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Cost of lameness in dairy herds: An integrated bioeconomic modeling approach

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ABSTRACT

Foot disorders are costly health disorders in dairy farms, and their prevalence is related to several factors such as breed, nutrition, and farmer's management strategy. Very few modeling approaches have considered the dynamics of foot disorders and their interaction with farm management strategies within a holistic farm simulation model. The aim of this study was to estimate the cost of foot disorders in dairy herds by simulating strategies for managing lameness. A dynamic and stochastic simulation model (DairyHealthSim) was used to simulate the herd dynamics, reproduction management, and health events. A specific module was built for lameness and related herd-level management strategies. Foot disorder occurrences were simulated with a base risk for each etiology [digital dermatitis (DD), interdigital dermatitis, interdigital phlegmon, sole ulcer (SU), white line disease (WLD)]. Two state machines were implemented in the model: the first was related to the disease-induced lameness score (from 1 to 5), and the second concerned DD-state transitions. A total of 880 simulations were run to represent the combination of the following 5 scenarios: (1) housing (concrete vs. textured), (2) hygiene (2 different scraping frequencies), (3) the existence of preventive trimming, (4) different thresholds of DD prevalence detected and from which a collective footbath is applied to treat DD, and (5) farmer's ability to detect lameness (detection rate). Housing, hygiene, and trimming scenarios were associated with risk factors applied for each foot disorder etiologies. The footbath and lameness detection scenarios both determined the treatment setup and the policy of herd observance. The economic evaluation outcome was the gross margin per year. A linear regression model was run to estimate the cost per lame cow (lameness score ≥3), per case of DD and per week of a cow's medium lameness duration. The bioeconomic model reproduced a lameness prevalence varying from 26 to 98% depending on the management scenario, demonstrating a high capacity of the model to represent the diversity of the field situations. Digital dermatitis represented half of the total lameness cases, followed by interdigital dermatitis (28%), SU (19%), WLD (13%), and interdigital phlegmon (4%). The housing scenarios dramatically influenced the prevalence of SU and WLD, whereas scraping frequency and threshold for footbath application mainly determined the presence of DD. Interestingly, the results showed that preventive trimming allowed a better reduction in lameness prevalence than spending time on early detection. Scraping frequency was highly associated with DD occurrence, especially with a textured floor. The regression showed that costs were homogeneous (i.e., did not change with lameness prevalence; marginal cost equals average cost). A lame cow and a DD-affected cow cost €307.50 ± 8.40 (SD) and €391.80 ± 10.0 per year on average, respectively. The results also showed a cost of €12.10 ± 0.36 per week-cow lameness. The present estimation is the first to account for interactions between etiologies and for the complex DD dynamics with all the M-stage transitions, bringing a high level of accuracy to the results.

Key words: lameness, disease cost, bioeconomic model, farm management

INTRODUCTION

Mastitis, deteriorated reproductive performance, and foot disorders are the 3 main health concerns in dairy cattle and the most costly diseases in dairy production (Esslemont and Kossaibati, 1996). Foot disorders play a large role in dairy herds, with a mean prevalence ranging from 5 to 55%, depending on country and livestock system (Manske et al., 2002; Whay et al., 2005;

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Barker et al., 2018; Charfeddine and Pérez-Cabal, 2017; Hernandez et al., 2002). Foot disorders are responsible for 90 to 99% of total lameness cases (Clarkson et al., 1996; Logue and Kempson, 1993; Murray et al., 1996; Somers et al., 2005) and can be separated into 2 main categories: noninfectious claw diseases [sole ulcers (**SU**) and white line disease (**WLD**)] and infectious diseases [interdigital phlegmon (**IP**), interdigital dermatitis (**ID**), and digital dermatitis (**DD**)]. Foot disorders have a negative effect on animal welfare, causing discomfort, increased lying time, altered feeding behavior, and aggravated pain expression (Whay et al., 2005), and lead to both direct additional expenditures (farm labor, hoof trimming, treatments) and indirect economic losses (reduced milk production, discarded milk, altered reproductive performance, poorer weight gain, early culling and interactions with other diseases, such as subclinical ketosis and mastitis; Galligan, 2006; Liang et al., 2017; Dolecheck et al., 2019). Previous estimates of the cost of lameness ranged between €190 and €322/case per year for uncategorized lameness (Liang et al., 2017) and were €152 to €571, €130 to €1,040, €130 to €512, and €43 to €389 for WLD, SU, IP, and DD, respectively (Esslemont and Kossaibati, 1996; Willshire and Bell, 2009; Cha et al., 2010; Häggman et al., 2015; Charfeddine and Pérez-Cabal, 2017; Dolecheck et al., 2019). These studies assumed etiologies as separated entities used to calculate costs, which is a bias in the cost calculation because foot diseases are an aspect of herd-level dynamics with multiple interactions between them. For example, WLD is significantly correlated with heel horn erosion and DD, as well as ID with DD (Manske et al., 2002a; Capion et al., 2009). The time of incidence, cow characteristics (parity), and diagnosis timing also influence the effect of foot disorders on cow performance (Booth et al., 2004; Dolecheck et al., 2019). Foot disorder occurrence also generates additional work for farmers as a direct cost or an opportunity cost detrimental to other useful tasks.

Critical risk factors for each infectious and noninfectious lameness disease have been well described (Oehm et al., 2019). At cow level, the breed, BCS, parity, lactation stage with the associated milk yield, and occurrence of any previous claw diseases are consistent risk factors for lameness (Solano et al., 2015; Westin et al., 2016; King et al., 2017; Hund et al., 2019; Thomsen et al., 2019; de Jong et al., 2021). Housing, especially the nature of the floor, cubicle comfort and bedding quality (Becker et al., 2014b; de Jong et al., 2021), and the preventive trimming frequency are crucial concerns for the occurrence of noninfectious foot disorders (Becker et al., 2014b; Sadiq et al., 2021). Hygiene (straw quantity, floor scraping frequency) is also a risk factor for infectious foot disorder occurrence (Becker et al., 2014b; Kester et al., 2014; Ariza et al., 2020; Robles et al., 2021). The literature also shows that different strategies are available for farmers to manage lameness (Mahendran and Bell, 2015; Sadiq et al., 2019), including immediate actions, such as curative trimming by professional trimmers, veterinarians, or farmers themselves, footblocks, antibiotic use, or footbath application. Other strategies include long-term actions, for example, improving housing management (flooring, strawing, general layout), working on the detection of lame cows as rapidly as possible or preventive and systematic trimming.

Dairy farm management is a complex, multifactorial activity, and most dairy farmers are looking for the best management strategy as a well-balanced monetary compromise between measures to keep all diseases under control (limited dairy performance deterioration) and farm profitability from an economical and time-based point of view. Bioeconomic modeling allows the mimicking of dairy farm daily activity to investigate these best management strategies to be adopted.

The objective of the present study was to estimate the cost of lameness considering the interactions between foot disorder etiologies. It used a multidisease herd-holistic approach based on a stochastic simulation model that simulates etiologies of foot disorders, their interaction and their risk factors.

MATERIALS AND METHODS

General Modeling: Dairy Health Simulator

The integrated bioeconomic modeling approach Dairy Health Simulator (**DHS**) was used and modified to precisely simulate foot disorder occurrence (**DHS_Lame**). This model was described in detail by Ferchiou et al. (2021; Figure 1) and has been applied to other infectious diseases, such as mastitis, endometritis, and metabolic imbalance. The model consists of a biological simulation model coupled to an economic optimization model. The biological model is defined on a cow-week basis and on the weekly probabilities for all cow events, including milk production, reproduction and diseases. It aims to achieve a long-term dynamic representation of a dairy herd. In brief, from birth to death, each animal is characterized weekly by his or her physiological and production status (e.g., male calf, female calf, pregnant, in-milk cow, and dry cow). This framework is applied to 3 main interconnected types of functions, namely, production (e.g., growth and milk production and reproduction), diseases (as damage to production), and treatment (as one type of damage control).

The male calves are systematically sold at one month of age, and the female calves basically stay in the herd.

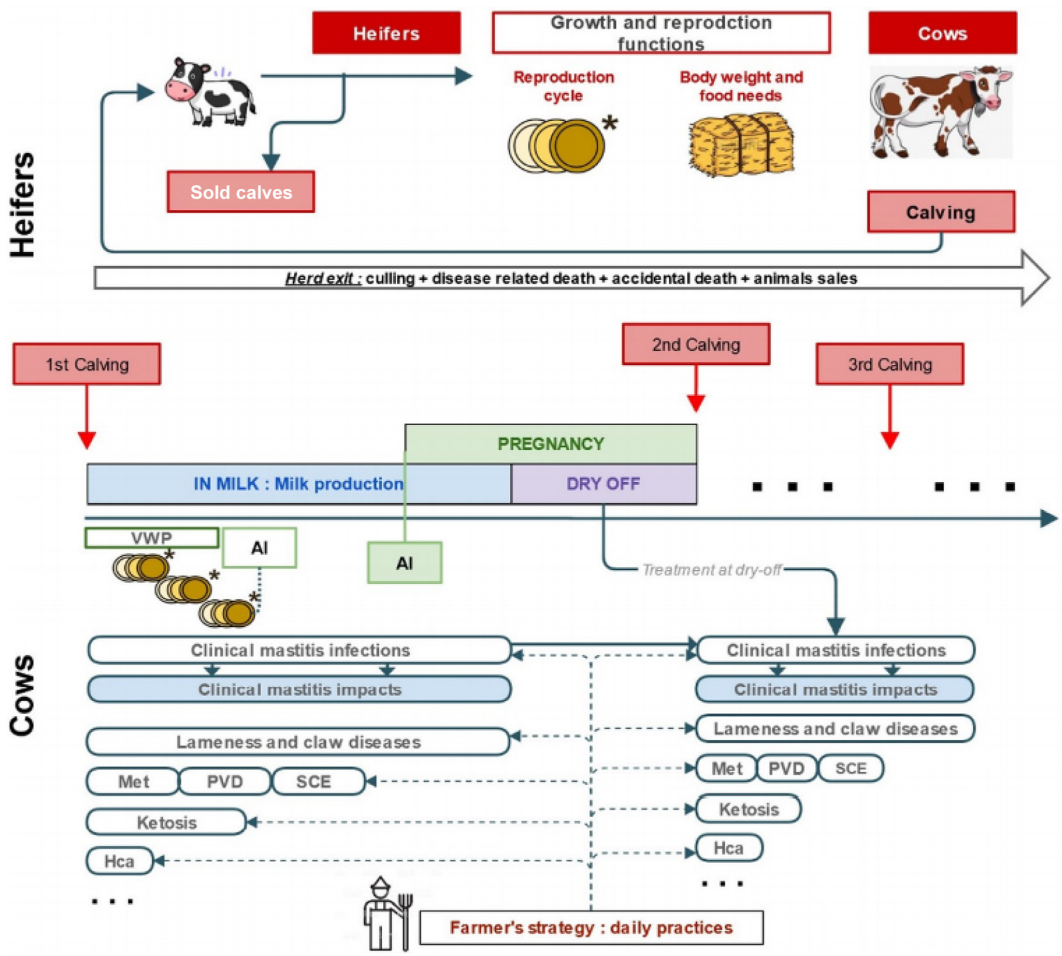

Figure 1. Schematic presentation of Dairy Health Simulator. VWP = farmer's voluntary waiting period before insemination; SCE = subclinical endometritis; PVD = purulent vaginal discharge; Met = metritis; ketosis = clinical and subclinical ketosis; Hca = hypocalcemia and milk fever. *An asterisk indicates cow reproduction simulation as a state machine with atypical cycle simulation.

The model includes an animal in the reproduction management loop as soon as the heifer gets her first ovarian cycle, which depends on both age and weight. Each ovarian cycle lasted 3 wk, with a probability of heat expression, a probability of heat detection by the farmer making the decision of whether to pursue AI, and the probability of becoming pregnant. During gestation, the probability of abortion is set. A probability of correct uterine involution in the very first weeks after calving is applied as a sine qua non condition for achieving a new cycle after the postcalving anestrus period and being eligible for a subsequent AI.

The simulated health disorders include dystocia, subclinical hypocalcemia, milk fever, placental retention, puerperal metritis, purulent vaginal discharge, subclinical endometritis, left and right abomasum displacement, subclinical ketosis, clinical ketosis, mastitis (declined according to the different responsible etiologies), and lameness. For every disease, there is a baseline initial risk of contracting it, with certain multiplier coefficients depending on the number of lactation, the week-in-milk period, and possible interactions with other diseases. For each health disease, a specific curative treatment is applied. Milk production is simulated by Wood's curve. Protein content, fat mass, and SCC are generated by a baseline function and a penalty-generating function due to a high SCC consecutive to mastitis occurrence.

A herd-size objective was fixed for in-milk cows to consider barn constraints, and the actual in-milk herd size was calculated weekly, including newly calved cows. To mimic typical farmer behavior, a set of rules was defined to render the culling decision dependent on herd size. Culling rules were applied to all cows each week and were based on cow milk yields, pregnancy status, lameness, and udder health. These criteria represent the main criteria used by farmers for culling decisions (Kerslake et al., 2018). The other health disorders were not considered in culling, but they act indirectly

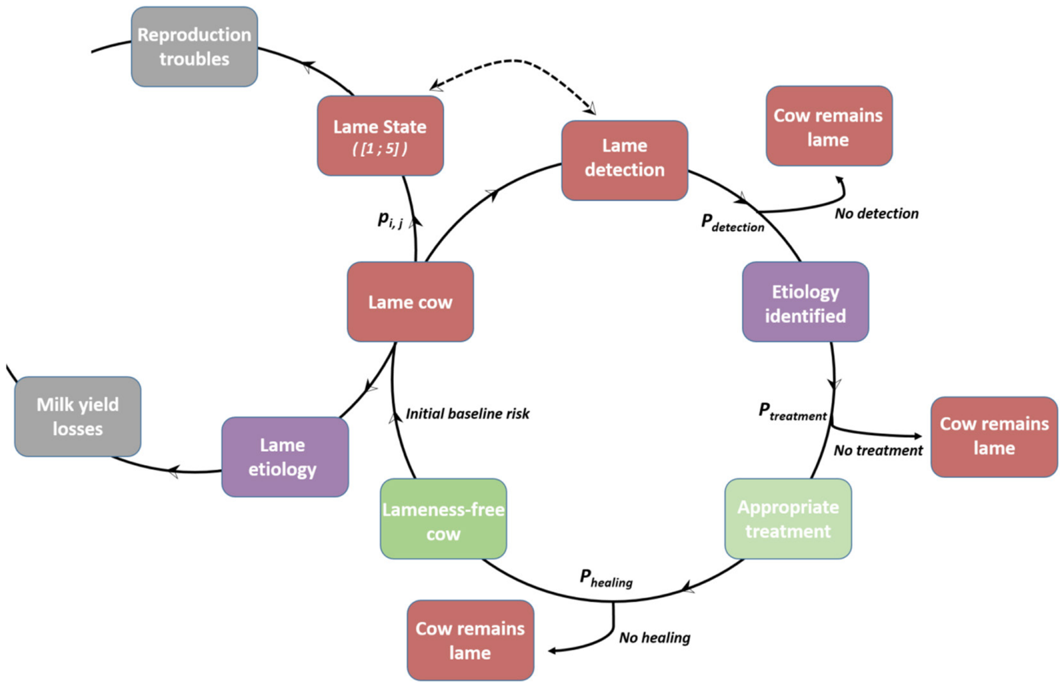

Figure 2. Schematic summary of lameness disease calibration. A cow becomes lame with an initial baseline risk for each etiology, and the degree of lameness (5-point scale) is determined with a probability $p_{i,j}$. Once the cow becomes lame, the etiology conditions the subsequent milk yield losses, whereas the lame state generates reproductive disorders. The detection by the farmer is based on his/her ability to detect the lame state ($P_{detection}$). Once the cow is detected as lame, the etiology is systematically correctly identified, and a probability of treatment ($P_{treatment}$) is applied. Then, the probability of healing ($P_{healing}$) is applied to determine whether the cow remains lame.

through milk yields, reproduction performance, udder health, and lameness. The criteria and thresholds used for culling depend on herd size to stabilize it near the objective. This biological mechanistic modeling approach is new because no previous study considered all these diseases simultaneously.

Specific Module Developed for Lameness

The model DHS_Lame integrates a specific herd-level lameness simulation module (Figure 2) considering 5 different foot disorders as the most recurrent according to both on-field veterinarian practices and a literature review. The 3 infectious foot disorders included IP, DD, and ID. The 2 noninfectious disorders considered were WLD (with all the clinical aspects grouped; e.g., white line fissure or white line abscess) and SU. The role of sole hemorrhages (**SH**) in lameness occurrence has clearly been identified (Manske et al., 2002a; Becker et al., 2014a) but SH were not integrated in the present model because a significant interrelationship with SU was demonstrated (Andersson and Lundström, 1981; Manske et al., 2002a), as well as heel horn erosion, whose interrelationship with ID was found in literature (Knappe-Poindecker et al., 2013). The occurrence of each foot disorder is simulated through a base risk and a specific risk factor associated with scenarios and cow characteristics. Each cow has a weekly base risk of becoming lame because of the occurrence of one or numerous foot disorder(s). This base risk depends on the cow parity and lactating stage. Multiplier coefficients, as a consequence of interactions between foot disorders and other disorders (e.g., mastitis and subclinical ketosis) are subsequently applied to the base risk.

A cow-level lame state is generated, and the lameness score (**LS**) is defined according to each etiology to reflect the severity of the clinical signs. Digital dermatitis infections are simulated as a state machine ranging between different DD states. The stage of DD lesion was determined as defined by Döpfer et al. (1997) as active lesions (M1, M2, and M4.1) and chronic lesions (M3 and M4), each associated with an LS distribution. Active lesions were considered as a source of different lameness levels, and chronic lesions were considered soundless with regard to a clinical lameness point of view. Milk productivity decrease is defined according to the lameness etiology, and reproductive deterioration is defined according to the cow's LS. A cow with lameness can be detected by the farmer according to the cow's LS. A nondetected high LS does not lead to any individual treatment but rather to deteriorated performance. A detected high LS results in deteriorated performances, requiring both individual and collective treatments (depending on the farmer's policy, see beyond) associated with a probability of healing. The initial lameness score (**LS**$_i$) for one cow can move onto another range of scores (**LS**$_j$) with probabilities depending on the foot disorder and the cow-specific pain tolerance. Consequently, for each occurrence, each cow has a certain probability $p_{i,j}$ to be lame at a certain severity degree depending on the disorder, as indicated in Equation 1.

$$LS_i \rightarrow LS_j \left(i;j\right) \in \left[1;5\right]^2, i < j. \quad [1]$$

Effect of Lameness on Production

Milk yield losses mainly depend on the etiology, both in loss amplitude and duration. Amory et al. (2008) described milk yield losses due to SU or WLD occurrence 5 wk before and after diagnosis. When an IP occurs, milk production throughout lactation decreases by 10% (Hernandez et al., 2002). The DD occurrence generates milk yield losses at different orders of magnitude according to M-stages. Cows with M0 (no lesion) or M4 lesions (chronic lesion) are not lame, and no milk losses are applied during these stages. Stages M1, M2 (active lesions), and M4.1 (reactivation of a chronic lesion) are considered proper active lesions causing frank lameness and spearhead the most important milk yield losses in the case of DD occurrence. Stage M3 (active lesion on the road to recovery or chronic stage) is evaluated as a source of intermediate lameness and, consequently, causes milk yield losses as well.

Two main negative consequences on reproduction have been withheld in the case of foot disorder: a higher risk of delayed ovarian cyclicity and a lower probability of heat expression for the lame cow (heat detection by farmers being unchanged). The detrimental effects remain as long as the cow is not treated after being detected as lame. The relationship between estrus expression and lameness was well described, with a decrease of estrus both in duration and intensity (Sood and Nanda, 2006; Walker et al., 2010, 2008) but no relationship between estrus expression and severity of lameness has been specifically quantified in the literature, and we consequently decided to associate a decreased risk of estrus expression with an increased locomotion score based on the author's experience.

The detection rate of lame cows first depends on the intensity of the LS. For example, to represent a "standard" farmer, all cows with LS $\geq$4 are identified as lame in the first 6 weeks after occurrence, whereas 28% of moderately lame cows (i.e., LS 3) are not recognized as lame by farmers after 24 weeks of observation (Alawneh et al., 2012). The lameness detection rate also differs according to the farmer's policy, observance quality, and interest in lameness issues.

Lameness Treatment

Once the cow was identified as lame, a specific treatment can be carried out by the farmer, veterinarian or trimmer, with a given probability of execution for each applicant. Treatment occurrence was expected to allow a return to the initial lameness status before disease occurrence. All the treatments depending on etiology are summarized in Supplemental File S1 (https://doi.org/10.6084/m9.figshare.22064753.v1; Robcis, 2023a).

The farmer is considered to identify the correct etiology once the cow is detected as lame. In the case of simultaneous occurrence of several claw diseases, the first-line treatment is concentrated on the etiology causing the highest degree of lameness. Other contemporary lameness disorders are treated in the same manner.

The curative treatment for IP retained is a parenteral benzylpenicilline-dihydrostreptomycine association. In spite of the possible ineffectiveness of trimming to improve lameness status (García-Muñoz et al., 2017), the treatment considered to cure WLD, SU, and ID is in a single curative trimming, with a wooden footblock application if necessary. Nonactive lesions of DD do not induce lameness, so no treatment was applied in this case. For active lesions of DD (M1, M2, M4.1), several therapeutic strategies are possible. Active DD lesions are first cured with a once-a-week topical oxytetracycline (**OTC**) spray application by the farmer after foot inspection at the milking parlor. The second-line cow-level therapeutic option is a bandage applied in addition to OTC spray application. This can be performed by the farmer himself; however, due to a lack of time, it is generally carried out by the trimmer or veterinarian during trimming sessions. The third-line therapeutic option is the introduction of a footbath for the whole herd before or after entering the milking parlor. Footbaths are useful when the DD mean herd-level prevalence exceeds 20% (Relun et al., 2012). Even if numerous footbath formulations are available, to ease our model, we chose a unique footbath composed of copper sulfate ($CuSO_4$) at a concentration of 5%, which demonstrates the best curative efficiency (Solano et al., 2017). This footbath is used during 4 consecutive milkings over 2 d at a 2-wk interval. The treatment of DD described above is applied only in cows with active lesions.

The last option, applicable to all causes of lameness as described above, is the decision to not treat the lame cow, even if it was identified as such. The used probabilities are inspired by a field study describing the usual farmer practice regarding lameness depending on

Table 1. Scenarios influencing the initial baseline risk of claw disease occurrence

		Risk factor[1]			
Category	Scenario	SU	WLD	DD	ID
Housing (type of flooring)	Concrete HOU_1	Referent	Referent	Referent	Referent
	Textured HOU_2	2 Kremer et al., 2007	2.5 Barker et al., 2009	2.7 Wells et al., 1999	2.7 Wells et al., 1999 (extrapolation)
Hygiene (scraping frequency)	>8 times/d SCRAP_1	Referent	Referent	Referent	Referent
	≤8 times/d SCRAP_2	1	1	2 Oliveira et al., 2017	2 Oliveira et al., 2017
Preventive trimming	Yes TRIM_1	0.7 Thomsen et al., 2019	0.7 Manske et al., 2002b	1	0.8 Somers et al., 2005
	No TRIM_2	Referent	Referent	Referent	Referent

[1]SU = sole ulcers; WLD = white line disease; DD = digital dermatitis; ID = interdigital dermatitis.

the degree of severity of the clinical signs (unpublished data).

Every therapeutic strategy has a success rate after a certain period of time, and as long as the recovery of the cow is not fully completed, zootechnical losses are applied (Supplemental File S1). The cow is considered healed when her LS returns to the initial level before foot disorder occurrence.

Scenarios

The model DHS_Lame allowed us to simulate 5 axes in lameness management and control scenarios (Table 1). The first scenario concerned herd housing, with 2 options for the type of floor: a concrete floor (reference scenario **HOU_1**) or a textured floor (scenario **HOU_2**), including grooved and slatted floors. The second scenario was related to the degree of hygiene, conditioned through the scraping frequency. Hygiene was identified as an important risk factor, especially for infectious claw disease occurrence. Oliveira et al. (2017) studied the risk of dermatitis occurrence with a scraping frequency >8 times/d (scenario **SCRAP_1**, considered as a satisfactory hygiene status) or ≤8 times/d (scenario **SCRAP_2**, considered as a deteriorated hygiene status). The third scenario addresses the existence of preventive trimming (scenario **TRIM_1**) or not (scenario **TRIM_2**) among the herd, with Manske et al. (2002b) describing that previous trimming spearheads less lesions at the next moment. The fourth panel of scenarios relates to the ability of the farmer to detect lame cows (scenario **LD**, lameness detection) and to apply a collective treatment. The standard detection rate (**LD_6**) was described by Alawneh et al. (2012) and was used as the reference scenario. Multiplier coefficients were applied with a step of 0.2 to the standard detection rate. Eleven different scenarios of detection rates (including the reference) were defined to represent better or worse farmer practices in terms of LD. A corresponding duration spent to detect lame cows is associated with each LD incident.

The fifth scenario was the detected DD prevalence threshold from which a $CuSO_4$ 5% footbath was collectively applied. Our baseline scenario is when the herd-level DD prevalence exceeds 20% (scenario **FB_4**; Relun et al., 2012). Ten footbath scenarios (**FB**) were defined as a variation of this threshold, from 0 (systematic collective footbath application) to 40%, with a step of 5%, in addition to an extreme case simulating a total absence of footbath use regardless of the DD prevalence (simulated through the DD prevalence threshold of 1.1).

Finally, 880 combinations, including the 5 lameness management scenarios, were simulated to mimic the on-field reality as closely as possible in terms of herd-level lameness management. A simulated stabilized herd was used as a unique starting base for all scenarios for a 728-wk simulation with 100 iterations each. The last 520 wk were included in the results analysis to obtain stable results.

Epidemiological Parameter Calculation

Lameness prevalence is calculated as the yearly mean of all of the weekly mean prevalence of cows whose LS ≥3, divided by the total in-milk cows of the same week, as indicated in Equation 2.

$$\text{Lameness prevalence}(\text{year } i) = \frac{\sum_{j=1}^{N}\left(\frac{\text{number of lactating cows with LS} \geq \text{on week } j}{\text{total number of lactating cows on week } j}\right)}{N}, \quad [2]$$

with N = total number of weeks in year i.

Digital dermatitis active state prevalence (**DD_activestates**) is determined as the yearly mean of all of the weekly mean prevalence of cows whose DD status is M1, M2, or M4.1, divided by the total in-milk cows of the same week, as indicated in Equation 3.

$$\text{DD active states prevalence}(\text{year } i) = \frac{\sum_{j=1}^{N}\left(\frac{\text{no. of lactating cows with a M.1, M.2, or M4.1DD status on week } j}{\text{total number of lactating cows on week } j}\right)}{N}, \quad [3]$$

with N = total number of weeks in year i.

The medium lameness duration (**MLD**) represents the mean period during which one given cow remains lame (i.e., the number of weeks during which one cow still maintains LS ≥3, expressed in weeks).

Gross Margin Calculation and Economic Regression to Assess Costs. The farmer's gross margin (**GM**) for the 880 combinations was calculated with Equation 4.

$$\text{GM}_\text{S} = \text{R}_\text{S} - \text{Exp}_\text{S}, \quad [4]$$

where R_S is the revenue and Exp_S is the farm expenses.

Revenue calculations are based on the farm's mean production, including milk revenues (MilkR), meat production revenues (MeatR), and animal revenues (AnimR; Equation 5).

$$\text{R}_\text{S} = \text{MilkR}_\text{S} + \text{MeatR}_\text{S} + \text{AnimR}_\text{S} \quad [5]$$

The farm expense calculations are based on the farm's medium operational expenditure (Equation 6), including feeding cost (FeedE), reproduction cost (ReproE), veterinary cost (VetE), treatment cost (TreatE), trimmer cost (TrimE), and strawing cost (StrawE):

$$\text{Exp}_\text{S} = \text{FeedE}_\text{S} + \text{ReproE}_\text{S} + \text{VetE}_\text{S} + \text{StrawE}_\text{S} \quad [6]$$

Numbers used for economic calibration of prices are presented in Supplemental File S3 (https://doi.org/10.6084/m9.figshare.22064801.v1; Robcis, 2023c).

The present model was built with a unique output, which is the milk production, including early culling and reproductive disorders, known to be critical consequences of foot disorders (Cha et al., 2010). Once one cow is culled due to lameness, the cost of milk not produced anymore was included in the MILKR_S parameter, and the price of the cow was included in the MEATR_S and ANIMR_S parameters. Reproductive disorders have direct consequence on the current or next lactation and are included in the MILKR_S parameter.

The differences in prevalence and MLD were assessed with a chi-squared test and a *t*-test, respectively. The linear regression of GM was performed with Python 3.5.4 2017 software, with variations in lameness prevalence, DD prevalence, and MLD, and with housing, trimming, and hygiene scenarios as cofactors (Equations 7–9).

$$GM_s = \alpha + \beta_{prev_{lame}} PrevLame_s + \beta_{Trimming} TRIM + \beta_{Housing} HOU + \beta_{Scraper} SCRAP + \varepsilon_s, \quad [7]$$

$$GM_s = \alpha + \beta_{prevDD} PrevDD_s + \beta_{Trimming} TRIM + \beta_{Housing} HOU + \beta_{Scraper} SCRAP + \varepsilon_s, \quad [8]$$

$$GM_s = \alpha + \beta_{MLD} MLD_s + \beta_{Trimming} TRIM + \beta_{Housing} HOU + \beta_{Scraper} SCRAP + \varepsilon_s. \quad [9]$$

The main data of interest were the coefficients $\beta_{prev_{lame}}$, $\beta_{prevDD,}$ β_{MLD}, which measure the cost associated with an additional lame cow, the cost of an additional DD infection and the cost of an additional week of lameness duration, respectively. Interactions within cofactors were systematically tested.

Parameters. For each etiology, the base risk was determined through a review of the literature to highlight a wide range of prevalence for each foot disorder leading to a mean prevalence (Supplemental File S2, https://doi.org/10.6084/m9.figshare.22064786.v3; Robcis, 2023b). All the probabilities of LS change after one given foot disorder based on both disorder-specific clinical presentation and the author's experience.

All the milk losses per etiology are summarized in Table 2. The results of Charfeddine and Pérez-Cabal (2017), who precisely quantified the cow-level daily milk losses depending on the severity of the DD lesions (mild vs. severe), were used. Milk losses for SU and WLD were obtained from Amory et al. (2008). To avoid any retroactive effect on milk production after diagnosis, in our mechanistic model, the milk losses before diagnosis were summed, and this sum was equally redistributed to yield drops reported after diagnosis in the case of SU or WLD occurrence. Milk losses due to IP were based on the results from

Table 2. Different lameness etiologies and subsequent milk yield losses (kg/mo)[1]

Item	IP	SU	WLD	DD_M0	DD_M1	DD_M2	DD_M3	DD_M4	DD_M4.1
Months after occurrence									
1	−173.2	−97.4	−48.32	0	−21	−21	−14	0	−21
2	−173.2	−102.16	−53.92	0	−21	−21	−14	0	−21
3	−173.2	−93.48	−62.6	0	−21	−21	−14	0	−21
4	−173.2	−97.96	−76.04	0	−21	−21	−14	0	−21
5	−173.2	−115.32	−89.76	0	−21	−21	−14	0	−21
Source	Hernandez et al., 2002	Amory et al., 2008	Amory et al., 2008	Charfeddine et al., 2017	Charfeddine et al., 2017	Charfeddine et al., 2017	Charfeddine et al., 2017	Charfeddine et al., 2017	Charfeddine et al., 2017

[1]IP = interdigital phlegmon; SU = sole ulcer; WLD = white line disease; DD_M-x = M-x stage digital dermatitis. Losses are applied per week after occurrence in our model, so all the values are divided by 4 to obtain the correct value to apply.

Hernandez et al. (2002). The percentage of milk losses was equally distributed each week of lactation in the case of IP occurrence.

The risk of delayed ovarian cyclicity associated with a lame state was highlighted to depend on the degree of lameness (Garbarino et al., 2004). Compared with LS ≤2 (lameness-free cows − reference), the risk is significantly higher for LS 4 (lame cows). The situation of LS 5 (severely lame) was extrapolated from the situation of LS 4. For LS 3 (mildly lame cows), the risk was not significant, but the trend was strong, suggesting that these results were maintained (Table 3).

There are several epidemiological models addressing DD dynamics to predict the probability for an M-x to turn into a stage M-y (Biemans et al., 2018; Capion et al., 2009; Holzhauer et al., 2008a). The results from Biemans et al. (2018) were maintained since they included the most important cohort of DD-infected cows. The probabilities of transitions from an unknown M-stage to an observed M-stage and vice versa were removed. Once DD occurs, the DD-stage-based machine runs on its own, completely independent from all the other sources of lameness, according to a transition matrix summarizing all the probabilities related to transitioning from one DD stage to another, including the probability of becoming infected by DD (i.e., transition from M0 to M-x, $x \in [1, 2, 3, 4, 4.1]$) at one point. Prices, costs and other epidemiological parameters are summarized in Supplemental File S2.

Table 3. Effect of lameness score (LS) on delayed ovarian cyclicity and heat expression

LS	Odds ratio for prolonged luteal phase	Odds ratio for heat expression
1	1	1
2	1	1
3	2.14	0.6
4	3.5	0.45
5	3.5	0.3
Source	Garbarino et al., 2004	Current study

RESULTS

Epidemiological Indicators

The stochastic simulation allowed a wide panel of foot disorder prevalence, ranging from 26% (scenario with a concrete floor, a preventive trimming, scraping frequency >8 times/d, detection rate more than 2-fold greater than the standard rate and a systematic collective footbath) to 98% (scenario with a grooved floor, no preventive trimming, scraping frequency ≤8 times/d, no time for lameness detection and no collective footbath regardless of the herd-level DD prevalence). The mean value was 55%. Digital dermatitis contributed, on average, to 36% of the total lameness prevalence, followed by ID (28%), SU (19%), WLD (13%) and IP (4%). The DD active state (M1, M2, M4.1) prevalence ranged from 7% (concrete floor, preventive trimming, better level of hygiene, no time dedicated to lameness detection, systematic use of collective footbath) to 60% (concrete floor, no preventive trimming, deteriorated hygiene, a lameness detection rate better than the standard rate by 60% and absence of collective footbath use), with 28% as the mean value. The MLD ranged from 4.6 wk (scenario with concrete floor, preventive trimming, improved hygiene, no attention to lameness detection and systematic use of collective footbath) to a maximum of 20 wk (scenario with textured floor, no preventive trimming, lower level of hygiene, optimal detection of lame cows, collective footbath used as soon as the DD active state prevalence reaches 40%). The mean value was 10.3 ± 3.5 wk. The prevalence of DD active states was highly correlated with lameness prevalence and MLD (r = 0.9 and 0.8, respectively).

Prevalence by Scenario

A significant difference in foot disorder prevalence was observed for HOU_2 compared with HOU_1 (prevalence = 59.4% for HOU_2 vs. prevalence = 51.5% for HOU_1; $P < 0.001$). This significant differ-

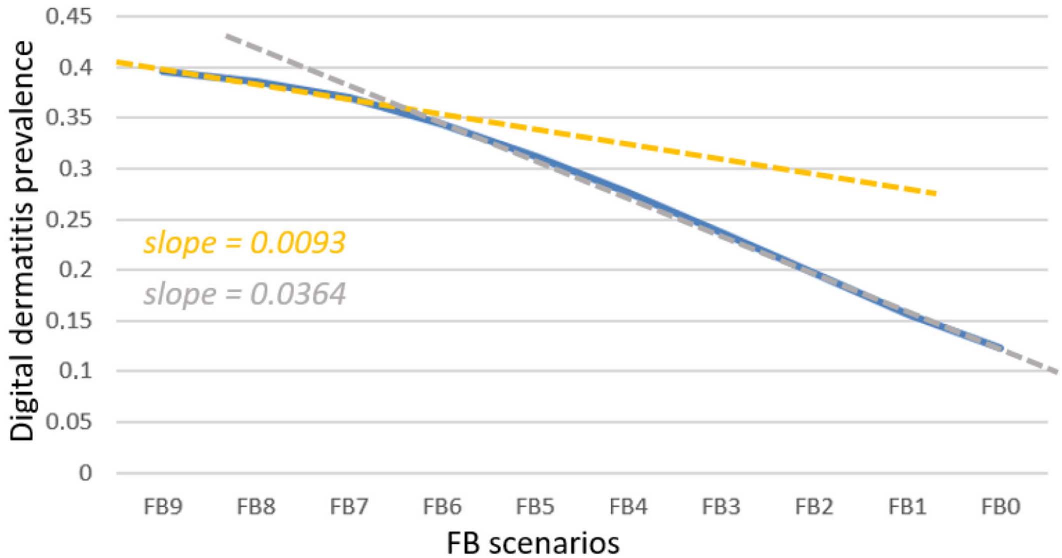

Figure 3. Relationship between digital dermatitis prevalence and footbath (FB) application threshold. The blue curve represents the evolution of the digital dermatitis prevalence depending on the threshold of FB application. The dashed yellow and purple lines represent the linear regression for the first and second parts of the curve, respectively, with the respective slope values indicated in the graph.

ence in prevalence was also observed for each lameness etiology ($P < 0.01$). A textured floor was statistically associated with a longer period of lameness compared with a concrete floor (MLD = 11.3 wk for HOU_2 vs. MLD = 9.4 wk for HOU_1; $P < 0.001$). A significant difference in foot disease prevalence was observed with preventive trimming (prevalence = 56.7% for TRIM_2 vs. prevalence = 54.2% for TRIM_1; $P = 0.02$). Trimming was significantly associated with SU and WLD prevalence (16.7% for TRIM_2 vs. 10.2% for TRIM_1; $P < 0.001$ and 10.7% for TRIM_2 vs. 7.5% for TRIM_1; $P < 0.001$, respectively). No significant association was observed between trimming and DD ($P = 0.43$), IP ($P = 0.49$) or ID ($P = 0.23$). Preventive trimming showed a stronger benefit with a textured floor compared with a concrete floor, notably for SU (Δprevalence of 3% for TRIM l_HOU_1 and of 10% for TRIM l_HOU_2; $P < 0.01$) and WLD (Δprevalence of 2% for TRIM l_HOU_1 and of 5% for TRIM l_HOU_2; $P < 0.01$). Cows were lame for a longer period in the case of no preventive trimming (MLD = 10.0 wk for TRIM_2 vs. MLD = 10.6 wk for TRIM_1; $P < 0.01$). Hygiene was significantly associated with foot disorder prevalence (prevalence = 54.3% for SCRAP_1 vs. prevalence = 56.6% for SCRAP_2; $P = 0.02$), as well as DD occurrence (prevalence = 26.9% for SCRAP_1 vs. prevalence = 29.1% for SCRAP_2; $P = 0.007$). Hygiene did not influence noninfectious claw disease occurrence ($P = 0.44$ for WLD and $P = 0.4$ for SU). Except for LD_1 (no lameness detection at all, considered an extreme case), the increase in detection by a 20% scale did not influence the overall prevalence of every etiology ($P > 0.05$). Regarding the threshold from which a collective footbath is applied to cure DD, a decrease in active DD lesions was unsurprisingly noticed through a 2-phase linear trend, with the first part between FB_9 and FB_8 and the second part between FB_7 and FB_0 (Figure 3). The slope of the first part was 26% less important than that of the second part of the linear decrease ($P < 0.01$).

Economic Analysis

The economic results showed that the milk yield losses represent by far the first component of lameness costs. The GM for the different prevalences and the combinations of scenarios is presented in Figure 4. For lameness (Figure 4A), the GM for HOU_2 was on average lower by 30% ($P < 0.001$) compared with HOU_1. This increase in GM when preventive trimming was twice as high for HOU_2 compared with HOU_1 (24% decrease vs. 12% decrease; $P < 0.001$). A deteriorated hygiene (SCRAP_2 vs. SCRAP_1) was associated with a lower GM only in the case of HOU_1 compared with HOU_2 ($P < 0.01$). Regarding the different scenarios of detection rate and footbath application, no evidence was found to explain the deep fluctuations in GM (Supplemental File S4, https://doi.org/10.6084/m9.figshare.22064804.v1; Robcis, 2023d). Similar trends were observed for DD and MLD (Figure 4B and C, respectively).

The results of the GM regression are presented in Table 4. Each case of lameness was associated with a decrease in yearly GM of €307.00 ± 8.40. A farmer with HOU_2 had a mean decrease in GM of €63,980 ± 286.30 compared with HOU_1. For TRIM_2 and SCRAP_2 compared with TRIM_1 and SCRAP_1, a decrease in GM of €28,080 ± 279.10 and €3,033.0 ± 279.10 is observed, respectively. One active case of DD was associated with a yearly GM decrease of €391.8 ± 10.0. MLD analysis showed that a cow with an average week spent in a lame state was associated with a GM decrease of €12.10 ± 0.36. The HOU_2, TRIM_2 and SCRAP_2 coefficients were very close for the 3 regressions.

DISCUSSION

Originality of the Methodology

In general, many bioeconomic models enable investigations of how strategies may affect some aspects in herd management. Yet, the present bioeconomic model is built on a way that it allows a comparison between strategies and their associated costs, permitting to classify them by order of interest for the farmer, helping the latter to make decisions (van Asseldonk et al., 2005; De Vries, 2006; Gussmann et al., 2018).

All previous studies that aimed to estimate the cost of lameness in dairy cattle considered the lameness diseases separately, and all the interactions between etiologies were mainly excluded (Cha et al., 2010; Charfeddine and Pérez-Cabal, 2017; Dolecheck et al., 2019). Simulating the lameness diseases separately without interactions does not appear to replicate the field situation well, where cows often face simultaneous etiologies. The literature reports close associations between lameness etiologies. To our knowledge, the present study is the first to use a holistic model and to simulate claw diseases and the potential interactions between them. The dairy herd is simulated in its wholeness, with consideration of lameness diseases, interactions between them and interactions with other important herd-level diseases such as mastitis or subclinical ketosis. This approach allows a robust simulation of herd dynamics and complexity.

The present model also accounted for the complex DD dynamics with all the M-stage transitions. This was the first time that this calibration was considered for lameness cost assessment. All these transitions are not easily predictable, and only 2 papers addressed them (Holzhauer et al., 2008a; Biemans et al., 2018). Distinguishing the M-stage added value to the results

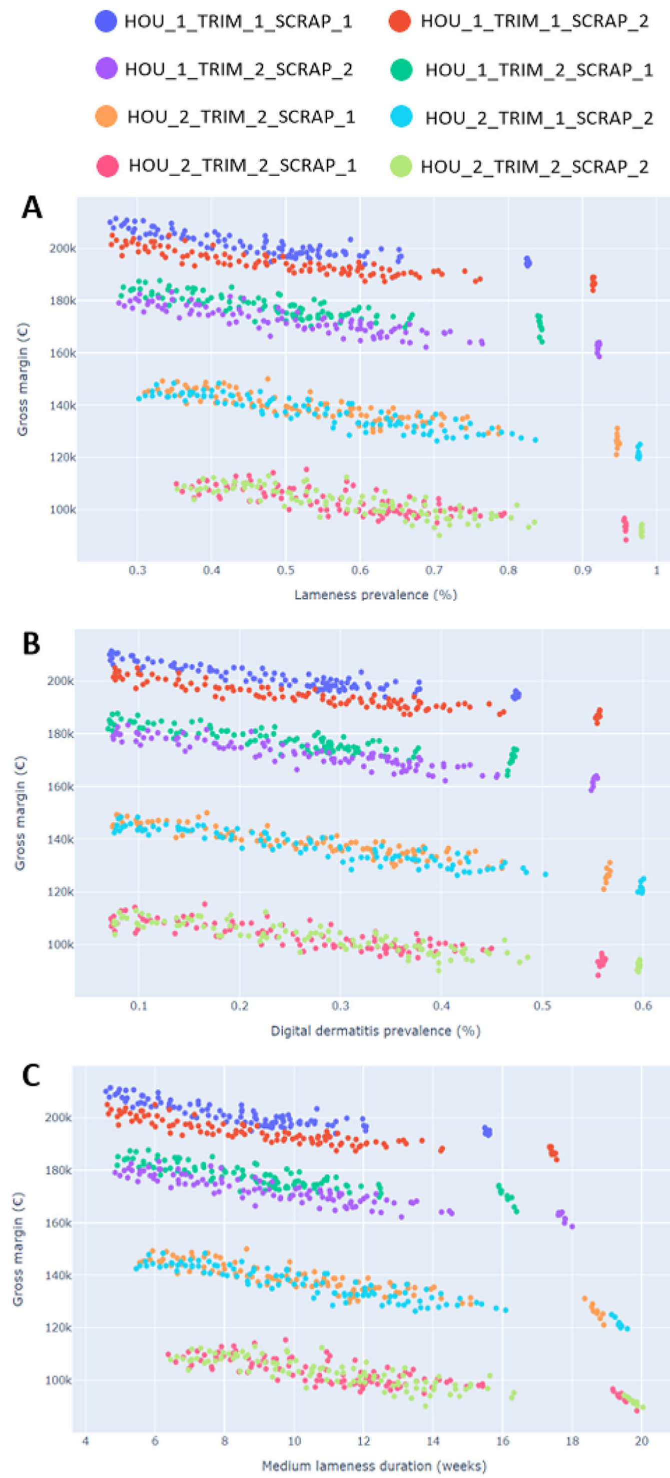

Figure 4. Relationship between gross margin and the different combinations of scenarios for (A) lameness, (B) digital dermatitis, and (C) medium lameness duration. HOU_1 = concrete floor; HOU_2 = textured floor; TRIM_1 = preventive trimming; TRIM_2 = no preventive trimming; SCRAP_1 = scraping frequency >8 times/d; SCRAP_2 = scraping frequency ≤8 times/d.

Table 4. Economic model, contribution of each scenario to lameness costs (R^2 of the regression = 0.988)

Scenario[1]	Coefficient	SD	95% CI
Lameness			
Intercept	217,400***	497.4	216,000 to 218,000
HOU_1	Referent		
HOU_2 (€)	−63,980***	286.3	−6,450 to −6,340
TRIM_1	Referent		
TRIM_2 (€)	−28,080***	279.1	−28,600 to −27,500
SCRAP_1	Referent		
SCRAP_2 (€)	−3,033.00***	279.1	−3,580.8 to −2,485.2
Change in GM per unit of prevalence (€)	−307.50***	8.4	−324.0 to −291.0
DD			
Intercept	212,500***	372.1	212,000 to 213,000
HOU_1	Referent		
HOU_2 (€)	−65,520***	268.4	−66,000 to −65,000
TRIM_1	Referent		
TRIM_2 (€)	−28,890***	268.4	−294,000 to −284,000
SCRAP_1	Referent		
SCRAP_2 (€)	−2,889.00	268.4	−3,415.7 to −2,362.3
Change in GM per unit of prevalence (€)	−391.80***	10.0	−411.5 to −372.1
MLD			
Intercept	208,100***	340.3	207,000 to 209,000
HOU_1	Referent		
HOU_2 (€)	−64,110***	301.4	−64,700 to −63,500
TRIM_1	Referent		
TRIM_2 (€)	−28,160***	294.1	−28,700 to −27,600
SCRAP_1	Referent		
SCRAP_2 (€)	−2,992.50***	294.3	−3,570.1 to −2,414.9
Change in GM per unit of prevalence (€)	−12.10***	0.36	−12.8 to −11.3

[1]DD = digital dermatitis; MLD = medium lameness duration; GM = gross margin; HOU_1 = concrete floor; HOU_2 = textured floor; TRIM_1 = preventive trimming; TRIM_2 = no preventive trimming; SCRAP_1 = scraping frequency >8 times/d; SCRAP_2 = scraping frequency ≤8 times/d.

***$P < 0.001$.

because they do not generate the same level of lameness, and the sizes of zootechnical consequences are different. The assessment of the cost of DD was consequently more precise.

Model Validation

Unfortunately, some pertinent data on clinical and epidemiological aspects of lameness in dairy hers have been missed in literature, so we decided to introduce data based on the author's experience, notably for the relationship between each foot disease and the engendered LS. An ex-post validation was done to be sure that our calibration was close from reality. We observed the epidemiological results of the model and see if the simulated diseases followed field situation. Lameness prevalence ranged from 26 to 98%, showing a high capacity of the model to represent field reality and its variability (Clarkson et al., 1996; Murray et al., 1996; Somers et al., 2003; Barker et al., 2010; Griffiths et al., 2018; Denis-Robichaud et al., 2020). This amplitude allowed a subsequent robust economic analysis. When all the etiologies were analyzed in detail, ranges of prevalence for all of them were in accordance with previous descriptive studies, highlighting, for example, that the SU within-herd prevalence ranged from 0% to 26% and the DD within-herd prevalence ranged from 0% to 74.3% (Manske et al., 2002a; Sogstad et al., 2005; Holzhauer et al., 2008; Capion et al., 2009; Tadich et al., 2010; van der Linde et al., 2010; Solano et al., 2016). The high correlation between the prevalence of DD actives states, the lameness prevalence and MLD indicated that DD is the most persistent lameness-generating claw disease in the herd, in agreement with concerns observed in the literature and in the field (Döpfer et al., 1997; Nielsen et al., 2009).

The recurrence in foot disorders is well described in literature and is estimated around 25% during one whole lactation and around 32% from one season to the following one (Randall et al., 2015; Mason, 2017). In the present study, this recurrence was simulated at the lactation-level through the M-stage machine mimicking the DD dynamics and with a supplemental risk factor when a SU occurred previously (Thomsen et al., 2019).

The applied cure rates after adequate treatment application are not depending on the delay between the detection and the treatment, even if the cure rates in lameness management are very poor with delayed treatment (Leach et al., 2012). Cure rates were fixed to ease the model and not to potentially overestimate the costs. Similarly, the use of nonsteroidal anti-inflammatory drug was not taken into account, although concomitant use of nonsteroidal anti-inflammatory drug significantly improves cure rates for foot diseases (Thomas et al., 2015).

Topical OTC-based treatment was chosen as first-intention option to cure DD. Cure rates are variable depending on the chosen therapy (Holzhauer et al., 2011, 2017). For example, Berry et al. (2012) showed a cure rate of DD of about 60% after using topical treatment with lincomycin.

The present model did not consider any association between ID and milk production. The literature on ID and milk production is not consistent and relatively old (Enevoldsen et al., 1991; Sogstad et al., 2005). Only one study analyzed the consequence of mild lesions of ID on milk yield, and the milk yield was not significantly associated with ID status (Sogstad et al., 2007). Moreover, on a clinical point of view, the grades 1 and 2 of ID do not influence milk yield and grade 3 is not often described on-field.

The relative risk of subclinical ketosis for lameness occurrence was described in some studies and summarized through a meta-analysis performed by Raboisson et al. (2014). This relative risk is described for lameness without distinguishing the etiology. In the present work, we decided to apply this relative risk only for noninfectious lameness diseases, namely, SU and WLD. It has been shown that cows with thicker digital cushions are more likely to have noninfectious claw horn disruption lesions (Bicalho et al., 2009; Newsome et al., 2017), whereas the digital cushion thickness is positively correlated with the body condition score of the cow, even if it is not the only explicative reason (Newsome et al., 2017). Body condition score fluctuations are the clinical expression of subclinical hyperketonemia, supporting the relationship between SCK and noninfectious lameness disorders used in the present work.

Economic Analysis

The major fluctuations in GM were due to the HOU, TRIM, and SCRAP scenarios (Figure 4). The type of flooring was clearly the factor associated with the highest cost for the farmer, especially when a textured floor was preferred (Table 4). The choice between both types of flooring is still a compromise between minimizing the risk of lameness events and avoiding the risk of slippery for cows (Sharma et al., 2019). A concrete floor has been associated with more stressful conditions for cows, with a significant increase in cortisol in the blood (Eicher et al., 2013). Preventive trimming and scraping frequency were the second and third contributing factors to cost for the farmer but were considered easier processes to execute for the farmer to gain in GM.

The economic evaluation performed here allowed us to evaluate the average cost of lameness and DD as well as the marginal cost. Unexpectedly, the marginal cost was found to be uniform and independent of the prevalence; a constant cost regardless of the prevalence means that marginal cost equals average cost, and the results only indicate average costs. This is demonstrated by raw descriptions of economic values as well as regression results, where no interaction was noticed as significant. The values of lameness or DD costs obtained in the regression refer to the change in GM accounting for the mean weekly prevalence, as defined in Equations 2 and 3. These estimations represent the average cost per case of lameness or DD because the yearly GM was adjusted by the average weekly mean prevalence for a given year.

The yearly cost of one lameness case cost was estimated to be €307.50 for the farmer, which is above the values found in previous studies, with a cost of €229 per first-case lame cow (Ettema et al., 2006) and €230 per lame cow per year (Enting et al., 1997). Thus, the cost remains at the same order of magnitude. The observed difference could be explained by the occurrence of potential simultaneous claw diseases due to simulated interactions in the present study, generating a higher degree of lameness.

An active case of DD was assessed at €391.80 in the present study, which is in accordance with the results from Charfeddine and Pérez-Cabal (2017; €389/cow per year for a severe case of DD). This cost is higher than that in other studies, with a range between €43 and €143, depending on the severity and parity of the affected cow (Willshire and Bell, 2009; Cha et al., 2010; Charfeddine and Pérez-Cabal, 2017; Dolecheck et al., 2019). For example, Dolecheck et al. (2019) described a cost for DD of €72 per case, whereas Charfeddine and Pérez-Cabal (2017) described a cost of €51 per case per year for a mild lesion. There are multiple reasons for such differences. First, the DD dynamics were considered in the present study, as in the study of Charfeddine and Pérez-Cabal (2017), whereas other studies simulated DD as a one-entity disease without any M-stage dynamics, which could have contributed to lower estimations of cost compared with the present results. The different M-stages do not generate the same levels of milk losses. Having no lameness-inducing lesions was not associated with any milk losses; mild lesions generate a mild level of milk losses, and severe lesions engender more important milk losses. Second, the results were not expressed in the same manner between the studies, and the expression as cost per cow per year present in the herd systematically leads to a lower cost compared with the cost expressed per cow per case or cow per year per lame cow. The prevalence highly influences the cost per lameness case, leading to better precision and better possibilities for extrapolation.

A similar herd-level economic approach was performed by Edwardes et al. (2022) by estimating the cost of suboptimal mobility. Based on the same 5-scale lameness scoring, the mean total annual direct economic loss was €1,129, €3,098, €4,354, and €480 for LS 2, LS 3, LS 4, and LS 5, respectively. In the present study, the lameness cost based on cows whose LS $\geq$3 was simulated and expressed at a yearly individual level, which is a different approach to presenting the results.

The present results show that an additional week spent as lameness costs €12.10 per case. To our knowledge, this is an original approach. Previous studies only addressed the cost of a new case of one given claw disease without specifically considering the period spent as lame for the cow. This new epidemio-economic indicator is of interest for veterinarians to convince farmers to detect lame cows as soon as possible and to promote healing strategies with the shortest delays.

Finally, the present work highlighted the contributory role of each risk factor in GM and defined potential actions for farmers. The farmer's decisions will be classified according to a balance between the positive impact on lameness management and the ease of application. First, improving lameness detection and using a collective footbath to achieve lower thresholds of DD prevalence are possibilities to save losses and are preferred as short-term actions. These results were in accordance with those of the study of Sadiq et al. (2019), showing that farmers were particularly sensitive to pain perception and that early detection of lame cows is the first way to improve foot health in herds. Middle- and long-term actions, such as scraping frequency, introduction of any preventive trimming and choice of flooring, are definitely the best actions to guarantee low lameness prevalence at the herd level. The importance of trimming was also highlighted by Mahendran et al. (2015), showing that trimming was an efficient option to decrease foot diseases in herds. Simultaneous actions on these 3 axes will be of additional interest for GM improvement: at a constant prevalence, a better strategy generates a better gross margin; however, a better strategy generates a decrease in prevalence and a subsequently better GM. The combination of these 2 actions drastically improves the GM of farmers.

CONCLUSIONS

This study confirmed that lameness has a negative effect on herd performance and GM. Milk yield losses widely represent the first component of lameness costs. It estimated lameness and DD costs at €307.50 ± 8.40 and €391.80 ± 10.00 per case, respectively. An original approach taking into account the lame state duration was productive, and one additional week spent in a lame state for one cow costs €12.10 ± 0.36 per case. This mechanistic, holistic and multi-interaction model, bringing a high level of accuracy to the results, is a helpful support for farmers for decision-making in lameness management.

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