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Economic impacts of constrained replacement heifer supply in dairy herds

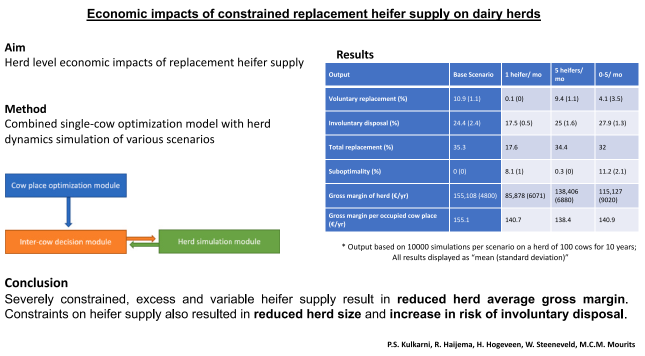
Pranav S. Kulkarni [a,c,*,1], Rene Haijema [b], Henk Hogeveen [a], Wilma Steeneveld [c], Monique C. M. Mourits [a]

[a] *Business Economics Group, Wageningen University & Research, Hollandseweg 1, 6706KN Wageningen, the Netherlands*
[b] *Operations Research and Logistics Group, Wageningen University & Research, Hollandseweg 1, 6706KN Wageningen, the Netherlands*
[c] *Department of Population Health Sciences, Faculty of Veterinary Medicine, Utrecht University, Yalelaan 7, 3584 CL Utrecht, the Netherlands*

HIGHLIGHTS

- Restrictions are placed on dairy heifer replacement supply due to current agricultural policies in NW-Europe.
- Study of the economic impact of a constrained heifer supply by combining cow replacement optimization with herd simulation.
- Sub-optimal heifer supply scenarios result in lower gross margin in comparison to the optimal replacement scenario.
- Severe constraints on heifer supply result in reduced herd size, voluntary disposal, as well as herd gross margin.
- Herd mate interdependence determines the economic optimization of replacement decisions under heifer supply constraints.

GRAPHICAL ABSTRACT



Economic impacts of constrained replacement heifer supply on dairy herds

Aim
Herd level economic impacts of replacement heifer supply

Method
Combined single-cow optimization model with herd dynamics simulation of various scenarios

Results

Output	Base Scenario	1 heifer/ mo	5 heifers/ mo	0-5/ mo
Voluntary replacement (%)	10.9 (1.1)	0.1 (0)	9.4 (1.1)	4.1 (3.5)
Involuntary disposal (%)	24.4 (2.4)	17.5 (0.5)	25 (1.6)	27.9 (1.3)
Total replacement (%)	35.3	17.6	34.4	32
Suboptimality (%)	0 (0)	8.1 (1)	0.3 (0)	11.2 (2.1)
Gross margin of herd (€/yr)	155,108 (4800)	85,878 (6071)	138,406 (6880)	115,127 (9020)
Gross margin per occupied cow place (€/yr)	155.1	140.7	138.4	140.9

* Output based on 10000 simulations per scenario on a herd of 100 cows for 10 years;
All results displayed as "mean (standard deviation)"

Conclusion
Severely constrained, excess and variable heifer supply result in **reduced herd average gross margin**. Constraints on heifer supply also resulted in **reduced herd size** and **increase in risk of involuntary disposal**.

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

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ABSTRACT

CONTEXT: In recent years, environmental policies, especially in North-western European countries have put pressure on the total livestock on a dairy farm. On closed dairy farms this primarily has resulted in a reduction of the heifer rearing unit to maintain the production unit. The economic consequences of constrained replacement heifer supply on herd level have not been investigated.
OBJECTIVE: The objective of this study is to study on herd level the economic impact of suboptimal replacement decisions due to a constrained replacement heifer supply.
METHODS: In this study, we combine a single-cow MDP (Markov Decision Process) optimization model with dairy herd dynamics simulation of 10 years to account for the interdependency among dairy cows within the herd of 100 cows. Besides the base scenario of following optimal replacement policy, we simulated three input scenarios of constrained, excess, and variable replacement heifer supply.
RESULTS AND CONCLUSION: In the base scenario, optimal replacement policy resulted in a herd gross margin of €155,108, 11% voluntary replacement rate, 24% involuntary disposal rate annually for a herd of 100 cows. Constrained as well as excess heifer supply resulted in lower gross margins of €85,878 and €138,406 respectively,

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[*] Corresponding author at: Business Economics Group, Wageningen University & Research, Hollandseweg 1, 6706KN Wageningen, the Netherlands.
E-mail address: pskul@ucdavis.edu (P.S. Kulkarni).
[1] Current address: One health Institute, School of Veterinary Medicine, University of California- Davis, 1089 Veterinary Medicine Dr, Davis, CA 95618, USA.

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compared to the base scenario. Constrained heifer supply also resulted in 39% reduction of herd size, involuntary disposal of 17.5% and no voluntary replacements (0.1%) on average per year. Variable heifer supply scenario resulted in lower gross margins (€115,127), lower voluntary replacement rate (4%), highest involuntary disposal rate (28%) but did not result in reduction of herd size, compared to the base scenario.

In conclusion, we developed a combination of cow level optimization with a herd level simulation to study the economic impacts of constrained replacement heifer supply. We found that severely constrained, excess, and variable heifer supply result in reduced herd average gross margin.

SIGNIFICANCE: Optimization replacement policy in case of limited heifer availability requires an inter-cow comparison to determine which cows need to be replaced first as this study shows. By demonstrating a simplified approach of combining individual cow optimization with herd dynamics simulation, we accounted for the inter-dependencies within herd. Such an approach can be instrumental in studying environmental impacts, longevity, and welfare of cows when heifer supply is constrained on a herd level.

1. Introduction

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

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

At present, new agricultural policies in North-western Europe are being implemented to reduce the environmental impact of dairy and other livestock farming systems. For example, the phosphate rights system (Kulkarni et al., 2021, 2023) as implemented in the Netherlands since 2017–18 puts pressure on dairy farmers to reduce the total number of livestock (i.e., to reduce mineral excess from manure) on their farms. Such an environment-oriented policy will motivate farmers to especially restrict the number of non-productive youngstock and thus the availability of replacement heifer stock on dairy farms. Consequently, optimization of replacement decisions based on the assumption of 100% heifer availability is increasingly at odds. A reduction in the replacement heifer supply might mean that farmers are unable to make optimal or near-optimal replacement decisions and therefore incur losses due to a sub-optimal replacement policy. The policy would not result in such a severe constraint on replacement heifer supply that the farmers are forced to reduce their herd sizes. However, the consequences of new policies might increase the risk of incurring losses due to involuntary disposal due to absence of a suitable heifer.

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

The aim of this study is to study on herd level the economic impact of suboptimal replacement decisions due to a constrained replacement heifer supply by combining a single-cow MDP (Markov Decision Process) optimization model with dairy herd dynamics simulation modelling to account for the interdependency among dairy cows within the herd. By generating different heifer supply scenarios, we aim to illustrate the loss in economic gains where the number of replacement heifers is insufficient or rather excessive.

2. Materials and methods

2.1. *Modellingframework*

In this study, the modelling framework employed consists of three modules: (i) a Cow-place optimization module, (ii) an Inter-cow decision module, and (iii) a Herd simulation module, as depicted in Fig. 1.

The Cow place optimization module optimizes the monthly reoccurring decisions on whether to keep, keep and inseminate, or replace a cow occupying a cow place, under the assumption of 100% heifer availability. This module will output an optimal replacement and insemination decision policy and a Retention Pay-Off (RPO; see 2.1.1 for details) value for a single cow place. The Inter-cow decision module decides subsequently whether the individually optimized decisions for each cow can be exercised given the number of available heifers at herd level. To account for the interdependency among dairy cows competing for the same limited supply of replacement heifers, this module ranks the dairy cows within the herd by their RPOs (as derived from the Cow place optimization module). If not enough heifers are available, only those cows with the highest ranks (lowest RPO values) are replaced. Finally, in the Herd simulation module the state dynamics of each cow is simulated, driven by the heifer supply corrected optimal decision policy. The final cow state transition results and the expected candidate cows for replacement are fed back to the Inter-cow decision module to start the next month's evaluation, explaining the indicated interaction between the modules in the Fig. 1. The main purpose of the Herd simulation module is to evaluate the economic impact of the replacement decision policy at the herd level.

Detailed information about the three modules is provided in 2.1.1, 2.1.2 and 2.1.3 respectively.

2.1.1. *Cow place optimization module*

The functionality of this module (Fig. 1) is to indicate the best decision to make for a single cow place, assuming there is always a heifer available to implement the best decision. The modelled optimization problem fits to the framework of Markov Decision processes (MDP; Puterman, 2014). Below we discuss the main components of the modelled MDP.

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

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

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

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

Biologically feasible combinations of levels of the four state variables resulted in a state space of 9720 unique state combinations for each cow place. The formulation of state variables was in line with previous works of Van Arendonk (1985) and Demeter et al. (2011), details can be found in Appendix 1.

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

- $d = 1$: "Keep": decision to keep the cow
- $d = 2$: "Inseminate": decision to keep and (re-)inseminate the cow
- $d = 3$: "Replace": decision to replace the cow by a new heifer

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

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

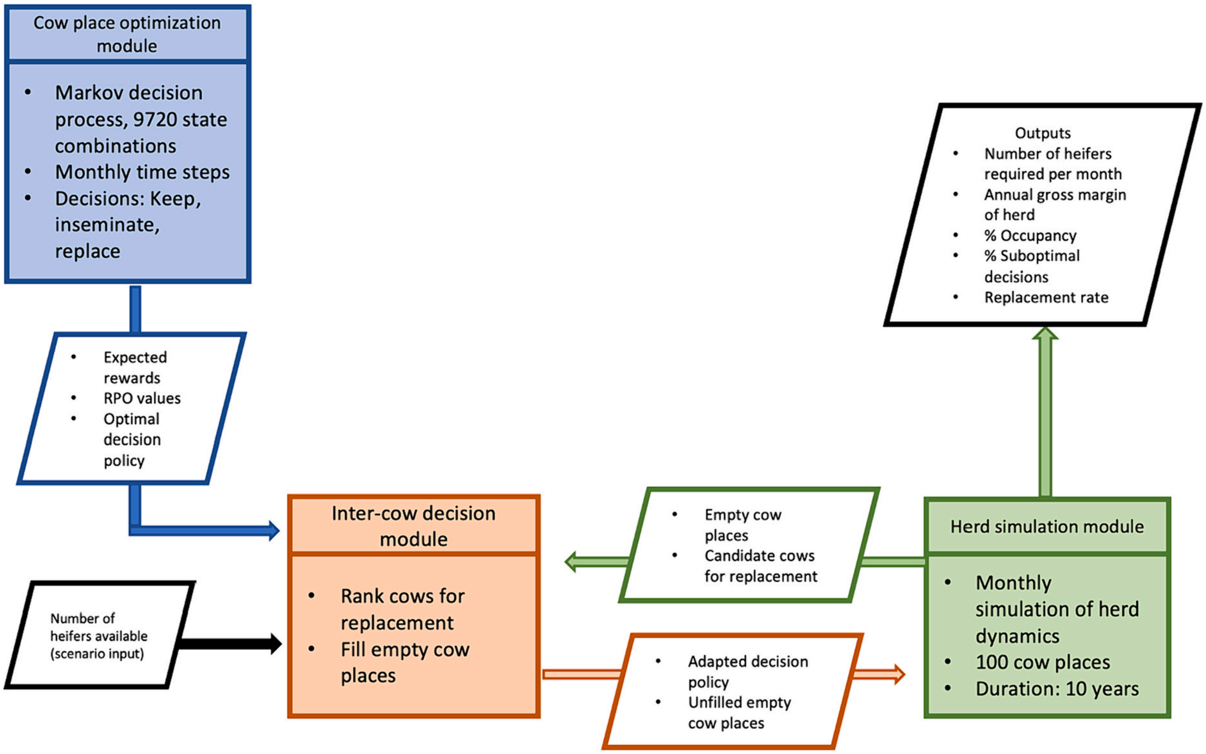

Fig. 1. Modelling framework of this study with three modules and their direction of interaction showing inputs and outputs.

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

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

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

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

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

Table 1

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

Input variable	Unit	Price	Source
Milk price	€/kg	0.46	Average from WECR for standard milk (4.36% fat; 3.54% protein); WECR, 2022
Feed cost	€/1000 VEM	0.35	Average of summer and winter ration from WECR, 2022
Calf revenue	€/animal	65	WECR., 2022
Carcass Value	€/kg slaughter weight	1.97	WECR. Agricultural prices 2022
	€/1st parity animal	1077	Body weight of 545 kg (60% dressing percentage)
	€/2nd parity animal	1176	Body weight of 595 kg (60% dressing percentage)
	€/3 + parities animal	1285	Body weight of 650 kg (60% dressing percentage)
	Involuntary disposal	0	Assumption; authors' expertise
Heifer rearing cost	€/heifer	2342	Lammersen, 2023
Heifer market price	€/heifer	1852	WECR, 2022
Insemination costs	€/month	23.2	WECR, 2022

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

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

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

where, $P(s^{'}|s,d)$ is the transition probability of going to state $s^{'}$, when in state s decision d is taken. The immediate reward associated to these transitions is $R(s,d)$, see eq. (1). γ is the discount factor for rewards and $V(s^{'})$ is the value of the new state $s^{'}$. The discount factor γ in this study was set at $0.95^{\frac{1}{12}}$ per year (5% per annum or 0.46% per month; author's expertise based on industry standard rate).

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

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

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

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

2.1.2. Inter-cow decision module

To study the effects of constrained heifer supplies, the Inter-cow decision module was developed (Fig. 1). This Inter-cow decision module uses the input information from the Cow place optimization module and from the Herd simulation module (details in 2.1.3). The required input information consists of the optimal decision policy assuming unlimited heifer supply, the number of candidate cows for replacement in each month (RPO < 0), the number of empty places in the herd (as a result of an involuntary disposed cow without replacement in previous month) and the number of available heifers as defined by scenario input.

In each time step, the module first attempts to fill the empty places in the herd with the available heifers. Secondly, depending on the number of heifers remaining available after filling those empty places, it compares the candidate cows for replacement based on their RPO values by ranking them in ascending order. Based on the number of heifers available, the top ranked candidate cows (cows with the lowest RPOs) are replaced, whereas for all the remaining candidate cows, the optimal "replace" decision is altered to a "keep" decision in the simulation. Subsequently, the Inter-cow decision module, conveys the adapted decision policy to the Herd simulation module as depicted in Fig. 1.

2.1.3. *Herd simulation module*

The Herd simulation module (Fig. 1) represents a dairy herd on a farm with a maximum housing capacity of 100 cow places. Cows in the Herd simulation module are represented by the same four state variables (i.e., lactation number, months in lactation, months in pregnancy and relative milk production level) as defined in the Cow place optimization module. Based on a random sample of 100 actual producing herds in the Netherlands (unpublished data from Kulkarni et al., 2021), a distribution of initial values of the four state variables was established (see Appendix 2). The purpose of this distribution is to simulate cow places containing cows in different stages of life as is seen in herds in practice.

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

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

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

2.2. *Evaluated heifer supply scenarios*

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

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

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

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

All three scenarios are analysed by performing 10,000 herd simulations similar to the base scenario (including the burn-in period of 15 months). At the end of the herd simulations of each heifer supply scenario, the same outputs as in the base scenario are calculated, namely, annual gross margin of the herd, replacement rate, rate of involuntary disposal, total replacement rate. Gross margin of the herd was defined as the marginal revenue from milk production minus the feed costs, insemination costs (if any) and the replacement costs (if any). Costs of durable assets such as buildings and machinery as well as farmer's labour costs were fixed, reflecting the mid- to long-term situation of dairy farms in the Netherlands (Houben et al., 1994; Kay et al., 2015). This definition was used consistently for all three scenarios in addition to the base scenario.

Additionally, average number of empty places in the herd per year is calculated and converted to annual percent-occupancy (where all places filled meant 100% occupancy). Using the occupancy, the average gross margin per occupied cow place was calculated based on the annual gross margin. The average number of suboptimal decisions made per year is also calculated and converted to percent-suboptimal decisions (where, 0% suboptimal decisions means that the herd followed the optimum policy as generated by the individual cow optimization module). Moreover, the excess number of heifers remaining after each time step is recorded. The model assumes that each excess heifer is sold to the market incurring a loss of € 490 since that is the average difference between the estimated heifer rearing cost and the purchase price of replacement heifers from the market. This loss is subtracted from the annual gross margin of the herd resulting in reduced gross margin due to presence of excess heifers for replacement. At the end of the simulations, the resulting outputs are compared to the results of the base scenario to evaluate the herd-level impact of heifer availability on cow replacement.

2.3. *Sensitivity analysis*

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

3. Results

From Table 2, the overall replacement rate in the base scenario was 35.3% (voluntary replacements + involuntary disposal). Since, in the

Table 2
Modelling results per heifer availability scenario indicating herd averages based on 10,000 simulations of 10 years.

Output [1,2]	Base Scenario	1 heifer/ mo	5 heifers/ mo	0–5/ mo
Voluntary replacement (%)	10.9 (1.1)	0.1 (0)	9.4 (1.1)	4.1 (3.5)
Involuntary disposal (%)	24.4 (2.4)	17.5 (0.5)	25.0 (1.6)	27.9 (1.3)
Total replacement (%)	35.3	17.6	34.4	32.0
Suboptimality (%)	0 (0)	8.1 (1)	0.3 (0)	11.2 (2.1)
Gross margin of herd (€/yr)	155,108 (4800)	85,878 (6071)	138,406 (6880)	115,127 (9020)
Gross margin per occupied cow place (€/yr)	155.1	140.7	138.4	140.9

[1] Explanation of terms in output column: Voluntary replacement, is the number of cows replaced per 100 cow-years; Involuntary Disposal, is the involuntary disposal of cows due to all reasons other than voluntary decision to replace such as health, failure of treatment, sudden death, euthanasia, etc.; Suboptimality, is the percent proportion of suboptimal decisions to the total number of decisions in each simulation (100 cows × 120 months = 12,000 decisions); Annual GM of herd, is the annual gross margin of the herd in euros defined as the marginal revenue from milk production minus the feed costs, insemination costs (if any) and the replacement costs (if any).; Gross margin per occupied cow place, is the annual gross margin divided by the number of cow places occupied by producing cows.

[2] SD in brackets.

Table 3
Summary of sensitivity analyses of base scenario to inputs of milk price, feed costs, carcass value and heifer rearing costs varying between +20% and − 20%.

Outputs	Base scenario	Milk price			
		80%	90%	110%	120%
Annual gross margin of herd	€ 155,108	−28%	−10%	+15%	+31%
Voluntary replacement	10.9%	−33%	−14%	+12%	+28%
Involuntary disposal	24.4%	0%	0%	0%	0%

Outputs	Base scenario	Feed cost			
		80%	90%	110%	120%
Annual gross margin of herd	€ 155,108	+1.1%	+1.1%	−1%	−1.1%
Voluntary replacement	10.9%	−1.1%	−1.1%	1.1%	+1.1%
Involuntary disposal	24.4%	−1.1%	−0.5%	−0%	−0.5%

Outputs	Base scenario	Carcass Value			
		80%	90%	110%	120%
Annual gross margin of herd	€ 155,108	−10%	−7%	4%	+5.5%
Voluntary replacement	10.9%	−45%	−30%	+23.5%	+26.1%
Involuntary disposal	24.4%	+62%	+62%	+0%	+1.1%

Outputs	Base scenario	Heifer rearing cost			
		80%	90%	110%	120%
Annual gross margin of herd	€ 155,108	+23%	+12.1%	−33%	−61%
Voluntary replacement	10.9%	+8%	+2.5%	−100%	−100%
Involuntary disposal	24.4%	−1%	−0.1%	+148%	+190%

base scenario, the simulation followed the optimal policy, none of the decisions were suboptimal. The annual gross margin of the herd was €155,108 per year in the base scenario. Similarly, occupancy was at 100% in the base scenario since no cow places were left unoccupied, the gross margin per cow place was € 155.1.

Compared to the base, the overall replacement rate was lower (~17.5%) in the scenario where one heifer was available per month (Table 2). Unlike that, the overall replacement rates for scenarios of five heifers available per month and variable heifer availability per month had comparable overall replacement rates of 34.4% and 32% respectively (Table 2). One heifer availability per month had the lowest estimated average annual gross margin of € 85,878.

The scenario of one heifer available per month and the variable heifer supply scenario showed some proportion of suboptimality in replacement decisions. In the one heifer available per month scenario, the herd occupancy was around 61% resulting in almost 1/3rd of the cow places in the herd being empty per year. Therefore, the gross margin per occupied cow place was € 140.7 for the 1 heifer per month scenario. In the 5 heifers per month scenarios, the herd occupancy was almost complete. For the variable supply of 0–5 heifers per month scenario, the herd occupancy was 82% resulting in gross margin per occupied cow place of € 140.9. For all of the four scenarios including the base scenario, the calving intervals did not change as per heifer availability and were around 411 days (13 months 21 days: results not shown). However, the calving success (results not shown) was highest for the one heifer available per month scenario (67%) but were similar for the remaining two scenarios as well as the base scenario (~63%).

3.1. Sensitivity analysis

From Table 3, the estimated average annual gross margin of the herd was highly sensitive to milk prices and heifer rearing costs and slightly sensitive to the carcass value. Reduction in the milk prices resulted in reduced gross margin since milk revenues formed the main part of gross margins. Increased heifer rearing costs increased the overall cost of replacement and were therefore decreased the gross margins. The voluntary replacement rate from the base scenario (optimal replacement rate) was highly sensitive for the milk price, carcass value and the heifer rearing costs (Table 3). The sensitivity to the carcass value and the heifer rearing costs stems from the fact that the replacement costs (carcass value – rearing costs) were dependent on these two inputs. Similarly, for involuntary disposal rate, sensitivity was observed mostly in carcass value and heifer rearing costs. The sensitivity of involuntary disposal to the carcass value and heifer rearing costs were opposite to the sensitivity of voluntary replacement. If heifer rearing costs increased or carcass value decreased, there was an increase in the replacement costs which discouraged the voluntary replacement rate thereby increasing the involuntary disposal rate.

4. Discussion

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

From the results, it could be seen that the annual gross margin on herd-level was lower for all three heifer supply scenarios compared to the base scenario (Table 2). Since the involuntary disposal was at 24.4% in the base scenario following optimal policy, it stands to reason to assume that at least two to three heifers per month are needed on average to avoid empty cow places. To maintain optimal or near optimal gross margin of the herd required an average of four heifers per month. The reduction in gross margin in the scenarios with excess heifers (5 heifers per month and 0–5 heifers per month) were attributed to the difference in the rearing cost of heifer and the market price at which the excess heifer could be sold (€ 490). When the heifer supply was constrained the majority of the replacements occurred due to involuntary disposal, whereas almost none of the voluntarily replacement decisions resulted in actual replacements. In the constrained heifer supply scenario, a lot of cow places in the herd remained empty (39% of the herd size), due to the occurrence of involuntary disposal and the lack of available heifers, resulting in a forced reduction in herd size. This also resulted in lower milk production per cow place in the herd and consequently, lower gross margins of the herd (Table 2). In the constrained heifer supply scenario, even though the cows occupying the cow places reduced, the fixed costs (i.e., costs for durable assets as buildings and machines) were not assumed to be reduced due to change in herd size as the number of cow places remained the same. Given that the model focuses on cow places in the herd and not on the actual cows occupying these cow places, the consideration of the differences in gross margins per occupied cow place (Table 2) did not influence replacement policy.

Literature on effects of excess or lack of replacement heifer supply on replacement rates is limited thereby making comparison of our results to previous studies difficult. The increase in empty cow places and subsequent decrease in gross margin of the herd, found in the heifer supply scenario of 1 heifer per month was similar to the findings of Nor et al. (2015) in which keeping less than optimal heifer stock resulted in empty cow places. In the base scenario where no constraints on heifer supply, the results could be more easily compared to the literature. The total replacement rate including involuntary disposal was 35% in the base scenario. This was comparable to the 28.4% culling rate estimated by the model from Demeter et al. (2011) considering the changes in economic inputs over the decade. The total replacement rate was comparable to the national culling rate reported by CRV (CRV, 2021) of 28% in the year 2020–202. Similarly, several studies, reported an average culling rate of 25% in the Netherlands in the past two decade which was slightly lower than the results of our base scenario (Nor et al., 2012; Kulkarni et al., 2021; Han et al., 2022).

From the sensitivity analyses (Table 3), it was clear that the base scenario was sensitive to the economic inputs such as milk prices, carcass value and heifer rearing costs but not to the feed costs. This showed that the consequences of changes in market prices could change the optimal policy for replacement regardless of constrained heifer supply, which agreed with the findings of Kalantari et al. (2010) and Demeter et al. (2011).

Unlike previous attempts to optimize the replacement decisions of cow in a multi-component system as seen in Ben-Ari and Gal (1986), Kristensen (1992), de Vries (2005) or Yates and Rehman (1998), in the present study, the replacement decisions were optimized by a single-component optimization module and the resulting optimal policy was applied in a Herd simulation module. This way, we circumvented the issue of precisely formulating the replacement decision objective on a multi-component level. The interdependency between the cows in the herds was addressed by creating an Inter-cow decision module which ranked cows for replacement. Since the cow rankings are based on their RPOs, the replacement policy followed was the best possible sub-optimal policy (for maximizing economic gains) in presence of a constraint on replacement heifer supply. If the heifer supply could not be assumed to be 100%, all cow places need to be judged simultaneously for a herd-level optimal policy. This would make the model very high in number of dimensions (curse of dimensionality). Using an optimization model to generate the sub-optimal decisions would imply prior knowledge of the heifer supply expected in each month, hence the best sub-optimal policy was chosen using the Herd simulation module.

The ranking strategy was similar to the RPOs based ranking used by many previous studies (for example, see De Vries, 2006, Kalantari et al., 2010). Since RPOs account for future profitability, in theory, the RPOs based ranking strategy should have distinct advantage over heuristic and ad-hoc replacement decisions (Groenendaal and Galligan, 2005). Kalantari and Cabrera (2012) concluded from their dairy DP model study that replacing cows with the lowest RPOs results in increased gains at herd level by improving the value of individual cow places over time. Unlike De Vries (2004), which showed the economic benefits of delaying replacement after culling in presence of seasonality in milk prices and heifer prices, our model was built under the assumption that milk prices and heifer prices do not change over the year (no seasonality). This assumption is justified for Dutch dairy conditions at the time the model was developed (WECR, 2019-2021). Inclusion of price uncertainties would certainly increase the variance around the expected average gross margin values.

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

The optimization module designed in this study is more straightforward compared to previously published optimization models. Most Dutch dairy farmers follow a closed farming system wherein they breed and rear their own replacement heifers. In order to simplify the modelling process, this interdependency between the female calves born and the heifer supply in the herd simulation was not accounted for. In fact, the heifer supply was separated and based on input scenarios rather than the number of calves born on the farm. This simplification also means that the optimization module is easier to deploy. It also makes it relatively easier to scale up for a herd level simulation study that accounts for interdependency between herd mates that occurs when heifer supply is constrained, and more cows are candidates for replacement. The maximum number of feasible state combinations in the Markov decision process (MDP) of the optimization module was 9720 with only a single level of decision optimization in an ordinary process. For example, compared to our optimization module, Demeter et al. (2011) had four levels of hierarchic MDP with 1,480,651 state combinations and Cha et al. (2014) had a three levelled MDP with 2,095,425 state combinations while incorporating health parameters. One of the major reasons for the limited success of previous optimization models being used in commercial decision support tools is the lack of user-friendliness and computational complexity (Groenendaal et al., 2004). Although the aim of this study was not to create a commercial product, in theory, the optimization module of this study can be expanded upon while being easier to understand and quick to deploy in larger more encompassing dairy models. In this study, the herd size was equal to 100 dairy cows to represent an average Dutch dairy farm. Accordingly, input values were parameterized using actual data from Dutch dairy farms. The modelling approach, as such, allows for any herd size, provided the data for larger herd sizes is available.

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

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

5. Conclusion

In conclusion, this study presented a new straightforward modelling approach combining single-component cow place optimization with multi-component herd simulation for replacement decisions under influence of environmentally driven policies. This study showed that severe constraints on replacement heifer supply as well as excess heifer supply resulted in reduced herd gross margins, while increasing involuntary disposal. The results of this study indicate that optimization of replacement decisions under heifer supply constraints requires accounting for inter-dependency between herd mates on a herd-level.

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CRediT authorship contribution statement

Pranav S. Kulkarni: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Rene Haijema:** Writing – review & editing, Supervision, Methodology, Investigation. **Henk Hogeveen:** Writing – review & editing, Funding acquisition. **Wilma Steeneveld:** Writing – review & editing, Supervision, Conceptualization. **Monique C.M. Mourits:** Writing – review & editing, Validation, Supervision, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103943.

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