhD project. To allow for a difference-in-difference study, large changes in herd longevity within farms are needed and the data available showed that farms were very stable in their longevity (Chapter 2). Consequently it is difficult to study causal effects of extended longevity on herd performance. To overcome the limitations of the observational data that I used or the budgetary limitations of an intervention study, I developed a dynamic stochastic bio-economic simulation model in Chapter 5 and 6 to evaluate the causal impact of extending dairy cow longevity on the economic and environmental performance of a dairy farm. This model, based on an earlier developed model (Kok et al., 2017), overcomes several limitations of empirical studies in two main ways. Firstly, it allows for the incorporation of external factors related to cattle longevity that are difficult to capture in observational studies, creating a more simplified representation of the real world. Secondly, by using dynamic simulation, it is able to account for the synergistic effects of longevity-related factors, which cannot be fully captured through the use of regression models that hold other variables constant.

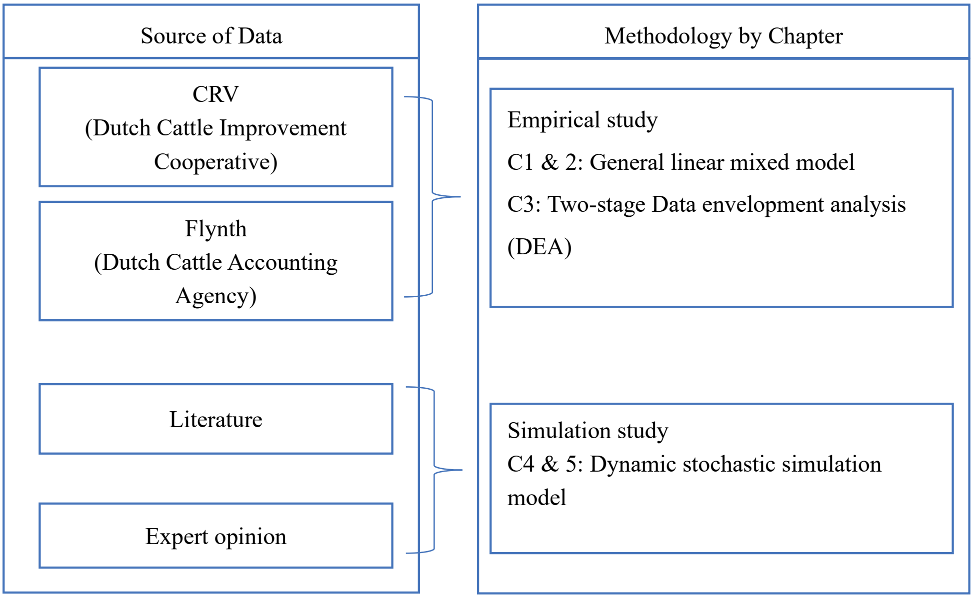

Figure 7.2 Overview of the data and methodologies used in different Chapters (C)

7.4 Business implications

Although Dutch dairy farms have better longevity performance compared with other countries (Dallago et al., 2021), there is still much room for improvement. This dissertation demonstrates the feasibility for a dairy farms to increase the longevity of their cows. According to the statistics presented in Chapter 2, the average age of a culled cow based on the 95th percentile is 2,674 days, which is roughly 7.3 years. In comparison to the average age of culled cows of 5.8 years, there is an opportunity to improve the dairy cattle longevity of 1.4 years. This is especially of relevance because under the current phosphate rights in the Netherlands, Dutch farmers already reduced their number of youngstock to meet the phosphate restriction requirement (Klootwijk et al., 2016). This dissertation provides insight that it is possible to further reduce the demand of replacement heifers and hence the number of required youngstock, by increasing dairy cow longevity without affecting herd performance in terms of milk production, reproduction, health and gross margin of the herd (Chapter 2 and 3). For the technical efficiency of a dairy farm, extending dairy cow longevity is not only considering the length of longevity of a dairy cow, but also the milk production intensity during her life. The results from Chapter 4 indicate that farmers can consider extending cow longevity if the average milk production level of the herd does not decrease with a higher proportion of older cows.

Adjusting reproduction and/or disease prevention management offers opportunities to extend cattle longevity, which also mitigate greenhouse gas emissions per unit milk (Chapter 5 and 6). Specifically, the results of Chapter 5 demonstrate that increasing the maximum number of inseminations per pregnancy from 4 to 6 times, resulted in a decrease of 0.011 kg CO_2-eq per kg FPCM. Given a yearly production of 14 billion kg of milk in the Netherlands (Kwakman, 2021), the contribution of a relaxation in the reproduction decision rule on mitigating GHG emissions from the dairy production can be substantial. The reduction in GHG emissions is roughly equivalent to the annual estimated CO_2 emissions from the electricity consumption of around 100,000 households in the Netherlands (Nowtricity., 2023; Statistics Netherlands., 2022).

7.5 Future research

This dissertation gives a comprehensive picture of the association of herd characteristics with dairy cow longevity in commercial Dutch dairy farms. However, the absence of strong associations suggests that variance in longevity among herds may be driven by other factors, like farmers' attitude toward culling and strategic farm management. Analysing these aspects can help to explain the main reasons behind culling decisions, which in turn can assist to reduce culling by developing tailored strategies. In addition, comparing farms with good and poor longevity performance can also provide valuable insights into bridging the longevity gap. For example, conducting a survey study on farms with different longevity performance can shed light on the main reasons for culling as well as the associated economic and environmental consequences. Moreover, farmers often report only one reason for culling, while multiple factors may contribute to the decision. For instance, lameness is known to negatively affect reproductive performance and milk production (Huxley, 2013). Therefore, further research on analysing the risk factors associated with dairy cow longevity, taking into account the interactions between these factors, would help to better pinpoint and subsequently target reasons for culling. The combined effect of these factors could potentially explain a greater variation of dairy cows' longevity among farms.

In this dissertation, adjusted reproductive measures were applied to all cows in a herd to reduce subfertility culling by increasing the conception rate. There are other measures that can also be used to increase conception rate, such as hormonal treatment (De Rensis et al., 2015). Younger cows exhibiting subfertility may encounter difficulties conceiving in later parities (Wathes et al., 2008). Therefore, categorizing these cows from early lactation and targeting a specific strategy (such as hormonal treatment) can increase the likelihood of conception. Furthermore, improving the probability of conception per oestrus cycle by improved oestrous detection, improved probability of conception (for instance by hormonal treatment) may also reduce the probability of culling because of subfertility. The impact of these measures may vary depending on how the targeted group of cows is categorized. For example, employing different timing and selection criteria stratified for diverse groups of cows, may lead to varying consequences and outcomes.

This dissertation conducted adjusted reproduction management and disease preventive management separately. Conducting future studies that integrate management strategies while considering optimal group strategies may potentially offer more efficient measures for enhancing cow longevity, as well as improving the economic and environmental performance of dairy farms.

New technologies are emerging to mitigate greenhouse gas (GHG) emissions in milk production. For instance, innovative manure management technologies like anaerobic digesters, composting systems, and separation technologies optimize the handling, treatment, and storage of manure. These methods reduce methane emissions, minimize nutrient runoff, and generate valuable by-products such as fertilizer or biofuels. However, studies examining the economic consequences of implementing these technologies are limited. Future research evaluating the economic and environmental impacts of these technologies is crucial in assessing their feasibility and potential benefits for widespread adoption.

7.6 Main conclusion

- In the Netherlands, the average longevity of dairy cattle at herd level, represented by age of culled milking cows, lifetime milk production and culling rate remained relatively constant over the years 2007 to 2016 (Chapter 2);
- There is potential for extending herd longevity without affecting herd performance in terms of milk production, reproduction, health and gross margin of the herd (Chapter 2 and 3);
- Despite, the relatively good overall technical efficiency of Dutch dairy farms, the efficiency performance varied for different inputs (Chapter 4);
- Extending the cow age at culling may lead to improved technical efficiency of dairy farms as long as the production intensity at cow level remains unchanged (Chapter 4);
- Dairy cow longevity can be extended by altering reproduction management decisions or disease prevention measures (Chapter 5 and 6);
- Extending cattle longevity by increasing the maximum number of insemination services improved both, the economic and environmental performance of the simulated dairy farms (Chapter 5);
- The implementation of disease prevention management measures can contribute to mitigate GHG emissions, but the economic effects were negative (Chapter 6).

7.7 References

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Summary

In the Netherlands, the average longevity of the dairy cows in a herd is about 5.8 years, ranging from 4.9 years to 7.3 years. This is, however, below the potential longevity of dairy cows. Extending dairy cow longevity has been considered an option to contribute to more sustainable milk production from an economic, environmental, as well as societal perspective. This is mainly because increased longevity could reduce the demand for replacement heifers, and increase the average herd production level as a result of a higher proportion of high-yielding multiparous cows within the herd. In addition, longevity is regarded one of the animal welfare indicators to reflect better health management practices. However, increased disease incidence due to older age can also result in milk losses or discard and higher disease treatment costs. Therefore, the objective of this dissertation was to evaluate the economic and environmental impacts of dairy farm management practices related to dairy cow longevity. Based on this objective the following specific subobjectives have been derived:

i. Evaluate the association of herd characteristics with dairy cattle longevity;

ii. Evaluate the association of dairy cattle longevity with farm gross margin;

iii. Evaluate the association of dairy cattle longevity with farm level technical inefficiency of milk production;

iv. Quantify the impact of reproduction management decisions on dairy cow longevity, herd profitability and greenhouse gas (GHG) emissions;

v. Quantify the impact of disease prevention management measures on dairy cow longevity, herd profitability and GHG emissions.

In **Chapter 2** the associations of herd performance indicators with herd-level dairy cow longevity under Dutch production conditions were evaluated. Longevity was expressed by three different measures, namely age at culling, lifetime milk production of culled cows and culling rate. The evaluated herd performance indicators included factors on milk production, youngstock rearing, reproduction and health performance as registered on 10 719 Dutch commercial dairy herds during the period 2007-2016. A mixed linear regression modelling approach was applied to evaluate the association of each of the three longevity measures with the selected herd performance indicators. The statistical results indicated that, averaged over herds and the evaluated period, the age of culled milking cows was 2 139 days (5.8 years, SD ± 298 days), the lifetime milk production of culled cows was 31 238 kg (SD ± 7 494 kg), and the culling rate was 0.24 (SD ± 0.08). The absence of strong associations between the longevity measures and herd performance indicators indicates that there is potential for extending cattle longevity without affecting the herd performance in terms of milk production, reproduction and health.

In **Chapter 3**, Dutch herd and farm accounting data (n = 855 herds) over the years 2007-2016 were analysed to investigate the association between dairy cow longevity and the economic performance of dairy herds. Data were analysed using generalized linear mixed models, with gross margin as the dependent variable. Descriptive statistics showed that the average age of culled cows was stable over the 10 years (range between 5.79 - 5.90 years). The gross margin was on average €24.80/ 100 kg milk (SD ± .67), with the lowest value in year 2009 and the highest value in year 2013. Gross margin was not significantly associated with age of culled cows and lifetime milk production of culled cows. This indicates that, within practice, there is potential for improving longevity in order to meet society's concerns on animal welfare and environmental pollution, without affecting the economic performance of the herd.

In **Chapter 4**, not only the total input and input-specific technical inefficiency of dairy farms were evaluated, but also its association with cattle longevity under Dutch production conditions was explored. Combining performance data and accounting data of commercial Dutch dairy herds from 2007-2014 resulted in a dataset with information on 1 037 commercial dairy herds. A two-stage approach was used for the analysis. First, input-specific technical inefficiency scores were computed using Data Envelopment Analysis (DEA). Output was measured by total farm revenues. Inputs included labor availability, land size, livestock units and the expenses on capital, seed & protection, veterinary services, livestock purchase & contract services, feed and others. Secondly, the associations of the obtained inefficiency scores with cattle longevity were studied by means of a bootstrap truncated regression analysis. Of the evaluated inputs, utilization of livestock units and feed was most efficient (inefficiency scores of 0.16 and 0.26, respectively). This contrasted with the poor input efficiency of capital and other goods & services; these inputs could be reduced with 52% without affecting output. Results of the regression analysis illustrated that age of culled cows was significantly negatively associated with each of the input inefficiencies, except for veterinary services. This was in contrast to the significant associations of input inefficiencies with lifetime milk production, which were mostly positive. From these findings, it is was concluded that dairy farms can improve their economic performance (technical efficiency) by extending the cow age at culling, as long as the production intensity at cow level remains unchanged.

Chapter 5 and 6 investigated the effect of extending dairy cow longevity on partial net return at herd level and greenhouse gas emissions per unit of milk by adjusting reproduction management decisions or applying disease prevention measures, using a dynamic stochastic simulation model. The model simulated lactations, calving and health status events of individual cows for herds of 100 cows. In **Chapter 5**, the evaluated scenarios differed in the maximum number of consecutive artificial insemination (AI) attempts (4, 5 or 6 services), or the production threshold at which subfertile cows were culled (20, 15, or 10 kg milk per day).

Average age at culling increased with an increased maximum number of AI services. The increase in longevity was larger when going from a maximum of 4 to 5 AI attempts (108 days) than from a maximum of 5 to 6 attempts (47 days). The average age of culled cows increased from 1 968 to 2 040 and 2 132 days when the subfertility culling standard was lowered from 20, to 15 and 10 kg milk per day, respectively. Average annual partial net return increased from €165 850 at a maximum of 4 AIs to €167 670 at a maximum of 6 AIs, but decreased from €168 190 at a subfertility culling threshold of 20 kg/day to €161 210 at a threshold of 10 kg/day. Greenhouse gas emissions decreased with an increased maximum number of AIs from 0.926 to 0.915 kg CO_2 equivalents per kg fat-and-protein-corrected milk (FPCM) at maximum 4 or 6 AIs respectively, while they increased from 0.926 kg at a threshold of subfertility culling of 20 kg/day to 0.928 kg CO_2 equivalents per kg FPCM at a threshold of 10 kg/day. Although lowering the subfertility culling standard had the potential to extend cattle longevity more than increasing the maximum number of AI services, only the latter benefited the farm's partial net return and mitigated greenhouse gas emissions.

In **Chapter 6,** simulations were conducted to evaluate the effect of increased cattle longevity on the technical and economic performance of a herd by applying preventive measures for clinical mastitis (7 measures) and lameness (5 measures). The incidence rate of clinical mastitis or lameness was updated in relation to the expected effectiveness of the evaluated preventive measure, using information from literature. The evaluated disease prevention measures had a smaller impact on dairy cow longevity than the reproduction management decisions evaluated in Chapter 5. For instance, introducing disease prevention measures increased the age of culled cows by a maximum of 57 days, whereas the age increase was on average 155 days or 164 days when maximum number of AI was increased from 4 to 6 services or the subfertility culling threshold was decreased from 20 kg/ day to 10 kg/ day. Similarly, the maximum decrease in GHG emissions resulting from the implementation of a disease prevention measure was 0.007 kg CO_2-eq per kg FPCM, while a change in number of maximum AI services from 4 to 6 resulted in a decrease of 0.011 kg CO_2-eq per kg FPCM. Moreover, while a relaxation in the maximum number of AI services from 4 to 6 services resulted in an average increase in partial net returns of €1 820 per year, the majority of disease prevention measures resulted in a net decrease due to additional costs outweighed the increase in partial net return.

The results, applied data and methodological approach were synthesized in **Chapter 7**, and final conclusions were drawn. The potential business implications following from this thesis and directions for future study were also discussed. Based on the main results, the main conclusions of this dissertation are summarized as follows:

- In the Netherlands, the average longevity of dairy cattle at herd level, represented by age of culled milking cows, lifetime milk production and culling rate remained relatively constant over the years 2007 to 2016 (Chapter 2);
- There is potential for extending herd longevity without affecting herd performance in terms of milk production, reproduction, health and gross margin of the herd (Chapter 2 and 3);
- Despite the relatively good overall technical efficiency of Dutch dairy farms, the efficiency performance varied for different inputs (Chapter 4);
- Extending the cow age at culling may lead to improved technical efficiency of dairy farms as long as the production intensity at cow level remains unchanged (Chapter 4);
- Dairy cow longevity can be extended by altering reproduction management decisions or disease prevention measures (Chapter 5 and 6);
- Extending cattle longevity by increasing the maximum number of insemination services improved the economic and environmental performance of simulated dairy farms (Chapter 5);
- The implementation of disease prevention management measures can increase cattle longevity and contribute to mitigate GHG emissions, but the economic effects are negative (Chapter 6).

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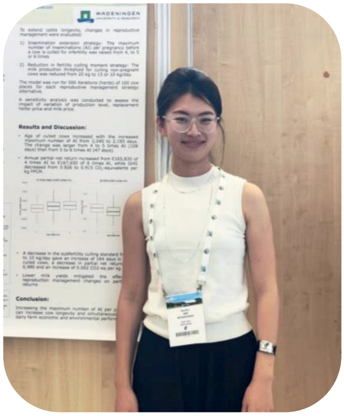
About the author



Ruozhu Han was born on April 9th, 1992, in Qingdao, China. Having spent 18 years in this picturesque coastal city, she pursued her studies at Jinan University, majoring in Finance. During this time, she concurrently completed a minor Bachelor's degree in Business English from Shandong University.

Driven by a desire to contribute positively to sustainable production practices in the agricultural sector, Ruozhu shifted her focus to agricultural topics for her Master's and PhD studies.

Since 2015, she furthered her studies at China Agricultural University, specializing in Management Science and Engineering. Throughout her master's program, she received structural education training in the field of agricultural economics. Her graduation thesis focused on analyzing consumer purchase intention for quality & safety insured Wuchang organic rice.

From 2018, she embarked on her PhD project within Business Economics group at Wageningen university and Research. Her research topic is 'Economic and environmental sustainability in relation to dairy cow longevity'. Throughout her doctoral journey, she quantitatively analyzed trade-offs between economic and environmental pillars of sustainability. She was able to access large databases to derive insights on the complexity of factors involved in sustainable practices, and communicating analytical insights in an action-oriented and easy-to-understand manner to decision makers.

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List of publications

Ruozhu, Han, Monique Mourits, Wilma Steeneveld, Henk Hogeveen. 2022, The association of dairy cattle longevity with farm level technical inefficiency. Frontiers in Veterinary Science., DOI:10.3389/fvets.2022.1001015

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I, Vredenberg, **Ruozhu, Han**, Monique Mourits, Henk Hogeveen, Wilma Steeneveld. 2021, An Empirical Analysis on the Longevity of Dairy Cows in Relation to Economic Herd Performance. Frontiers in Veterinary Science., DOI:10.3389/fvets.2021.646672

Ruozhu, Han, Akke Kok, Monique Mourits, Henk Hogeveen. 2023, Effects of extending dairy cow longevity by adjusted reproduction management decisions on partial net return and greenhouse gas emissions: A dynamic stochastic herd simulation study. (submitted)

Ruozhu Han
Wageningen School of Social Sciences (WASS)
Completed Training and Supervision Plan

Name of the learning activity	Department/Institute	Year	ECTS*
A) Project related competences			
A1. Managing a research project			
WASS PhD Introduction	WASS	2020	1
Writing research proposal	WUR	2018-2019	6
'Determination of Input-Specific Technical Inefficiency in Relation to Dairy Cattle Longevity'	ISESSAH, Selangor, Malaysia	2021	1
'Determination of technical inefficiency in relation to dairy cattle longevity'	AgEconMeet, Göttingen, Germany	2022	1
'Economic and Environmental sustainability in relation to dairy cattle longevity'	SDDDC webinar	2020	1
'Economic and environmental impacts of cattle longevity extension by altered reproductive management decisions'	ISESSAH, Helsinki, Finland	2023	1
PhD discussion group BEC	WUR	2018-2022	2
A2. Integrating research in the corresponding discipline			
Visual Research Methods	WASS	2020	2
Quantitative Data Analysis: Multivariate Techniques	WUR	2019	2
Econometrics, AEP 21306	WUR	2019	6
B) General research related competences			
B1. Placing research in a broader scientific (social sciences and WUR) context			
The art of modelling	PE&RC and WIMEK	2021	3
Mixed linear models	PE&RC and WIMEK	2021	0.6
Essentials of modelling	PE&RC and WASS	2023	1.5
VEEC study day: Improving Animal Welfare	VEEC	2022	1
B2. Placing research in a societal context			
Write magazine article	BEC	2020-2022	1

C) Career related competences			
C1. Employing transferable skills in different domains/careers			
Searching and organising literature for PhD candidates	WUR Library	2019	0.6
Project and time management	WGS	2021	1.5
Career orientation	WGS	2021	1.5
Total			**33.7**

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

Colophon

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