Estimating US dairy clinical disease costs with a stochastic simulation model

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ABSTRACT

A farm-level stochastic model was used to estimate costs of 7 common clinical diseases in the United States: mastitis, lameness, metritis, retained placenta, left-displaced abomasum, ketosis, and hypocalcemia. The total disease costs were divided into 7 categories: veterinary and treatment, producer labor, milk loss, discarded milk, culling cost, extended days open, and on-farm death. A Monte Carlo simulation with 5,000 iterations was applied to the model to account for inherent system variation. Four types of market prices (milk, feed, slaughter, and replacement cow) and 3 herd-performance factors (rolling herd average, product of heat detection rate and conception rate, and age at first calving) were modeled stochastically. Sensitivity analyses were conducted to study the relationship between total disease costs and selected stochastic factors. In general, the disease costs in multiparous cows were greater than in primiparous cows. Left-displaced abomasum had the greatest estimated total costs in all parities (\$432.48 in primiparous cows and \$639.51 in multiparous cows). Cost category contributions varied for different diseases and parities. Milk production loss and treatment cost were the 2 greatest cost categories. The effect of market prices were consistent in all diseases and parities; higher milk and replacement prices increased total costs, whereas greater feed and slaughter prices decreased disease costs.

Key words: clinical disease, disease cost, stochastic modeling

INTRODUCTION

Cow health influences dairy farm profitability and alters biological mechanisms and productivity (Dijkhuizen and Morris, 1997; Galligan, 2006). Health issues change dairy cow performance, which affects current profits and future value of a cow. Disease influences profit-

ability through direct and indirect effects (Dijkhuizen and Morris, 1997; Galligan, 2006). Furthermore, health conditions partially determine culling policy because of changes in the cow's potential value. Common dairy diseases include ketosis, lameness, left-displaced abomasum (**LDA**), mastitis, metritis, hypocalcemia, and retained placenta (**RP**). Robust epidemiological studies have focused on the effects of disease on dairy cow performance, especially for mastitis, lameness, and reproductive failure, which were generally ranked as the most expensive health issues in the dairy industry (Kossabati and Esslemont, 1997; Juarez et al., 2003).

Mastitis is mostly caused by pathogenic bacteria invading and multiplying in the mammary gland (Harmon, 1994). The cost of mastitis has varied largely in previous studies. Halasa et al. (2007) summarized the cost of mastitis from 1990. Per-case cost varied from €102 (subclinical mastitis in the United Kingdom, equal to \$116 in 2016 US dollars) to €287 (in England, equal to \$325 in 2016 US dollars). Per-cow base mastitis cost varied from €2 (in Scotland, equal to \$2.27 in 2016 US dollars) to €31 equal to (in Ohio, equal to \$35.1 in 2016 US dollars). The top 2 cost categories were decreased milk production and treatment (Seegers et al., 2003; Cha et al., 2011; Heikkilä et al., 2012). The estimated average cost of clinical mastitis in 5 large New York Holstein dairy herds was \$71 per cow per year (\$179 per case), in which the highest loss was from a decrease in milk production (Bar et al., 2008).

Lameness is a foot or leg condition caused by multiple factors (Sanders et al., 2009). Lameness affects the dairy cow's productivity, welfare, and profitability (Cha et al., 2010). A recent US estimate with dynamic programming showed the estimated mean costs at \$177.62 per case, ranging from \$120.70 to \$216.07 for different lameness types (Cha et al., 2010).

Retained placenta and metritis have a complex relationship. Retained placenta is widely considered to be a predisposing factor for metritis (Sandals et al., 1979; Markusfeld, 1984; Bartlett et al., 1986). A common definition of RP is either the presence of fetal membranes 24 h or later after parturition, or fetal membranes retained for more than 6 h (Laven and Peters,

Received June 5, 2016.

Accepted October 3, 2016.

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1996). Metritis is an inflammation of the uterus due to bacterial invasion (Sandals et al., 1979; Bartlett et al., 1986; Drillich et al., 2001; Bellows et al., 2002). Both RP and metritis have detrimental effects on milk production and reproductive performance (Gröhn and Rajala-Schultz, 2000; Bellows et al., 2002; Gilbert et al., 2005). In addition, metritis increases culling risks and could require antibiotic treatment (Bartlett et al., 1986; Rajala-Schultz and Gröhn, 1999; Pol and Ruegg, 2007). Guard (2008) estimated that the total cost of retained placenta and metritis was \$315 per case in the United States.

Left-displaced abomasum is the predominant type of displaced abomasum in the United States (80–90%; Coppock, 1974). In a study of 161 multiparous cows in Oregon, the incidence of LDA was 4.3% during the first 7 wk in lactation (Qu et al., 2013). Left-displaced abomasum appears when the abomasum is filled with gas and subsequently trapped by the descending rumen to the left side of the abdominal cavity (Coppock, 1974; Markusfeld, 1986). The cost of LDA varied from \$250 to \$400 per case, depending on whether surgery was needed (Geishauser et al., 2000).

Ketosis occurs due to a negative energy balance, especially a glucose imbalance (Baird, 1982; Beem, 2003). The clinical ketosis incidence rate ranges from 2 to 15% (Beem, 2003). Ketosis leads to lower milk production and higher culling costs (Gröhn et al., 1998; Rajala-Schultz and Gröhn, 1999; Rajala-Schultz et al., 1999). Guard (2008) estimated the total ketosis cost at \$232 per case, including \$5 for the treatment.

Hypocalcemia, or milk fever, is low plasma calcium shortly following parturition (Horst et al., 1997; Kossaibati and Esslemont, 1997); milk fever is result of clinical hypocalcemia. The prevalence of subclinical hypocalcemia was 33% and clinical hypocalcemia was 5% in pasture-based systems (Roche, 2003). Hypocalcemia reduced the productive life of dairy cows by 3.4 yr. (Horst et al., 1997) and caused a decrease in milk production (Rajala-Schultz et al., 1999; Wilson et al., 2004). The total cost was estimated at \$220 per case (Kossaibati and Esslemont, 1997); Miller and Dorn (1990) summarized that culling cost was the greatest part of total hypocalcemia cost.

Dijkhuizen and Morris (1997) suggested that modeling was an essential tool to understand economics in the dairy production system. With computer simulation, stochastic programming has been used to estimate disease costs and find optimal management strategies in large-scale models. The stochastic model captured the variation in key variables using the Monte Carlo simulation with a large number of iterations. In each iteration, as one trial, the model drew a number from a distribution for each stochastic variable. After many

iterations, the model eventually covered the variations of stochastic variables. The objective of our study was to use a farm-level stochastic model with Monte Carlo simulation to estimate the cost of common dairy diseases in the United States with variation in farm and market conditions. The relationships among farm conditions, market prices, and total disease costs were further analyzed in this study.

MATERIALS AND METHODS

Basic Model

This farm-level, stochastic, Monte Carlo simulation model was first described by Bewley et al. (2010). The model was constructed in Microsoft Excel 2010 (Microsoft Corp., Redmond, WA) with @Risk 6.1.2 (Palisade Corporation, Ithaca, NY). The basic model was deterministic; however, several key variables were modeled stochastically, including dairy related market prices (milk, feed, slaughter, and replacement cow prices), product of conception rate and heat detection rate (**PHC**), rolling herd average milk production (**RHAM**), and age at first calving (**AFC**). The stochastic model takes the parameter variation into calculation to generate the results with a distribution, representing variation in results. A deterministic model does not assess these variations. This model was designed to describe and examine a cow's value with variation in farm and market conditions. To increase model accuracy and detail, the model was modified from the original monthly based model (Bewley et al., 2010) to a daily based model because the replacement decision is made on a daily basis. This model was constructed with the flexibility for users to input their farm-level parameters into this model as inputs instead of default parameters.

Farm-Level Model with Average Cow

This farm-level model used an average cow to represent all cows in the herd. This model assumed the herd structure was steady across time, and if a disease occurred it would not change the herd structure. Productive lifetime was set as 6 parities, which meant the model calculated the average cow's daily performance until the end of the sixth lactation regardless of the estimated optimal culling time. All daily production and reproduction data were calculated based on the methodology described in Bewley et al. (2010). Parameters calculated each day for each cow included milk production, BW, and DMI; reproduction performance included pregnancy status and days carrying calf. The lactation curve developed by Oltenacu et al. (1981),

Table 1. Farm performance characteristics used in stochastic modeling of dairy cow culling and reproductive performance economics¹

Variable	Value	Source
Number of milking cows	170.20	DairyMetrics
Heifers (0 to 12 mo as a percent of total herd)	42.0	DairyMetrics
Heifers (≥ 13 mo as a percent of total herd)	47.9	DairyMetrics
Percent of herd in 1st lactation	36.1	Dhuyvetter et al. (2007)
Percent of herd in 2nd lactation	26.0	Dhuyvetter et al. (2007)
Percent of herd in 3rd lactation	17.7	Dhuyvetter et al. (2007)
Percent of herd in 4th lactation	11.0	Dhuyvetter et al. (2007)
Percent of herd in 5th lactation	5.8	Dhuyvetter et al. (2007)
Percent of herd in 6th (or greater) lactation	3.4	Dhuyvetter et al. (2007)
Days in milk designated do not breed	300	Bewley et al. (2010)
Cull milk yield (kg)	15.86	Bewley et al. (2010)
Mature cow live weight (kg)	721.42	NRC (2001)
Slaughter cow weight (kg)	621.91	Dhuyvetter et al. (2007)
Calf birth weight (kg)	41.73	Kertz et al. (1997)
Voluntary waiting period (d)	58.50	DairyMetrics
Gestation length (d)	280	Norman et al. (2007)
Baseline culling rate (%; 1st parity, all culls other than diseases)	13.0	Bewley et al. (2010)
Percent heifer calves	46.6	Silva del Rio et al. (2005)
Weaned heifer death rate (%)	1.8	NAHMS (2007)
Age at first calving (mo.)	26.20	DairyMetrics
Days dry	59.6	NAHMS (2007)
Initial rolling herd average (kg)	9,708.24	DairyMetrics
Heat detection rate (%)	44.20	DairyMetrics
Conception rate (%)	42.25	DairyMetrics
Butterfat (%)	3.90	DairyMetrics
Protein (%)	3.10	DairyMetrics
Time of target BCS in DIM (d)	112	Friggens et al. (2004)

¹DairyMetrics, Dairy Records Management Systems, Raleigh, NC.

modified by Marsh et al. (1988) and Skidmore (1990), was used to estimate daily milk production. Dry matter intake was estimated based on the NRC (2001) equations.

Model Input

Default input variables were collected from published literature or from Dairy Records Management Systems (Raleigh, NC; Table 1). The report was calculated on June 14, 2015, and included 10,524 Holstein herds with at least 20 cows in the United States. Financial parameters are listed in Table 2. Rolling herd average milk production, HDR, CR, and AFC were modeled

stochastically using data from Dairy Records Management Systems; the simulated values are listed in Table 3.

Stochastic Prices Module

In this model, market prices (milk price, corn price, soybean price, alfalfa price, replacement heifer price, and slaughter price) were predicted for the year of 2015 (Table 4). Heifer calf and bull calf prices were also predicted for 2015; the calf price was further calculated, adjusting for the sex ratio (Table 4). Prediction prices were based on historical price variation and future price baseline data. Derived from historical prices, a correla-

Table 2. Financial inputs used in stochastic modeling of dairy cow culling and reproductive performance economics

Variable	Value	Source
Discount rate (%)	8.00	Hyde and Engel (2002)
Calf value (\$)	100	Kalantari and Cabrera (2012)
Yearly veterinary costs (\$)	63.27	Kalantari and Cabrera (2012) ¹
Semen costs (\$ per unit)	15	VanRaden and Cole (2014)
Dry cow feed price (\$/kg of DMI)	0.15	Bewley et al. (2010)
Financial losses at disposal (\$, for idle production)	61.61	Groenendaal et al. (2004) ¹
Cull cow price adjustment (%)	10	Dhuyvetter et al. (2007)
Discarded milk value per day, primiparous cows (fed to calf, \$)	1.80	McArt et al. (2015)
Discarded milk value per day, multiparous cows (fed to calf, \$)	2.70	McArt et al. (2015)

¹Adjusted for inflation to 2015 dollars.

Table 3. Simulated cow performance metrics used in stochastic modeling of dairy cow culling and reproductive performance economics

Item	Mean	SD	Range (5–95%)
Rolling average herd milk production (kg/cow per year)	10,079	1,826	6,925–13,197
Age at first calving (mo)	26.0	2.70	21.32–30.70
Heat detection rate (%)	45.2	17.20	15.48–74.84
Conception rate (%)	42.23	13.48	21.22–65.87

tion between stochastic market prices was set in the price prediction to avoid extreme results. The historical milk, corn, soybean, and alfalfa prices for 1971 to 2014; the slaughter price for 2009 to 2014; and the replacement price for 1971 to 2014 were collected from the Understanding Dairy Markets website (<http://future.aae.wisc.edu/>; Gould, 2015). The slaughter prices for 1970 to 2008 were defined from the historical prices data from the USDA-National Agricultural Statistics Service values for beef cow and cull dairy cows sold for slaughter (USDA-NASS, 2009). Baseline market prices (except replacement heifer price) were obtained from the Food and Agricultural Policy Research Institution's 2014 US Baseline Briefing Book: Projections for Agricultural and Biofuel Markets (FAPRI, 2014). Replacement heifer price was not reported in the FAPRI (2014) report. To obtain the replacement-heifer price baseline, a regression analysis was conducted between historical replacement price and slaughter price between 1992 and 2014. The final equation was

$$\begin{aligned} \text{Replacement price} &= 30.24 (\pm 9.81) \\ &\times \text{slaughter price} - 216.06 (\pm 357.55) \times \text{year} \\ &- 559,046.97 (\pm 19,512.83), \end{aligned}$$

where replacement price = market replacement cow price (per cow), and slaughter price = market slaughter price (per kg). All calf prices for both sexes were collected through the Agricultural Market Service (Robin L. Cusato-Wood, USDA Agricultural Marketing Service, Moses Lake, WA, personal communications) from 1990 to 2014. A similar prediction as replacement price was applied to calculate calf prices in 2015 using historical prices from 1992 to 2014. The final equations were

$$\begin{aligned} \text{Heifer calf price} &= 15.5 (\pm 7.55) \\ &\times \text{slaughter price} - 472.49 (\pm 275.32) \\ &\times \text{year} - 30,675.64 (\pm 15,025.43) \text{ and} \\ \text{Bull calf price} &= -1.35 (\pm 1.75) \times \text{slaughter price} \\ &- 227.40 (\pm 63.85) \times \text{year} + (\pm 3,484.50), \end{aligned}$$

where replacement price = market replacement cow price (per cow), and slaughter price = market slaughter price (per kg).

Revenues and Costs

Revenues and costs depended on animal performance and market prices. Daily revenue included milk sale, calf value, and slaughter value. Daily costs included feed cost, veterinary routine exams cost, breeding cost, and financial disposal losses (the cost generated after involuntary culling for lacking immediate replacement cow). Daily revenues and costs were calculated from daily performance and market prices.

Retention Pay-Off Module

Retention pay-off (**RPO**) is a widely used technique in the decision-making process of dairy cattle replacement or culling. The daily based RPO module was modified from the monthly based module described by Bewley et al. (2010). The net present value of the current cow's future profit was used to determine the optimal replacement moment. Retention pay-off represented the extra amount of money to spend on disease or reproductive failure control (Groenendaal et al., 2004). The optimal replacement moments appeared when RPO was less than or equal to zero.

Daily marginal net revenue (**MNR**) represented daily cash flow of the average cow. Daily MNR consisted of revenues minus costs, including the slaughter value change due to BW difference and financial disposal loss

Table 4. Predicted 2015 market prices and mean market prices for 2005 to 2014

Item	2015 market prices	Mean market prices for 2005–2014
Milk (\$/kg)	0.42 ± 0.05	0.39 ± 0.08
Lactating cow feed (\$/kg)	0.18 ± 0.03	0.19 ± 0.06
Replacement cow (\$/cow)	1,711 ± 208	1,608 ± 238
Slaughter (\$/kg)	1.92 ± 0.29	1.41 ± 0.46
Heifer calf (\$/calf)	273.10 ± 98.55	294.83 ± 214.82
Bull calf (\$/calf)	186.85 ± 47.58	135.3 ± 63.20

due to base involuntary culling risk (Groenendaal et al., 2004; Bewley et al., 2010):

$$\begin{aligned} \text{MNR}_i = & \text{Revenue}_{\text{milk},i} + \text{Revenue}_{\text{calf},i} + \text{Revenue}_{\text{slaughter},i} \\ & - \text{Cost}_{\text{feed},i} - \text{Cost}_{\text{feed},i} - \text{Cost}_{\text{mortality disposal},i} \\ & - \text{Cost}_{\text{veterinarian},i} - \text{Cost}_{\text{breeding},i}, \end{aligned}$$

where MNR = marginal net revenue, $\text{Revenue}_{\text{milk},i} = \text{Price}_{\text{milk}} \times \text{daily milk production}_i$, $\text{Revenue}_{\text{calf},i} = 0$ or calf value (only at calving), $\text{Revenue}_{\text{slaughter},i} = \text{Price}_{\text{slaughter}} \times (\text{BW}_i - \text{BW}_{i-1})$, $\text{Cost}_{\text{feed},i} = \text{Price}_{\text{feed}} \times \text{DMI}_i$, $\text{Cost}_{\text{mortality disposal},i} = \text{Probability}_{\text{death},i} \times \text{financial disposal cost}$, $\text{Cost}_{\text{veterinarian},i}$ = average daily veterinarian cost for routine exams, $\text{Cost}_{\text{breeding},i} = 0$ or daily breeding costs (after voluntary waiting period). Performance of a replacement cow was identical to the average cow due to the farm-level model setting, not considered genetic improvement. The economic opportunity of the replacement cow was calculated in terms of maximal average discounted net revenue or maximal annuity net revenue (ANR_{max}), which was the highest ANR value from the following day to the end of productive life (end of sixth parity) or the next optimal replacement time. Maximal annuity net revenue was dynamic across time, and the optimal replacement moment appeared at each time ANR reached to the closest ANR_{max} :

$$\text{ANR}_i = \frac{r \times \left[\sum_{j=1}^i \frac{(p_j \times \text{MNR}_j)}{(1+r)^j} \right]}{1 - \frac{1}{(1+r)^{\sum_{j=1}^i p_j \times m_j}}},$$

where ANR_i = annuity net revenue for replacement cow at day i , p_i = probability of surviving until the end of day i , m_i = length of period i (d), and r = discount rate, 0.0211%. According to the definition, RPO was the summation of daily differences between closest ANR_{max} and daily MNR until the next nearest optimal replacement time. Finally, RPO for day i was set as the cumulated differences between following daily MNR (MNR_i) and ANR_{max} , accounting for the survival probability due to inevitable voluntary culling:

$$\text{RPO}_i = \frac{\sum_{j=i+1}^{\text{ORM}} [p_j \times (\text{MNR}_j - \text{ANR}_{\text{max}})]}{(1+r)^i},$$

where RPO_i = retention pay-off value of the present cow in day i , and ORM = optimal replacement moment

(d). The results of RPO were then incorporated into the calculations for costs of days open and disease culling.

Disease Cost

All the disease costs were estimated for clinical cases only. Total disease costs were summarized into 7 categories: veterinary and treatment cost, milk production decrease, culling cost, discarded milk due to antibiotic use, death loss, cost of extended days open (DO), and labor costs. Each disease cost category was calculated individually and summed to find the total cost of each disease. The total disease costs were calculated separately for primiparous and multiparous cows.

Veterinary and Treatment Cost

An online survey was employed to collect clinical disease veterinary and treatment cost and producer labor cost from dairy veterinarians, industry consultants, researchers, hoof trimmers, and producers. This survey was conducted through SurveyMonkey (Palo Alto, CA). Four questions were listed in this survey for 1 clinical case of each disease (Table 5), inquiring about veterinarian service rate (\$/h), treatment cost (\$/case), veterinarian treatment and diagnosis time (min/case), and producer treatment and diagnosis time (min/case). Participants answered the questions by selecting an option from a dropdown list of individual questions for each disease. In the monetary-related questions, the answer options ranged from \$0 to \$300 with an interval of \$5. In the time-related questions, the range of answer options was from 0 to 60 min with a 5-min interval. The total veterinary cost was the product of veterinary service time and the associated service rate. The cost of producer labor was the product of producer diagnosis and treatment time by producer wage (\$32.49 per h), which was adjusted for inflation from the 2009 farm manager wages (\$29.21 per h, Bureau of Labor Statistics, 2015).

Microsoft Excel 2013 was used to analyze the original survey responses in terms of the mean, standard deviation, 2.5 percentile, and 97.5 percentile. The mean, 2.5 percentile, and 97.5 percentile from each of the survey question responses were used as the mean, minimum, and maximum to fit individual PERT distribution. As one type of scaled β distribution, the PERT distribution is a 3-point estimation adjusting for skewness using mean, minimum, and maximum (Bewley et al., 2010). Within the same disease, a correlation among 4 question responses was applied on those 4 PERT distributions to avoid the extreme and unrealistic simulated results. The distribution fitting and simulation were

Table 5. The descriptive analysis results from original survey responses for each survey question, including the mean and SD

Item	How much money will the producer spend to treat the disease per case? (\$)	Veterinarian hourly service rate (\$/h)	How much time does the average veterinarian spend to diagnose and treat one case of this disease? (min)	How much time does the average producer spend to diagnose and treat one case of this disease? (min)
Mastitis	43.86 ± 29.92	87.86 ± 51.44	10.23 ± 9.70	15.48 ± 12.84
Metritis	56.59 ± 36.63	90.95 ± 52.19	13.18 ± 9.07	14.50 ± 9.58
Ketosis	22.73 ± 22.02	87.63 ± 53.00	13.81 ± 11.28	16.75 ± 12.49
Lameness	41.90 ± 46.25	92.78 ± 44.27	22.75 ± 13.13	22.25 ± 12.19
Left-displaced abomasum	81.59 ± 81.76	130.75 ± 42.56	48.64 ± 14.97	25.00 ± 24.06
Retained placenta	46.59 ± 42.63	92.89 ± 50.12	11.14 ± 8.16	16.25 ± 13.17
Hypocalcemia	30.87 ± 42.71	93.25 ± 48.59	18.04 ± 14.36	20.48 ± 12.34

conducted with Microsoft Excel 2013 and @Risk Monte Carlo simulation add-in 6.0 (Palisade Corp.). Veterinary and treatment costs were modeled stochastically based on the survey responses to include large variation from the survey. This simulation was run for 10,000 iterations first and then used in the total disease costs calculation. Veterinary and treatment costs were assumed equal across parities. This 2-step simulation help eliminate the variation from survey responses.

Producer Labor Cost. The cost of producer labor was collected from the survey results discussed above. Producer labor cost was also assumed to be equal across all parities.

Disease Incidence and Timing. The default disease incidence rates were collected from Wilson et al. (2004), which also provided milk loss data (Table 6). As disease incidence varied across parities, disease incidence rates were separated for the first, second, and later parities (Wilson et al., 2004).

Disease timing varied at different DIM during the same parity. For example, hypocalcemia only happened within the first 2 wk after calving. Disease timing was modeled according to Kinsel (1998). Disease incidence and timing data were further used in culling, milk loss, and discarded milk modules to adjust production loss according to the lactation curve.

Milk Loss. Milk loss was the not-produced milk production as result of disease effects; however, discarded milk (due to antibiotic use) was the nonsalable part

of milk production. The decreased milk production associated with a reduction in feed intake was calculated based on a ratio of the average daily feed intake and average daily milk production and was separated for the primiparous and multiparous cows.

The milk loss was calculated separately for the primiparous and multiparous cows. The stochastic milk loss value was based on the milk loss result published by Wilson et al. (2004). The 95% confidence interval (ranging from 2.5 to 97.5 percentiles) was converted from the reported mean and standard deviation of each disease milk loss. The 2.5 percentile, mean, and 97.5 percentile values were modeled stochastically into an individual PERT distribution for each disease as the minimum, mean, and maximum.

Calculated weekly, milk production decrease data were specified for the first, second, third, fourth, and later weeks after disease occurrence. As the effect of disease on milk loss continued to change after the occurrence, the amount of milk loss per case was assigned to the occurring week, then adjusted for the disease incidence (Kinsel, 1998) during that week. The entire lactation milk loss was the sum of milk loss for each week.

Discarded Milk. Discarded milk represents the amount of milk production during the antibiotic treatment period and the following milk withholding period (if needed). Antibiotics were used only for mastitis, metritis, and lameness. To summarize each disease antibiotic use at the farm level, Pol and Ruegg (2007) reported antibiotic treatment in terms of daily doses per cow per year as the unit. Instead of using the 96% antibiotic usage probability on infectious lameness reported in Pol and Ruegg (2007), 5% usage data from Guard (2008) was selected and applied in this model for antibiotic treatment possibility in lameness.

Antibiotic type and associated treating methods (intramammary or parenteral) varied for different diseases. The treatment period quotient was the product of the total defined daily doses multiplied by the daily dosage, limited by each antibiotic product specified for the treating method. The treatment period length of

Table 6. Disease incidence collected from Wilson et al. (2004) and separated for the first, second, and later parities

Disease (%)	Incidence		
	1st parity	2nd parity	≥3rd parity
Mastitis	12.14	20.39	20.39
Lameness	33.20	30.90	30.90
Metritis	13.90	4.40	4.40
Retained placenta	7.20	12.20	12.20
Left-displaced abomasum	2.20	2.90	2.90
Ketosis	12.30	12.60	12.60
Hypocalcemia	NA ¹	5.20	5.20

¹Not applicable.

each antibiotic was then converted from days per cow per year to days per clinical case. Data using each type of antibiotic product were from Pol and Ruegg (2007). The following milk-withholding period of each drug was collected from the Food Animal Residue Avoidance Databank (www.farad.org), focusing on lactating cows. The total milk discarded period was the length of antibiotic treatment plus milk withholding (if occurred). The treatment period length of each disease was a weighted result based on each possible antimicrobial usage length and associated usage possibility. Another discrete distribution was built on the disease treatment probability based on the antibiotic treatment percentage of each disease.

Discarded milk value as pasteurized milk fed to calves was included to compensate for the loss of milk withholding. Discarded milk value was \$1.80 per cow per day for first-lactation cows and \$2.70 for later lactations (McArt et al., 2015), then multiplied by the withholding period length.

Culling and Death. The culling and death costs were estimated by the RPO value of the cow, which considers the future value of the current cow and the replacement heifer as well. This method was described in Bewley et al., (2010).

Reproduction. In this model, the detrimental effects of disease on reproduction were reflected in an extended DO. The change of DO fitted into separate stochastic PERT distribution for each disease using the mean and 95% (between 2.5 and 97.5%) range reported in a meta-analysis study on the effect of disease on reproductive performance (Fourichon et al., 2000). The cost of DO was calculated for parities 1, 2, 3, 4, 5, and 6 individually. The cost of DO value was the first day in lactation RPO (**FDRPO**) difference between an average cow and a disease affected cow (a detailed description can be found in Liang, 2013):

$$\text{Cost of DO}_{k,l} = \text{FDRPO}_{\text{average},l} - \text{FDRPO}_{k,l}, \quad [5]$$

where cost of $\text{DO}_{k,l}$ = cost of extended DO due to disease k in parity l , and $\text{FDRPO}_{k,l}$ = RPO on the first day in lactation in parity l of a cow with disease k . In this model, cost of DO was reported for primiparous and multiparous cows; the latter was the weighted cost of DO value in each parity by the correspondent herd demographic percentage.

Simulation

Simulations were conducted to calculate the disease costs with the stochastic variables of interest, including the stochastic factors (RHAM, PHC, AFC, milk price,

feed price, replacement heifer price, and slaughter price). In each simulation, 5,000 iterations and Latin Hypercube sampling were used with a static seed of 31,517 to ensure all simulations provided repeatable results.

Sensitivity Analysis

For each disease, sensitivity analysis was conducted through a multivariate regression analysis between the stochastic factors and total disease cost to test the effects of selected stochastic factors using the @Risk sensitivity analysis function. The result was presented in terms of disease cost change with 1 standard deviation increase in each stochastic factor.

RESULTS AND DISCUSSION

Veterinarian, Treatment, and Labor Cost Survey Results

One hundred thirty-seven people clicked the website link, and 47 of them started the survey. Eventually, 19 respondents completed the survey (completion rate 13.87%). Eleven of the final respondents were veterinarians, 5 were industry consultants, 2 were dairy farmers, and 1 was a researcher.

The descriptive statistics of original survey responses are shown in Table 5 (mean $\pm$ SD); the simulated survey results after 5,000 iterations were shown in Table 7. In general, treatment costs were greater than veterinary fees (Table 7). Left-displaced abomasum had the greatest veterinary fee, treatment cost, and producer labor cost, followed by lameness (Table 7).

Compared with Guard (2008), veterinary and treatment costs were much higher for most diseases. Admitting that some of the common dairy clinical diseases were correlated, our survey considered each disease separately without a potential treatment carryover effect. The variation of all the responses was large, reflected considerably on the standard deviation in the original responses (Table 6) and the range between 5th and 95th percentile in the simulated results (Table 7). Treatment cost was relatively subjective according to the specific disease case treatment and control plan of different producers and veterinarians. Pathogen type, severity, age, production, and presence of other diseases influence treatment decisions. On the management side, producers or veterinarians always have personal preferences for diagnosis and treatment. Farm size, location, and management could also affect disease treatment.

In this model, the per-case veterinary and treatment cost data were not adjusted for the veterinarian visiting

Table 7. Mean and SD of simulated veterinary cost, treatment cost, and producer labor cost for each disease¹

Item	Cost		
	Veterinary cost ² (\$)	Treatment cost (\$)	Producer labor cost ³ (\$)
Mastitis	19.16 ± 15.27	57.46 ± 27.72	11.58 ± 6.00
Metritis	21.81 ± 17.01	67.08 ± 31.65	9.74 ± 4.51
Ketosis	20.99 ± 13.29	32.34 ± 19.30	11.96 ± 5.99
Left-displaced abomasum	87.30 ± 29.99	114.30 ± 62.35	15.63 ± 8.48
Retained placenta	17.61 ± 9.53	69.47 ± 41.52	11.86 ± 6.30
Lameness	36.57 ± 17.54	70.52 ± 44.31	13.10 ± 6.12
Hypocalcemia	30.13 ± 15.33	58.24 ± 37.97	12.60 ± 5.98

¹The mean, 2.5 percentile, and 97.5 percentile data from the survey responses were fit into a PERT distribution and a 10,000-iteration simulation was conducted on this distribution to estimate the final costs.

²The veterinary cost was the combination of veterinary service and the associated hourly rates.

³The producer labor cost was the product of producer diagnosis plus treatment time and the average producer hourly wage (\$34.60/h).

frequency. The costs of veterinary and treatment contributed to the total disease costs separately from the other categories and would not affect further sensitivity analysis results. Different veterinary and treatment cost data could lead to different disease cost results. In spite of the large variability and low response rate, the survey results were still valuable for our study and future research. Lacking information of dairy disease treatment and veterinarian cost, previous literature used expert's experience numbers or estimation numbers for disease treatment cost, which could be more subjective than this survey.

RPO

The daily RPO of an average cow is depicted in Figure 1 with 2015 market prices. In general, the RPO value showed the similar changing pattern in each parity. The optimal replacement moment, when the RPO value dropped below zero for the first time, was at 229 DIM in the first lactation under 2015 market conditions (Figure 1), which was much earlier than previous results (third lactation in Bewley et al., 2010; 12th lactation in Groenendaal et al., 2004; sixth lactation in Heikkilä et al., 2012). Although this phenomenon is not common in

Figure 1. The retention pay-off value from the first parity to the end of the sixth parity, with the 2015 market conditions.

practice, Cabrera (2010) reported cows were optimally culled during first lactation under market conditions with a low milk price, high slaughter price, and high replacement price. The earlier optimal replacement time indicated less RPO value because greater RPO represented greater profitability and culling cost, which deferred the optimal replacement time (Bewley et al., 2010).

Compared with the 10-year historical average market conditions from 2005 to 2014, the 2015 market condition had a relatively higher slaughter price and slightly lower prices on feed replacement heifer (Table 4). This combination of market conditions explained the comparatively low RPO value in this model. As a consequence, the RPO-based culling costs and cost of DO were less than in previous literatures in general.

Total Disease Costs

Total disease costs, separated for primiparous and multiparous cows, are presented in Table 8. In general, disease costs were greater for multiparous than primiparous cows. Left-displaced abomasum was the most expensive disease across all parities. Contribution of each cost category to the total cost depended on the disease and parity number (Table 8). For example, the largest contributor to total mastitis cost was decreased milk production; however, the largest contributor to the total LDA cost was veterinary and treatment cost.

This model estimated the farm-level average disease costs per clinical episode, which indicated that each result from this model had been weighted for all the infection incidences and farm conditions. Some results from this model were lower than the results from previous epidemiological studies.

Mastitis. The average mastitis cost was \$325.76 $\pm$ 71.12 per case for primiparous cows and \$426.50 $\pm$ 80.27 per case for multiparous cows. Total mastitis cost of primiparous cows were in the range given by Halasa et al. (2007; \$3.80 to \$360 per clinical case,); however, the total costs for both primiparous and multiparous cows were higher than \$179 per case in Bar et al. (2008) and \$155.08 per case in Cha et al. (2011).

The cost of reduced milk production was the largest portion of total costs, contributing \$162.17 $\pm$ 44.26 and \$165.17 $\pm$ 39.86 per case for primiparous and multiparous cows, respectively. This result agreed with the statement from Seegers et al. (2003), that a decrease in milk production was the major economic loss caused by mastitis. For all parities the cost of producer labor was \$11.58 $\pm$ 6.00 per case, and the cost of veterinary and treatment was \$77.74 $\pm$ 33.15 per case. Cha et al. (2011) and Heikkilä et al. (2012) both found that

Table 8. Mean $\pm$ SD of total disease costs and the contribution from each category, separated for the primiparous cows (P1) and multiparous cows (P2)

Item (\$)	Parity	Veterinary and treatment	Labor	Discarded milk	Decreased milk production	Culling	Extended days open	Death	Total costs
Mastitis	P1	77.74 $\pm$ 33.15	11.53 $\pm$ 6.00	53.55 $\pm$ 35.43	162.17 $\pm$ 44.26	10.26 $\pm$ 3.95	-1.54 $\pm$ 2.24	12.05 $\pm$ 1.83	325.76 $\pm$ 71.12
	P2			65.44 $\pm$ 41.90	165.17 $\pm$ 39.86	10.32 $\pm$ 10.85	86.16 $\pm$ 22.24	12.82 $\pm$ 1.88	426.50 $\pm$ 80.27
Lameness	P1	104.20 $\pm$ 54.76	13.12 $\pm$ 6.12	2.01 $\pm$ 9.24	23.83 $\pm$ 19.05	24.98 $\pm$ 7.80	5.86 $\pm$ 10.39	11.10 $\pm$ 1.67	185.10 $\pm$ 64.46
	P2			2.24 $\pm$ 11.18	37.81 $\pm$ 17.74	54.41 $\pm$ 17.18	83.33 $\pm$ 20.69	11.56 $\pm$ 1.70	333.17 $\pm$ 68.76
Metritis	P1	90.03 $\pm$ 39.59	9.77 $\pm$ 4.52	33.58 $\pm$ 21.85	3.29 $\pm$ 1.54	7.25 $\pm$ 1.49	11.41 $\pm$ 16.85	16.26 $\pm$ 2.50	171.69 $\pm$ 47.88
	P2			41.12 $\pm$ 26.10	9.23 $\pm$ 3.09	9.49 $\pm$ 10.01	84.67 $\pm$ 22.34	17.39 $\pm$ 2.55	262.65 $\pm$ 56.15
Retained placenta	P1	84.69 $\pm$ 44.40	11.94 $\pm$ 5.96	NA ¹	48.37 $\pm$ 22.70	NA	5.41 $\pm$ 9.59	NA	150.41 $\pm$ 51.43
	P2			NA	134.93 $\pm$ 36.59	NA	84.79 $\pm$ 22.11	NA	313.49 $\pm$ 64.66
Left-displaced abomasum	P1	197.22 $\pm$ 70.28	15.50 $\pm$ 8.48	NA	169.80 $\pm$ 72.36	25.73 $\pm$ 8.20	2.54 $\pm$ 8.11	21.69 $\pm$ 3.33	432.48 $\pm$ 101.94
	P2			NA	280.84 $\pm$ 77.49	37.71 $\pm$ 40.02	85.28 $\pm$ 22.16	23.46 $\pm$ 3.45	639.51 $\pm$ 114.10
Ketosis	P1	52.44 $\pm$ 21.29	11.76 $\pm$ 5.59	NA	1.00 $\pm$ 0.65	4.72 $\pm$ 1.06	1.67 $\pm$ 5.38	5.42 $\pm$ 0.84	77.00 $\pm$ 24.00
	P2			NA	6.67 $\pm$ 1.69	6.87 $\pm$ 7.30	85.29 $\pm$ 22.12	5.80 $\pm$ 0.85	180.91 $\pm$ 63.74
Hypocalcemia	P2	85.25 $\pm$ 42.58	12.59 $\pm$ 5.98	NA	6.01 $\pm$ 2.02	8.46 $\pm$ 9.28	85.28 $\pm$ 22.17	46.79 $\pm$ 6.87	246.23 $\pm$ 52.25

¹Not applicable.

the cost of milk loss and treatment were the 2 most expensive cost categories in total mastitis cost.

The milk discard period was 4.36 ± 2.42 d and the associated discarded milk loss was $\$53.55 \pm 35.43$ and $\$65.44 \pm 41.90$ per case for primiparous and multiparous cows, respectively. Different discarded milk costs across parities were due to the greater daily average milk production in multiparous cows. The cost of discarded milk in our study was greater than the \$20 in Bar et al. (2008) and \$33 in Guard (2008), in which the discarded milk period data were assumed from experts' experience. Although the antibiotic treatment data in our model were collected from a regional rather than a national study, this stochastic model applied the cost variations to the final results through the Monte Carlo simulation.

Death costs were $\$12.05 \pm 1.83$ and $\$12.82 \pm 1.88$ per case for primiparous and multiparous cows, respectively; explained by the greater BW of older animals. Culling cost was $\$10.26 \pm 3.95$ and $\$10.32 \pm 10.85$ for primiparous and multiparous cows, respectively. The mastitis related cost of DO was $\$-1.54 \pm 2.24$ for primiparous cows and $\$86.16 \pm 22.24$ for multiparous cows. Costs of culling and extended days open were based on the daily RPO value. The cost of days open for primiparous cows was negative and much lower than the previous studies (Bar et al., 2008; Guard, 2008; Cha et al., 2011) because 2015 market conditions had a much higher slaughter price but slightly higher replacement cow price than the 10-yr average prices. This price combination shrunk the value of keeping a cow in the herd so that the cost of DO decreased. Low costs of DO in primiparous cows were found in all 7 diseases included in this model; costs of DO were similar for multiparous cows for all diseases. In addition, the extended days open, caused by mastitis, was comparatively short, ranging from -0.9 to 1.6 d (Fourichon et al., 2000).

Lameness. The total lameness costs were $\$185.10 \pm 64.46$ and $\$333.17 \pm 68.76$ per case for primiparous and multiparous cows, respectively. This estimation was close to €192 (\$227) in Ettema and Østergaard (2006) and \$177.62 in Cha et al. (2010), but lower than 229.79 Dutch guilders (\$132) in Enting et al. (1997), £246.22 (\$421.53) Kossaibati and Esslemont (1997), and \$469 in Guard (2008). The greatest portion in total lameness cost was from veterinary and treatment cost ($\$104.20 \pm 54.76$ for all parities), which was approximately at the same level as \$106 from Guard (2008), but the variation is large. This variation may be due to the different definitions of lameness the respondents referred to when they were taking the survey. Some mentioned hoof trimming as part of the lameness treatment cost,

which would increase the estimation by increasing the preventative hoof trimming cost.

The culling costs were $\$24.98 \pm 7.80$ and $\$54.41 \pm 17.18$ per lameness case for primiparous and multiparous cows, respectively. Cost of DO were $\$5.86 \pm 10.39$ and $\$83.33 \pm 20.69$ for primiparous and multiparous cows, respectively. Across all diseases, lameness had a relatively high cost of extended days open. Cha et al. (2010) found the effect of decreased fertility on lameness cost to be high across different lameness types. Other studies also claimed that lameness could extend the calving interval greatly through different aspects, such as an increased difficulty of heat detection (Lee et al., 1989; Barkema et al., 1994).

Milk production decrease caused by lameness was $\$23.83 \pm 19.05$ and $\$37.81 \pm 17.74$ per case for primiparous and multiparous cows, respectively; this was less than the cost of \$169 per case from Guard (2008). The effects of lameness on milk production were not absolutely clear. Some researchers have observed detrimental effects (Rajala-Schultz et al., 1999; Warnick et al., 2001), whereas other studies failed to find the effect or stated a positive effect of lameness on milk production (Dohoo and Martin, 1984; Sanders et al., 2009). The interaction of disease incidence and milk production was not included in this model, which explained incompatible results compared with Guard (2008) that high-producing cows had a higher lameness risk than low-producing cows. In addition, the high feed price reduced a part of the economic loss of milk production in this model.

The simulated mean milk-withholding period was 0.12 ± 0.65 d. The discarded milk costs were $\$2.01 \pm 9.24$ and $\$2.24 \pm 11.18$ per case for primiparous and multiparous cows, respectively; this was close to the result of Guard (2008). The producer labor cost was $\$13.12 \pm 6.12$ per case; death costs were $\$11.10 \pm 1.67$ and $\$11.56 \pm 1.70$ per case for primiparous and multiparous cows, respectively.

Metritis. The total metritis costs were $\$171.69 \pm 47.88$ per case for primiparous cows and $\$262.65 \pm 56.15$ per case for multiparous cows, higher than the \$106 in Bartlett et al. (1986). The veterinary and treatment cost was $\$90.03 \pm 39.59$ and the labor cost was $\$9.77 \pm 4.52$ per case. The simulated mean milk-withholding period was 2.62 ± 1.51 d, and the discarded milk cost was $\$33.58 \pm 21.85$ per case for primiparous cows and $\$41.12 \pm 26.10$ per case for multiparous cows. The costs of decreased milk production were $\$3.29 \pm 1.54$ per case for primiparous cows and $\$9.23 \pm 3.09$ per case for multiparous cows. The culling costs were $\$7.25 \pm 1.49$ per case for primiparous cows and $\$9.49 \pm 10.01$ per case for multiparous cows. The costs of DO were $\$11.41$

± 16.85 per case for primiparous cows and $\$84.67 \pm 22.34$ per case for multiparous cows. Death costs were $\$15.43 \pm 2.26$ per case for primiparous cows and $\$16.67 \pm 2.33$ per case for multiparous cows.

Retained Placenta. The total RP costs were $\$150.41 \pm 51.43$ per case for primiparous cows and $\$313.49 \pm 64.66$ per case for multiparous cows. Primiparous cows had a lower cost than the estimation of $\$319$ per case from Shaver (1997); however, multiparous cows had a similar cost. The cost associated with veterinary and treatment was $\$84.69 \pm 44.40$ and the cost of producer labor was $\$11.94 \pm 5.96$. The fiscal losses due to milk production decrease were $\$48.37 \pm 22.70$ per case for primiparous cows and $\$134.93 \pm 36.59$ per case for multiparous cows. The costs of DO were $\$5.41 \pm 9.59$ per case for primiparous cows and $\$84.79 \pm 22.11$ per case for multiparous cows.

Retained placenta culling cost and on-farm death cost were not included in this model. The culling risk data in this model was collected from Rajala-Schultz and Gröhn (1999), who indicated that RP was not a major risk factor in involuntary culling. With a strong positive relationship with metritis (Bartlett et al., 1986; Drillich et al., 2001), the RP culling risk might have been transferred into the metritis culling risk.

The combined per-case costs of retained placenta and metritis ($\$322$ in the primiparous cows and $\$576$ in the multiparous cows) were greater than $\$315$ in Guard (2008). However, RP and metritis costs were calculated separately in this model, not considering the interrelationship between RP and metritis.

LDA. The average LDA costs per case were $\$432.48 \pm 101.94$ for primiparous cows and $\$639.51 \pm 114.10$ for multiparous cows. The greatest portion was from the cost of veterinary and treatment at $\$197.22 \pm 70.28$ per case, in agreement with the range ($\$100$ to $\$200$ per case) given by Shaver (1997). The necessity of surgery to treat an LDA may explain the increased cost of veterinary and treatment. Geishauser et al. (2000) stated that conducting a surgery to cure LDA would increase the total cost by $\$150$ per case. The second highest cost category was from milk production loss ($\$169.80 \pm 72.36$ per case for primiparous cows and $\$280.84 \pm 77.49$ per case for multiparous cows), in agreement with Miller and Dorn (1990) that the cost of milk loss was high in the total cost of LDA. Due to the high culling risk related to LDA, the culling cost was $\$25.73 \pm 8.20$ per case for primiparous cows and $\$37.71 \pm 40.02$ per case for multiparous cows. Costs of on-farm death were $\$21.69 \pm 3.33$ per case for primiparous cows and $\$23.46 \pm 3.45$ per case for multiparous cows. Costs of extended days open were $\$2.54 \pm 8.11$ per case for primiparous

and $\$85.28 \pm 22.16$ per case for multiparous cows. The labor cost was $\$15.50 \pm 8.48$ per case.

Ketosis. The total ketosis cost was $\$77.00 \pm 24.00$ per case for primiparous cows and $\$180.91 \pm 63.74$ per case for multiparous cows; both were much less than the previous estimation at $\$232$ per case (Guard, 2008). The greatest difference was from the milk production loss portion. This model estimated the milk loss cost at $\$1.00 \pm 0.65$ per case for primiparous cows and $\$6.67 \pm 1.69$ per case for multiparous cows. Milk loss results were much lower than the $\$91$ from Guard (2008). Ketosis has higher incidence in higher-producing cows than lower-producing cows. High-producing cows returned to high-producing levels after ketosis and express the cow's genetic potential; however, the milk loss from her genetic potential during ketosis was not recognized.

The veterinary and treatment cost was $\$52.44 \pm 21.29$ and the producer labor cost was $\$11.76 \pm 5.59$ per case; those 2 categories were lower than the $\$170$ per cow treatment cost from Varga (2004). The ketosis culling cost was $\$4.72 \pm 1.06$ per case for primiparous cows and $\$6.87 \pm 7.30$ per case for multiparous cows. The death cost was $\$5.42 \pm 0.84$ for primiparous cows and $\$5.80 \pm 0.85$ for multiparous cows.

Hypocalcemia. Hypocalcemia was assumed to only occur in multiparous cows. The total cost of hypocalcemia was $\$246.23 \pm 52.25$ per case, which was higher than McArt et al. (2015; $\$117$ per case, on average). The largest portion was from increased veterinary and treatment costs at $\$85.25 \pm 42.58$ per case. The culling cost was $\$8.46 \pm 9.28$ (3% of the total hypocalcemia cost) and the death cost was $\$46.79 \pm 6.87$ (19% of the total hypocalcemia cost) per case. As hypocalcemia caused a higher on-farm mortality risk and a greater culling risk (Horst et al., 1997), the contributions of culling and death to the total cost were relatively greater than other diseases. Miller and Dorn (1990) stated that culling took the largest portion in the total hypocalcemia cost. This model partially demonstrated that the culling cost was the second highest portion in the hypocalcemia cost, following the veterinary and treatment costs. The milk production decrease valued $\$6.01 \pm 2.02$ and labor cost was $\$12.59 \pm 5.98$ per case; in addition, the cost of extended days open was $\$85.28 \pm 22.17$ per case.

For all diseases (except hypocalcemia), the total costs for multiparous cows were greater than that of primiparous cows due to greater average daily milk production (29.75 vs 30.52 kg/d), greater daily RPO value, and elevated BW. Average daily milk yield in multiparous cows are higher than primiparous cows; as a result, the discarded milk value was higher in multiparous cow

Table 9. Change in each disease total cost with 1 SD increase in each market price for primiparous and multiparous cows

Item	Primiparous cows				Multiparous cows			
	Milk price	Feed price	Replacement heifer price	Slaughter price	Milk price	Feed price	Replacement heifer price	Slaughter price
Mastitis	43.09	−25.73	4.17	0	41.76	−22.66	0	12.45
Lameness	0	−4.04	22.45	−14.73	8.88	−5.08	0	15.12
Metritis	0	0	20.33	−13.53	6.85	0	0	13.06
Retained placenta	12.34	−9.14	0	0	27.34	−18.24	−8.01	20.01
Left-displaced abomasum	36.22	−29.77	11.60	0	60.33	−40.87	0	15.33
Ketosis	−1.05	0	4.91	−2.80	2.67	−1.73	0	13.14
Hypocalcemia	NA ¹	NA	NA	NA	0	0	0	19.45

¹Not applicable.

than primiparous cows. In addition, cost of DO and on-farm death cost were also higher in multiparous cows.

Sensitivity Analysis

Market Price. With 1 standard deviation increase in milk price, replacement cow price, and feed price, the total mastitis cost would change by \$43.09, \$4.17, and \$−25.73 per case, respectively, in primiparous cows (Table 9). This result was in agreement with Bar et al. (2008), who reported the higher milk price or replacement cow price would increase mastitis cost; Heikkilä et al. (2012) found a similar result. Slaughter price change had no effect on mastitis cost on primiparous cows; however, 1 standard deviation increase in slaughter price increased total mastitis cost by \$12.45 on multiparous cows. Meanwhile, replacement price had no effect on the multiparous cows' mastitis cost.

Market prices influenced lameness cost with the same trend for both primiparous cows and multiparous cows (Table 9). One standard deviation increase in the replacement cow price increased the per-case lameness cost by \$22.45 in the primiparous cows and had no effect on the multiparous cows. One standard deviation increase in the milk price would increase the per-case lameness cost by \$8.88 on multiparous cows. One standard deviation increase in the slaughter price reduced the per-case lameness cost by \$14.73 in primiparous cows and increased \$15.12 in multiparous cows' lameness per-case cost. One standard deviation increase in the feed price decreased the per-case lameness cost by \$4.04 in the primiparous cows and \$5.08 in the multiparous cows.

In primiparous cows, 1 standard deviation increase in milk price increased the per-case disease costs of RP and LDA by \$12.34 and \$36.22, respectively (Table 9). However, 1 standard deviation higher milk price slightly decreased ketosis cost per case in primiparous cows by \$1.05. One standard deviation increase in feed price decreased the per-case disease costs by \$9.14 and \$29.77

in RP and LDA in primiparous cows, respectively. One standard deviation increase in replacement heifer price increased metritis, LDA, and ketosis costs per case by \$20.33, \$11.60, and \$4.91, respectively, in primiparous cows; 1 standard deviation increase in slaughter price decreased metritis and ketosis costs per case by \$13.53 and \$2.80, respectively.

In multiparous cows, 1 standard deviation increase in milk price increased the per-case disease costs of metritis, RP, LDA, and ketosis by \$6.85, \$27.34, \$60.33, and \$2.67, respectively (Table 9). One standard deviation increase in feed price decreased the per-case disease of RP, LDA, and ketosis by \$18.24, \$40.87, and \$1.73, respectively. One standard deviation increase in replacement decreased RP cost by \$8.01 per case in multiparous cows. One standard deviation increase in slaughter price increased the per-case cost of metritis, RP, LDA, ketosis, and hypocalcemia by \$13.06, \$20.01, \$15.33, \$13.14, and \$19.45, respectively, in multiparous cows.

Market prices consistently affected the total disease costs in both primiparous cows and multiparous cows. Higher milk prices would increase the disease cost and higher feed prices would decrease the disease cost. Higher replacement prices would increase disease cost in primiparous cows and have very small effects on multiparous cows. Higher slaughter price would decrease disease costs in primiparous cows while increasing disease cost in multiparous cows. Replacement price had a higher effect in primiparous cows than in multiparous cows, meanwhile slaughter price had the opposite effect. The reason for this was that the replacement price was only used in the first-lactation FDRPO calculation when a primiparous cow's market value switched from the replacement cow value to the slaughter value (Liang, 2013); however, slaughter price was used through the entire life span to calculate the cow's salvage value. The influence of increased milk and feed price was greater in multiparous cows than in primiparous cows (except mastitis) due to the higher milk production

Table 10. Change in each disease total cost with 1 SD increase in herd performance stochastic variable for primiparous and multiparous cows

Item	Primiparous cows			Multiparous cows		
	Rolling herd average milk production	PHC ¹	Age at first calving	Rolling herd average milk production	Pregnancy rate	Age at first calving
Mastitis	29.22	−11.05	−1.84	26.99	0	0
Lameness	−5.78	−2.99	0	7.68	0	12.09
Metritis	−3.90	−1.63	0	7.49	0	0
Retained placenta	0	−2.44	0	10.32	−6.66	−8.01
Left-displaced abomasum	10.27	−11.42	−7.00	25.52	12.28	0
Ketosis	−3.16	0	−0.69	1.33	3.46	0
Hypocalcemia	NA ²	NA	NA	1.92	2.80	0

¹PHC = product of heat detection rate and conception rate.

²Not applicable.

loss and greater discarded milk amount (if applicable). Moreover, the higher feed price could offset part of the cost of decreased milk production because of the related lower feed intake. Higher feed price reduced the cow's RPO value (Groenendaal et al., 2004; Bewley et al., 2010), which further reduced the total disease cost.

The epidemiological difference of each disease determined the sensitivity of market price on disease cost. The influence of milk or feed price was high if milk production-related effects (i.e., milk loss or discarded milk) were the largest contributors among all the detrimental effects caused by this disease. Similarly, the effect of the replacement and slaughter price would be greater in the total cost of a disease that had a high culling risk. Compared with mastitis, the replacement price and slaughter price had a greater effect on lameness due to the higher culling risk (Rajala-Schultz and Gröhn, 1999).

Herd Performance. The sensitivity analysis was conducted on 3 herd-performance factors: RHAM, PHC, and AFC. The effects of herd performance on the total cost of each disease are shown in Table 10. The PHC affected disease costs by changing the calving interval length and the related performance. The AFC changed the time to first lactation that resulted in a different feed intake and associated cost. The RHAM changed disease cost through influencing the daily average milk production, which affected the discarded milk costs, the RPO-based culling and cost of DO, and milk losses. Lacking the quantified milk loss data based on milk production level, the RHAM affected the milk losses by changing the saved feed value, which was calculated based on the daily feed efficiency.

Individual herd-performance factors had different effects on different diseases and parities. The effect of herd performance were very different in the multiparous cows compared with the primiparous cows, and might be explained due to the fact that multiparous cows were aging and approaching their maturity with

a better production. Another potential reason was that the early first optimal culling time appeared in the first lactation under 2015 market conditions. Disease costs of primiparous cows and multiparous cows reacted differently to herd-performance parameters because of the different stages on the RPO changing trend. Furthermore some diseases (i.e., RP and LDA) had larger influence on production and reproduction in the multiparous cows than primiparous cows.

One standard deviation increase in RHAM decreased the total costs of lameness, metritis, and ketosis, but increased the total costs of mastitis and LDA in the primiparous cows (Table 10); RHAM was related to discarded milk costs, milk losses, and culling cost. Mastitis and LDA had relatively greater portions of discarded milk value and decreased milk production value in total disease costs in primiparous cows; thus, the effects of RHAM were positive on both of the diseases. Greater RHAM decreased the cows' RPO before the first optimal replacement moment (Liang, 2013). The lower RPO value shrank the culling cost in primiparous cows. As a result, higher milk production decreased total costs of the disease that had a relatively higher culling risk and lower decreased milk production after occurrence. In multiparous cows, 1 standard deviation increase in RHAM increased the costs of all diseases.

One standard deviation increase in PHC decreased disease costs on primiparous cows. Increasing PHC from the baseline value (18%) could decrease the cost of DO in primiparous cows. In multiparous cows, PHC had no effects on mastitis, lameness, and metritis; increasing 1 standard deviation in PHC would decrease RP cost and increase LDA, ketosis, and hypocalcemia costs moderately. Age at first calving was tested in the model; however, the results showed its effects were very small (Table 10).

Compared with previous disease economic studies, our model included the variation in the cow and market factors, which enabled the model to estimate the flex-

ible disease cost under different conditions. Although LDA had the greatest costs in our study, considering the correspondent incidence, the monetary effect should not be overestimated on the farm level. One limitation of this model was that the interrelationships between diseases were not included due to the potential complexity of the disease correlations. In reality, the correlation between diseases could change disease incidence and affect the farm profit. The proportion of each cost category and the epidemiological sensitivity of total disease costs were more important than the actual number of disease costs.

Clinical disease costs estimated in our study are useful as average costs for future reference. In addition to the mean and standard deviation of disease cost, the sensitivities of herd performance and market price on disease costs are also essential for daily farm decision-making in practice. Disease costs vary differently on farms with different farm and market conditions, and decision-makers needed to adjust their decisions according to the cost sensitivity. Understanding cost sensitivity may help the decision-maker to be flexible with decisions about treatment or culling associated with disease costs in different situations.

CONCLUSIONS

Our model estimated the common dairy disease costs under the 2015 market conditions with flexible model inputs. Disease costs were expensive and influenced considerably by herd performance and market factors. Herd performance and market conditions were the most influential factors affecting total disease cost.

ACKNOWLEDGMENTS

The authors appreciate the financial support provided by Elanco Animal Health (Greenfield, IN) to support this research. The authors thank Matthew Borchers, Karmella Dolecheck, Elizabeth Eckelkamp, Lauren Mayo, Derek Nolan, Amanda Stone, I-Ching Tsai, Barbara Wadsworth Jones, and Maegan Weatherly (all from University of Kentucky) for their help in editing this manuscript.

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