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The cost of different types of lameness in dairy cows calculated by dynamic programming

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ABSTRACT

Traditionally, studies which placed a monetary value on the effect of lameness have calculated the costs at the herd level and rarely have they been specific to different types of lameness. These costs which have been calculated from former studies are not particularly useful for farmers in making economically optimal decisions depending on individual cow characteristics. The objective of this study was to calculate the cost of different types of lameness at the individual cow level and thereby identify the optimal management decision for each of three representative lameness diagnoses. This model would provide a more informed decision making process in lameness management for maximal economic profitability. We made modifications to an existing dynamic optimization and simulation model, studying the effects of various factors (incidence of lameness, milk loss, pregnancy rate and treatment cost) on the cost of different types of lameness. The average cost per case (US$) of sole ulcer, digital dermatitis and foot rot were 216.07, 132.96 and 120.70, respectively. It was recommended that 97.3% of foot rot cases, 95.5% of digital dermatitis cases and 92.3% of sole ulcer cases be treated. The main contributor to the total cost per case of sole ulcer was milk loss (38%), treatment cost for digital dermatitis (42%) and the effect of decreased fertility for foot rot (50%). This model affords versatility as it allows for parameters such as production costs, economic values and disease frequencies to be altered. Therefore, cost estimates are the direct outcome of the farm specific parameters entered into the model. Thus, this model can provide farmers economically optimal guidelines specific to their individual cows suffering from different types of lameness.

1. Introduction

Lameness has a detrimental effect on herd productivity, and is second only to mastitis in this respect (Esslemont and Kossaibati, 1996). In addition, lameness severely compromises the welfare of affected animals (Webster, 1986). Negative effects of lameness include a decrease in milk yield (Rajala-Schultz et al., 1999; Warnick et al., 2001) and fertility (Lucey et al., 1986; Collick et al., 1989; Lee et al., 1989; Hernandez et al., 2001) and an increase in risk of culling (Collick et al., 1989; Kossaibati and Esslemont, 1997; Sogstad et al., 2007).

Existing studies examining the costs of lameness have calculated the total cost of lameness by herd. These studies, however, are not particularly useful for farmers in making economically optimal decisions relating to individual cows suffering from lameness. We made modifications to an existing dynamic optimization and simulation model, studying the effects of various factors (incidence of lameness, milk loss, pregnancy rate and treatment cost, where pregnancy rate = heat detection x conception rate) on the cost of lameness (Gröhn et al., 2008). This model focused

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on non-specific lameness only; however, lameness is comprised of several conditions which can be categorized as follows: (1) non-infectious lameness which includes sole ulcers, white line disease/abscesses and toe ulcers and (2) infectious lameness which includes digital dermatitis, interdigital dermatitis and foot rot (Bergsten, 1997; Collick et al., 1997; Ossent et al., 1997).

These inherent differences in types of lameness need to be modeled in order for the results to be practically applicable at the farm level. Hence, in the current study, we developed a model which can incorporate three different types of lameness.

The objective of this study was to calculate the cost of different types of lameness (sole ulcer, digital dermatitis and foot rot). This would enable us to determine the optimal management decision of whether it may or may not be economically optimal for a cow to be (1) replaced with a heifer, (2) kept in the herd (and treated if she has a lameness case), but not inseminated or (3) kept and inseminated (and treated if she has a lameness case), for each of the three representative lameness diagnoses. We did this by modifying an existing economic model (Bar et al., 2008a).

2. Materials and methods

2.1. Lameness categorization

We categorized lameness into non-infectious lameness, infectious lameness and foot rot. This categorization is based on clinical expression, treatment decisions and consequences of the lameness. As the non-infectious and infectious categories are comprised of several types of lameness within themselves, we selected one condition which was representative of each category. The parameters we needed for our model exist in the literature for the different types of lameness, not by category of non-infectious and infectious; therefore, sole ulcer was chosen to represent the non-infectious lameness category and digital dermatitis the infectious lameness category. We categorized foot rot (interdigital phlegmon) (Greenough et al., 1997) separately, as it is less costly than digital dermatitis, generally rarer in occurrence and treatment differs from other infectious types of lameness (R.C. Bicalho, Cornell University, pers. commun.).

2.2. Replacements and inseminations optimization and simulation model

We modified an existing optimization and simulation model which was developed to study the cost of generic clinical mastitis in dairy cows (Bar et al., 2008a). The model is described in detail in the publication by Bar et al. (2008a).

The model was built using multi-level hierarchic Markov process (MLHMP) software as the application program interface (Kristensen, 2003), and was constructed as a 3-level hierarchic Markov process comprised of: the founder (parent) level containing state variables of permanent traits throughout the cow's life span, the child level divided into stages representing one whole lactation and the grandchild level divided into stages of 1 month. The possible actions that could be taken at this final level are: (1) replace the cow with a calving heifer, (2) keep the cow for another month without insemination (and treat her if she has lameness) or (3) keep the cow for another month and inseminate her (and treat her if she has lameness) (Bar et al., 2008a). Fig. 1 is a schematic representation of the model used in the current study on lameness.

At the founder level, five milk yield categories (kg) were modeled as: −5, −2.5, 0, +2.5, and +5 from the mean level of milk production per day. At the child level, eight possible whole lactation stages were modeled. At the grandchild level, 20 lactation stages (months) were modeled. In each stage the cow was described by one level within each of the following states: five temporary milk yield levels, nine pregnancy states (0 = open, 1–7 = 1–7 months pregnant and milking and 8 = last 2 months of pregnancy and dry (not milking)), 1 involuntarily culled state and 13 lameness states. The pregnancy states were included as a characteristic specific to individual cows. The lameness states were defined as: 0 = no lameness, 1 = first occurrence of sole ulcer (observed at the end of the stage enabling immediate culling with no loss to treatment or production), 2, 3 and 4 corresponding to 1, 2, 3 and more months after the first case of sole ulcer (this does not mean reoccurrence, but rather time horizon since the first case of sole ulcer), respectively, 5 = first occurrence of digital dermatitis and 9 = foot rot (with numbers from 6 to 8 and 10 to 12 corresponding to 1, 2, 3 and more months after the first case of the lameness, respectively, and again, this does not mean reoccurrence, but rather time horizon since the first case of digital dermatitis or foot rot). In the case of a reoccurrence, if a cow has a reoccurrence of e.g. sole ulcer, she will return to state 1. The objective function maximized by the model was the discounting criterion (Kristensen, 2003), which maximizes the net present value of the cow using a yearly interest rate of 8%, described further below (De Vries, 2006; Bar et al., 2008a).

2.3. Optimization technique

By combining the advantages of the two types of iteration methods used to solve the Markov process (namely value iteration and policy iteration), a new notion of a hierarchic Markov process was developed by Kristensen (1988, 1991), which forms the basis of our dynamic program. This allows us to obtain exact solutions to large state space problems as described below (Kristensen, 1996).

Our model is structured in such a way that a cow can be replaced until time infinity, hence, at the founder (parent) level, we have an infinite time horizon. At the subprocess (child and grandchild) levels, however, we have a finite time horizon (i.e., the lifespan of a specific cow).

Under a finite planning horizon, the value iteration method is ideal as it is exact. The optimal policies are identified by the following equation:

$$f_i(n) = \max_d \left\{ r_i^d + \beta \sum_{j=1}^{u} p_{ij}^d f_j(n-1) \right\}, \quad i = 1, \ldots, u \qquad (1)$$

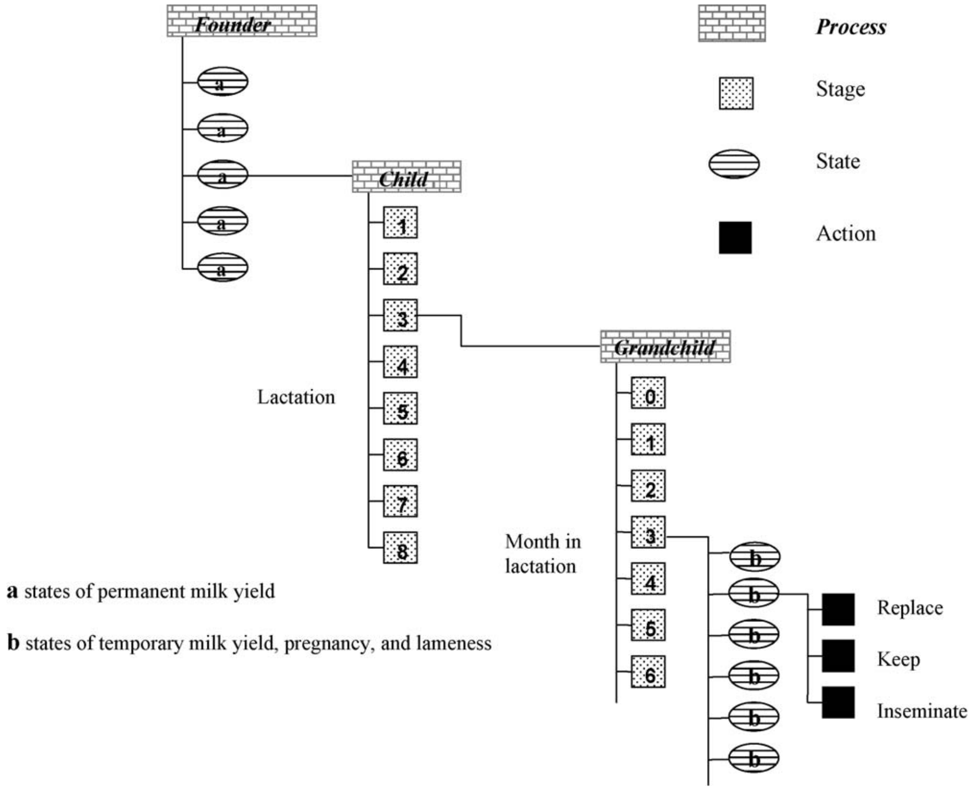

Fig. 1. Schematic representation of the structure of the multi-level hierarchic Markov process optimization and simulation model, to determine the average cost of lameness in dairy cows.

where the decision d maximizing the right-hand side is optimal for state i at the stage in question. The function $f_i(n)$ is the total expected discounted rewards when the process starts from state i and continues for n stages before ending. The rewards (economic net returns) depending on state i and action d are denoted by r_i^d. The transition probability of going from state i to j given decision d, is represented by p_{ij}^d (where there are $1, \ldots, u$ possible states). And β is the discount factor where $\beta = \exp(-r)$, and where r is the interest rate.

Under the infinite time horizon, the value iteration method is inefficient because many iterations are needed to reach convergence. On the other hand, the policy iteration method converges relatively quickly and gives exact results. The iteration cycle of the policy iteration involves choosing an arbitrary policy s (a set of decision rules for each state) and solving a set of linear simultaneous equations (in our case, five linear simultaneous equations corresponding to each permanent milk yield level) as described below:

$$f_i^s = r_i^s + \beta \sum_{j=1}^{u} p_{ij}^s f_j^s, \quad i = 1, \ldots, u \tag{2}$$

where f_i^s is the total present value of the expected future rewards of a process starting in state i and running over an infinite number of stages following the constant policy s. In our case, we solved $u = 5$ linear simultaneous equations, with unknowns $f_1^s, \ldots, f_5^s$.

Kristensen (1988, 1991) combined the benefits of both policy and value iteration, by applying value iteration to the subprocesses and using these results in the final step of the policy iteration method of the main process. Hence, in our model, at the founder level, we have used policy iteration, and at the child and grandchild levels, value iteration (Fig. 1).

2.4. Model parameters

Model parameters specific to the three different types of lameness are given in Table 1.

Model parameters and prices and costs were taken from De Vries (2006) and Bar et al. (2008a). Pregnancy rate was set to 0.21 per month. The voluntary waiting period was 60 days. The maximum calving interval was 20 months and the involuntary culling risk at calving was 2%.

The calving heifer cost (all costs in US$) was 1600, average monthly cow maintenance cost was 150 and insemination cost/month of insemination was 20. The average price for a calf born was 200. The milk price was $0.31/kg and the feed cost/kg of dry matter was set at $0.20. The cull price for voluntarily culled cows was set at $0.74/kg of body weight.

The transition probabilities are specific to the cow, the stage of lactation she is in and the unique combination of variables (i.e., pregnancy status, type of lameness, etc.) which apply to her. Hence many transition probabilities were used in the model.

Table 1
Model parameters specific to the three different types of lameness.

Parameter	Time period	Sole ulcer	Digital dermatitis	Foot rot	Reference
Milk loss (kg/d)	1st lactation, 1st month	1.07	0.42	0.70	Warnick et al. (2001)
	1st lactation, following months	1.07	0.28	0.37	
	2nd lactation, 1st month	2.40	0.91	1.38	
	2nd lactation, following months	2.91	0.76	1.01	
Pregnancy rate adjusted by odds ratios:		0.52	0.71	0.65	Hernandez et al. (2001)
Treatment cost ($)		65	58	34	Greenough et al. (1997)
Risk (%)	Months 1 and 2	1.41	0.87	1.35	Booth et al. (2004)
	Months 3 and 4+	1.70	1.00	0.34	Booth et al. (2004)

2.5. Methodology of estimating lameness cost

The average net returns per cow per year for a herd without lameness (by type) were compared with the average net returns for a herd with lameness (by type), while keeping other parameters constant. The profit or loss was divided by the lameness incidence to generate the herd average cost per case of lameness. As the cost of lameness was minimized under optimal treatment decisions, it is possible that these values differ from actual farm figures.

The net present value (NPV) is the current value of an action where the benefits and costs of the action are calculated until the end of the time horizon. This is achieved by discounting the various benefits and costs by an annual interest rate over that time period. The interest rate of 8% we used is based on a corresponding 4% monetary and 4% risk interest rate. The discounting factor (β) is equal to $\exp(-r)$ where $r = 0.08$, i.e. $\beta = 0.92$. The retention payoff (RPO) value is the NPV of retaining a cow compared with the NPV of her replacement (Bar et al., 2008b), i.e. $\mathrm{NPV}_{\mathrm{retaining}} - \mathrm{NPV}_{\mathrm{replacing}}$.

3. Results

3.1. Lameness costs

The simulated herd results of lameness by type in the dynamic programming model are illustrated in Table 2. These costs are averaged across all cow characteristics (parity, month of lactation, etc.). The average cost per case of lameness type was calculated by dividing the cost of lameness by lameness cases (as a percentage). Therefore, the average cost per case (US$) of sole ulcer, digital dermatitis and foot rot was 216.07 (26.36/0.122), 132.96 (9.44/0.071) and 120.70 (5.19/0.043), respectively. It was recommended that 92.3% of sole ulcer cases, 95.5% of digital dermatitis cases and 97.3% of foot rot cases be treated. For the remainder of cows, the recommended policy is to cull immediately.

The model allows us to calculate values for individual cows dependent on their characteristics. We can also calculate the value of an individual cow relative to her replacement and thereby determine the optimal course of action. For example, a cow with low permanent (genetically determined) milk yield, average temporary (based on day-to-day measurements) milk yield, in lactation 2, month 13 with sole ulcer and not pregnant has a retention payoff value (US$) of −135.07 if she is treated but not inseminated, and −155.19 if she is treated and inseminated. This means it would be economically optimal to sell her in this case, as her retention payoff value is negative.

3.2. Exogenous factors affecting the cost of lameness

The effects of milk loss, decreased fertility and treatment cost on the average cost of a lameness case are shown

Table 2
The effects of different types of lameness (sole ulcer, digital dermatitis, foot rot) on net return, lameness cases, % of lameness cases treated, average cost of lameness and average cost per case, following an optimal replacement policy.

	Net return[a]	Lameness cases[b]	% of lameness cases treated[c]	Average cost of lameness (US$)	Average cost per case[d] (US$)
No lameness[e]	426.05				
All[f]	384.31	23.5	94.1	41.74	177.62
Digital dermatitis and foot rot[g]	410.67				
Only sole ulcer[h]		12.2	92.3	26.36	216.07
Sole ulcer and foot rot	393.75				
Only digital dermatitis		7.1	95.5	9.44	132.96
Sole ulcer and digital dermatitis	389.50				
Only foot rot		4.3	97.3	5.19	120.70

[a] Net returns in US$ per cow and year.
[b] Incidence of lameness (cases per 100 cow years).
[c] Percent of treated lame cows per all lame cows.
[d] Average cost per lameness case.
[e] Lameness incidences set to 0.
[f] All three different types of lameness.
[g] Incidences of digital dermatitis and foot rot included only.
[h] The added effects of sole ulcer only.

Table 3
The effects of milk loss, decreased fertility and treatment cost on the average cost of a lameness case following an optimal replacement policy.

Lameness type	Cost per case (in US$)			
	Milk loss	Decreased fertility	Treatment cost	Total
Sole ulcer	82.97	71.84	61.25	216.06
Digital dermatitis	35.41	41.37	56.18	132.96
Foot rot	33.54	54.16	33.00	120.70

in Table 3. Milk loss contributed most to the total cost per case of sole ulcer (38%), followed by the effect of decreased fertility (33%) and treatment cost (28%). This was reversed in the case of digital dermatitis, where treatment cost was the main component of the total cost per case (42%), followed by the effect of decreased fertility (31%) and milk loss (27%). For foot rot, the effect of decreased fertility contributed almost 50% to the total cost, followed by milk loss (28%) and treatment cost (27%).

Increasing the milk price by 20% resulted in an increase in the average cost per case (US$) of lameness: from 177.62 to 190.08 in the all lameness model (a 7.0% increase) (Table 4). The opposite trend was observed when milk price was reduced by 20% (a 7.1% decrease).

The replacement cost is calculated by subtracting the beef price from the heifer cost. We increased and decreased the replacement cost by 20% by adjusting the heifer price only (Table 4). When we increased the replacement cost by 20% we found the average cost per case (US$) increased from 177.62 to 193.12 in the lameness model (an 8.7% increase). The opposite trend was observed when the replacement cost was reduced by 20% (an 8.4% decrease).

The cost per case (US$) was higher when the incidence of all the different types of lameness was halved (Table 4).

Increasing the pregnancy rate by 20% resulted in a reduction in the average cost per case (US$) (Table 4).

3.3. *Retention payoff of open healthy and lame cows*

The retention payoff can be calculated for individual cows depending on their unique characteristics. Here we have two hypothetical examples. Retention payoffs under an optimal policy for cows free of lameness and with different types of lameness, specific to an open (non-pregnant), second lactation cow with average milk yield per 305-day lactation are shown in Fig. 2. The optimal policy recommended by the model (keep but not inseminate, keep and inseminate or replace) is also illustrated. The RPO (US$) of these cows at calving was 1275, 1100, 1089 and 908 for no lameness, digital dermatitis, foot rot and sole ulcer, respectively. The average cost at calving was calculated by subtracting the RPO for the different types of lameness from the RPO for no lameness. Therefore, the average cost at calving was 175 (1275–1100), 186 (1275–1089) and 367

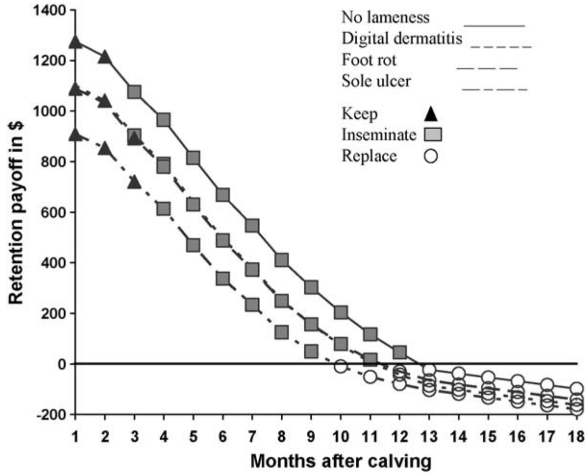

Fig. 2. Retention payoffs under an optimal policy for hypothetically open (non-pregnant) cows free of lameness and with different types of lameness, specific to a second lactation cow with average milk yield per 305-day lactation (*note*: foot rot and digital dermatitis graphs overlap).

Table 4
Effect of increasing and decreasing milk price and replacement cost by 20%, halving the incidence of all three different types of lameness and increasing pregnancy rate by 20% on lameness cases and the average cost per case for all lamenesses, and each different type of lameness.

Scenario	All[a]		Sole ulcer[b]		Digital dermatitis		Foot rot	
	Lameness cases[c]	Average cost per case[d]	Lameness cases[c]	Average cost per case[d]	Lameness cases[c]	Average cost per case[d]	Lameness cases[c]	Average cost per case[d]
Milk price +20%	23.7	190.08	12.2	235.33	7.2	137.36	4.3	130.44
Milk price −20%	23.4	165	12.1	200.93	7.1	125.93	4.2	113.43
Replacement cost +20%	23.4	193.12	12.1	237.69	7.1	141.69	4.2	133.10
Replacement cost −20%	23.7	162.79	12.2	199.67	7.2	122.78	4.3	111.63
Halving incidence of all 3 different types of lameness	11.6	183.02	6	225.33	3.5	136.29	2.1	126.19
Increasing pregnancy rate by 20%	23.5	167.02	12.1	206.20	7.1	123.80	4.3	111.40

[a] All three different types of lameness.
[b] Sole ulcer only.
[c] Incidence of lameness (cases per 100 cow years).
[d] Average cost per lameness case.

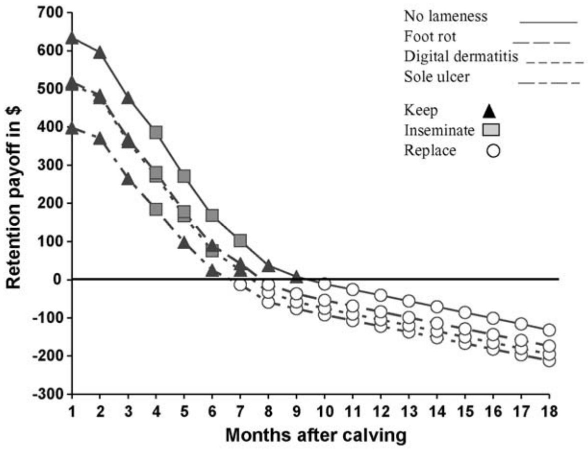

Fig. 3. Retention payoffs under an optimal policy for hypothetically open (non-pregnant) cows free of lameness and with different types of lameness, specific to a second lactation cow with permanent milk yield of 1500 kg per 305-day lactation less than the average in the herd.

(1275–908) for digital dermatitis, foot rot and sole ulcer, respectively. A negative RPO indicates a cow should be culled. This was observed at month 12 for no lameness, month 11 for both digital dermatitis and foot rot and month 9 for sole ulcer.

Fig. 3 demonstrates the RPO of open cows in their second lactation with permanent milk yield of 1500 kg per 305-day lactation less than the average in the herd. The RPO of these cows at calving was 634, 518, 513 and 398, respectively for no lameness, foot rot, digital dermatitis and sole ulcer. Therefore, the average cost at calving was 116 (634–518), 121 (634–513) and 236 (634–398) for foot rot, digital dermatitis and sole ulcer, respectively. The culling recommendation occurred at month 9 for no lameness, month 7 for both digital dermatitis and foot rot and month 6 for sole ulcer.

3.4. Endogenous factors affecting the cost of lameness

Tables 5 and 6 are a cross-sectional view of Figs. 2 and 3 at 4 and 8 months after calving, respectively.

The cost of lameness is dependent on endogenous factors, i.e., permanent milk yield potential, pregnancy status and lactation (Tables 5 and 6). For a cow 4 months after calving (Table 5), we found the average cost of lameness among the low milk producers was greater in pregnant cows compared with open cows. In contrast, the opposite was the case for average milk producing cows.

The average cost of lameness was greater in younger cows compared with older cows, which is explained by the latter group having a smaller remaining lifespan. This same trend was observed for high milk producing cows, as for average milk producing cows. However, the average costs differed for low producing open cows.

Generally, the average cost of digital dermatitis was greater than that for foot rot, although this was not consistent across all milk yield levels (e.g., open, average yielding cows).

Table 5
Average costs (in US$) of three types of lameness in cows with different levels (low, average, and high) of permanent (genetically determined) milk yield potential 4 months after calving, obtained by the insemination and replacement optimization model.

Lactation	Permanent milk yield potential																	
	Low						Average						High					
	Open			Pregnant			Open			Pregnant			Open			Pregnant		
	SU[a]	DD[b]	FR[c]	SU[a]	DD[b]	FR[c]	SU[a]	DD[b]	FR[c]	SU[a]	DD[b]	FR[c]	SU[a]	DD[b]	FR[c]	SU[a]	DD[b]	FR[c]
1	140	96	81	104	74	55	289	161	167	104	74	55	401	215	237	104	74	55
2	173	104	93	162	91	77	345	175	184	162	91	77	453	224	249	162	91	77
3	147	88	72	160	90	76	289	150	153	160	90	76	380	189	204	160	90	76
6	124	78	61	118	76	59	154	91	76	150	87	73	249	131	129	150	87	73

[a] Sole ulcer.
[b] Digital dermatitis.
[c] Foot rot.

Table 6
Average costs (in US$) of three types of lameness in cows with different levels (low, average, and high) of permanent (genetically determined) milk yield potential 8 months after calving, obtained by the insemination and replacement optimization model.

Lactation	Permanent milk yield potential																	
	Low						Average						High					
	Open			Pregnant			Open			Pregnant			Open			Pregnant		
	SU[a]	DD[b]	FR[c]	SU[a]	DD[b]	FR[c]	SU[a]	DD[b]	FR[c]	SU[a]	DD[b]	FR[c]	SU[a]	DD[b]	FR[c]	SU[a]	DD[b]	FR[c]
1	3	3	3	104	74	55	266	160	163	104	74	55	415	239	262	104	74	55
2	8	8	8	68	68	68	253	146	146	162	90	77	403	221	239	162	91	77
3	11	11	11	26	26	26	193	119	111	160	90	76	331	182	191	160	90	76
6	0	0	0	0	0	0	37	37	37	81	81	67	184	112	102	150	87	73

[a] Sole ulcer.
[b] Digital dermatitis.
[c] Foot rot.

At 8 months after calving, the average cost was generally greater for cows suffering from sole ulcer, while being similar for both digital dermatitis and foot rot (except for low milk producing open cows, where average costs did not differ between the different types of lameness) (Table 6).

3.5. Annual exit from the herd (comprised of causes independent of the model, i.e. involuntary exit and culling recommended by the model)

The annual exit from the herd was 34.8% (comprised of 16.4 from model recommended culling, and 18.4 from causes independent of the model, i.e. death) when all three diseases were in the model. This increased to 38% (20.2%, 17.8%) when milk price was increased by 20% and decreased to 32.5% (13.4%, 19.1%) when milk price decreased by 20%. An increase in replacement cost by 20% resulted in an annual exit of 33.1% (14.1%, 19%), and an increase to 38.5% (20.8%, 17.7%) when replacement cost was reduced by 20%. When the incidence of lameness was halved, the annual exit was 34.1% (15.4%, 18.7%), and when the pregnancy rate was increased by 20% the culling rate was 32.7% (13.2%, 19.5%).

4. Discussion

Traditionally, studies which placed a monetary value on the effect of lameness have calculated the costs at the herd level without taking into account individual cow characteristics. Therefore, these costs which have been calculated from previous studies are not particularly useful for farmers in helping them make economically optimal decisions for their individual cows. Further, rarely do these studies differentiate among different types of lameness.

The objective of this study was to calculate the cost of different types of lameness at the individual cow level. This model would provide a more informed decision making process in lameness management for maximal economic profitability, and would be specific to individual cow characteristics. We made modifications to an existing dynamic optimization and simulation model (Bar et al., 2008a), studying the effects of various factors (incidence of lameness, milk loss, pregnancy rate and treatment cost) on the cost of different types of lameness.

In our previous study (Gröhn et al., 2008) we investigated the cost of generic lameness in individual cows. In the current study, we have taken this one step further, to ascertain if there are discrepancies in cost between different types of lameness, and if so, quantify these differences.

As detailed in Gröhn et al. (2008), the cost of lameness (US$) was comprised of 40% from milk loss, 26% from decreased fertility and 34% from treatment costs. In the basic scenario, 94% of lameness cases were recommended to be treated. The cost per case of lameness was 7% higher with a 20% increase in milk price and 8% lower with a 20% decrease in milk price. Lower replacement heifer price (20%) reduced the cost per lame case by 9.6%.

From our current study, we found the average cost per case (US$) of sole ulcer, digital dermatitis and foot rot was 216.07, 132.96 and 120.70, respectively. Milk loss contributed most to the total cost per case of sole ulcer (38%), followed by the effect of decreased fertility (33%) and treatment cost (28%). This was reversed in the case of digital dermatitis, where treatment cost was the main component of the total cost per case (42%), followed by the effect of decreased fertility (31%) and milk loss (27%). For foot rot, the effect of decreased fertility contributed almost 50% to the total cost, followed by milk loss (28%) and treatment cost (27%). Over 94% of cows were recommended to be treated for all these types of lameness (specifically, 92.3%, 95.5%, and 97.3% for sole ulcer, digital dermatitis, and foot rot, respectively).

When milk price was increased by 20%, the culling rate increased from 16.4% (in the scenario with all three types of lameness) to 20.2%. This is because as the milk price increases, higher milk producing cows become more valuable, hence it is profitable to replace lower producing cows. The opposite was the case when milk price was reduced, which is not surprising.

As expected, when replacement cost increased by 20%, fewer cows (14.1%) were recommended to be culled compared with the basic scenario with all three types of lameness. The opposite was seen when replacement cost was reduced.

As anticipated, the culling rate decreased when incidence of lameness was halved (from 16.4% to 15.4%); however, the reduction was greater when pregnancy rate was increased by 20% (culling rate was 13.2%) as fewer cows are culled due to infertility.

Few studies have examined the cost of different types of lameness, and none have approached this problem at the individual cow level. A study conducted by Ettema et al. (2009) calculated the cost of lameness (converting from € to US$) as 44, 95 and 371 for digital dermatitis, interdigital hyperplasia and hoof horn disease respectively. This study differentiated lameness into separate categories, but was researching the problem at the herd level, not the individual level. In a study by Kossaibati and Esslemont (1997), the cost of lameness (converted from £ to US$) per lame cow was 472.66, 257.97 and 836.01 for digital dermatitis, interdigital dermatitis and sole ulcer, respectively. In contrast, a study by Enting et al. (1997) showed that the total cost (converted from NLG to US$) per lame cow was 154.80 per year, and the total loss per average cow present in the herd was 33.65.

Our research was specific to cow characteristics; we were able to undertake a more comprehensive analysis of the costs of lameness. Further, the cost of disease depends on the fate of the cow. If the cow is to be culled, milk loss effects and fertility effects are not applicable anymore. If the cow is pregnant, disease effects on fertility are not applicable. Pregnant cows were almost always recommended to be kept in the herd until the next lactation. Because the lameness losses in these cows are only treatment cost and milk loss and these were assumed to be the same for both high yielding cows and low yielding cows, the cost of lameness is the same for all these pregnant cows.

For example, we found the average cost of lameness was much greater in open, low milk producing cows at 4 months after calving, compared with an equivalent cow at 8 months after calving, as the former are more likely to conceive. In contrast, the average cost of lameness was greater in low milk producing pregnant cows in general, as they will stay longer in the herd compared with open cows, hence the resultant milk loss during this time will contribute to cost. Lameness was more costly for open than pregnant average milk producing cows, as open cows are exposed to the additional effect of reduced fertility.

In our model we did not include diseases that could have predisposed cows to the three different types of lameness nor the interaction between different types of lameness and nutrition on incidence of lameness (Holzhauer et al., 2008a,b). This could be an area of development.

In our model, when a cow is replaced, she is always replaced by an average cow, i.e., a replacement cow for a high producer is the same as that for a low producing cow. Further, intuitively, one would assume that a high producing cow loses more milk to lameness (compared with an average or low producer); however, we have assumed this to be the same due to lack of data on this issue.

We did not model seasonality and milk component variations, or the exact shape of the lactation curves beyond 10 months, as these issues were beyond the scope of our study objectives. A limitation includes the assumption that the farmer has complete knowledge of cow traits, and that a replacement heifer immediately enters the milking herd following a cow replacement, which is not always the case (Bar et al., 2008a).

This model provides versatility as it allows for parameters such as production costs, economic values and disease frequencies to be altered. Therefore, cost estimates are the direct outcome of the farm specific parameters entered into the model. Thus, this can provide farmers economically optimal guidelines specific to their individual cows suffering from different types of lameness.

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