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ESTIMATING THE ECONOMIC LOSSES FROM DISEASES AND EXTENDED DAYS OPEN WITH A FARM-LEVEL STOCHASTIC MODEL

Di Liang
University of Kentucky, di.liang@uky.edu

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Dr. Jeffrey M. Bewley, Major Professor

Dr. David L. Harmon, Director of Graduate Studies

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THESIS

A thesis submitted in partial fulfillment of the

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By

Di Liang

Lexington, Kentucky

Director: Dr. Jeffrey M. Bewley, Assistant Professor of Animal Science

Lexington, Kentucky

ABSTRACT OF THESIS

ESTIMATING THE ECONOMIC LOSSES FROM DISEASES AND EXTENDED DAYS OPEN WITH A FARM-LEVEL STOCHASTIC MODEL

This thesis improved a farm-level stochastic model with Monte Carlo simulation to estimate the impact of health performance and market conditions on dairy farm economics. The main objective of this model was to estimate the costs of seven common clinical dairy diseases (mastitis, lameness, metritis, retained placenta, left displaced abomasum, ketosis, and milk fever) in the U.S. An online survey was conducted to estimate veterinary fees, treatment costs, and producer labor data. The total disease costs were higher in multiparous cows than in primiparous cows. Left displaced abomasum had the greatest costs in all parities ($404.74 in primiparous cows and $555.79 in multiparous cows). Milk loss, treatment costs, and culling costs were the largest three cost categories for all diseases. A secondary objective of this model was to evaluate the dairy cow's value, the optimal culling decision, and the cost of days open with flexible model inputs. Dairy cow value under 2013 market conditions was lower than previous studies due to the high slaughter and feed price and low replacement price. The first optimal replacement moment appeared in the middle of the first parity. Furthermore, the cost of days open was considerably influenced by the market conditions.

KEYWORDS: disease economics, cost of days open, stochastic, farm-level, sensitivity analysis

Di Liang
Student Signature

Oct. 14th, 2013
Date

ESTIMATING THE ECONOMIC LOSSES FROM DISEASES AND EXTENDED DAYS OPEN WITH A FARM-LEVEL STOCHASTIC MODEL

By

Di Liang

__________Dr. Jeffrey M. Bewley

Director of Thesis

___________Dr. David L. Harmon

Director of Graduate Studies

_____________Date: Oct. 14th, 2013

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Growing up in a small city in southern China, animal agriculture was far away from my childhood. All by coincidence, I majored in Animal Science at China Agricultural University, where I found my interests in dairy cattle not surprisingly. Going with the flow, I decided to come to the U.S. and further study in dairy management. With the two-year graduate school experience in University of Kentucky, I harvested much more than I expected, as well as tears.

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FREQUENTLY USED ABBREVIATION

AFC = Age at the first calving

CDO = Cost of days open

DO = Days open

FDRPO = First day in lactation retention pay-off value

FORM = First optimal replacement moment

HDR = Heat detection rate

MNR = Marginal net revenue

NPV = Net present value

ORM = Optimal replacement moment

P1 = The first parity, the primiparous cows

P2 = The second and later parities, the multiparous cows

PR = Pregnancy rate

RHAM = Rolling average herd milk production

RPO = Retention pay-off

SD = Standard deviation

VWP = Voluntary waiting period

CHAPTER ONE

Literature Review

INTRODUCTION

Dairy health economics is essential for the dairy industry for helping decision-making and farm management. Health issues influence dairy cows productivity and associated profit. Previous studies have provided estimations about the impact of dairy health performance on dairy farm profit. This literature review covers the existing research methods and results in dairy health economics.

DAIRY PRODUCTION SYSTEM

The dairy production system contains three elements: resources, products, and people. As a ‘producing machine’ in the dairy production system, the dairy cow uses resources (i.e., feed, milking equipment, and labor) to produce dairy products (milk, meat, and calves) for people (consumers) (Dijkhuizen and Morris, 1997, Galligan, 2006). Resources determine the costs of the production processes and the output of the production system, which influence revenue (Figure 1.1). Because of disease control and herd management, the health performance of a cow influences production processes and leads to product variation (Dijkhuizen and Morris, 1997, Galligan, 2006). Healthy cows have a greater slaughter weight and are able to produce larger quantities of higher quality milk, indicating greater profits.

HEALTH PERFORMANCE EFFECTS ON THE DAIRY PRODUCTION SYSTEM

Different diseases have different effects. Whether the disease is infectious or not largely determines the effects. The influence of the non-infectious disease is on the individual level, however the infectious disease has a hazard for multiple animals (Dijkhuizen and Morris, 1997). Cow health influences the revenue of the dairy production system, altering biological mechanisms and productivity. The mechanism changes are always on the individual animal level and the productivity changes are on both the individual and herd levels.

Mechanisms Change

Disease affects dairy cows' mechanisms directly and indirectly. Dijkhuizen and Morris (1997) categorized the disease-caused mechanism changes into three classes: ingestion, feed digestibility, and physiological processes. Disease type determines the appearance of each mechanism change; not all the following effects show up in the same disease.

Effect on Ingestion. Most diseases reduce feed ingestion because of the pain during feed consumption and the physical difficulties in the tongue and limbs. The reduced feed intake (lost appetite) is different from the lower feed conversion efficiency. A depression in feed conversion efficiency leads to lower productivity even with normal feed intake; yet, the anorectic effect only reduces feed intake, without affecting feed conversion efficiency (Dijkhuizen and Morris, 1997).

Effect on Feed Digestibility. Disease barely influences digestibility. Much research has found that the lower feed conversion efficiency due to disease was not the direct cause of the productivity decrease (Dijkhuizen and Morris, 1997).

Effect on Physiological Process. Disease influences many physiological processes including respiration, nutrient metabolism, and manure excretion. The most fundamental change is in protein metabolism. The protein degradation is greater than protein synthesis to help the immune system. Furthermore, the disease-caused insufficient feed intake will reduce the protein supply and limit the lower-priority metabolic processes (i.e., body reserve and muscle growth). Moreover, the toxin (i.e., pathogenic toxin) impairs the physiological process, such as the digestive tract or organic matter digestibility (O'Kelly and Kennedy, 1981, Dijkhuizen and Morris, 1997).

Productivity Changes

Management and disease affect the health performance of dairy cows; yet, the interaction between the disease and management also changes the productivity. In some cases, good management (i.e., effective vaccines or clean housing) could help with disease prevention and recovery. On the other hand, disease affects the cow's health condition, which determines the efficiency and progress of management. Furthermore, appropriate management could reduce disease costs. For example, quarantining the sick cow with an infectious disease could prevent the pathogen from spreading to other healthy animals. Thus, management could influence animal health performance by mitigating or exacerbating diseases' detrimental effects (Galligan, 2006).

Productive and Reproductive Performance. In the dairy production system, the amount of product and the corresponding market price determines the product value (Galligan, 2006). Milk, meat, and calves are the three major outputs. Product quality partially influences the dairy product price.

Disease always decreases the quantity and quality of milk production through metabolic changes, including energy metabolism, mammary gland physiology, or the immune system (Galligan, 2006). Many studies found that disease could slow down the growth rate of dairy cows. Animals' slaughter value depends on meat quality and slaughter weight. Slaughtered animals may have lower meat quality because of the disease (i.e., lesion), in terms of a lower ratio of meat to fat or protein content (Dijkhuizen and Morris, 1997). Some diseases would make meat less attractive for consumers, which also decrease slaughter value. In addition to the direct production value from the dairy production system, health performance also influences byproducts, such as the capacity for work and manure for fuel and fertilizer (Dijkhuizen and Morris, 1997).

Reproductive performance is a crucial factor for the dairy farm because of the vast impact of reproductive performance on the dairy production system (De Vries, 2006b, Giordano et al., 2012). Reproductive performance has a long-term effect on the entire lactation, including length of calving interval, milk production, and breeding costs. Dairy diseases could affect reproductive performance, resulting in a longer calving interval, lower average daily milk production, and fewer calves (Fourichon et al., 2000, Meadows et al., 2005, Inchaisri et al., 2010). Reproductive performance is also an essential risk factor in the culling decision (Beaudeau et al., 1995). In addition, disease-related poor reproductive performance (i.e., the extended days open or higher abortion risk) can lead to fewer newborn calves during a certain period, which will reduce the revenue from selling calves and the availability of replacement cows (Boichard, 1990).

Pre-optimal Removal. Pre-optimal removal from the herd has two categories: on-farm death and pre-optimal culling. Typically, research has demonstrated that longer herd productive life would increase economic benefits (Dijkhuizen and Morris, 1997). Disease or management failure could increase the risk of fatality (Galligan, 2006). On-farm death terminates the productive life without any residual value (i.e., slaughter value).

Culling is different from on-farm death. Culling depends on the manager's decision according to the current performance and future value of an individual cow (Lehenbauer and Oltjen, 1998, Dhuyvetter et al., 2007). Each dairy cow has an optimal time to achieve the maximal economic profit. However, disease or management failure would reduce the maximal profit because those failures affect productive and reproductive performance and the associated potential future value (Galligan, 2006). Culling is preferred when the future value of the current cow is lower than the cost of replacing with a young replacement cow. Death or pre-optimal culling removes the cow out of the production system, ends her productive life, and reduces the total profit (Groenendaal et al., 2004).

Input Costs Change. Most of the changes in the input costs due to health issues are from the veterinary fees, labor costs, and treatment costs. In regard to management, the main input cost is to establish a proper management that will work better with a specific farm. (Galligan, 2006).

Herd Productivity Level. Disease alters the normal productive performance. If the producer uses genetic selection, the disease-influenced productive performance reduces expression of full genetic potential. In addition, some diseases would shorten the productive life so that the cow is removed before the manager observes her genetic merits. The poor health performance, especially poor reproduction, could reduce the herd size through generations.

DAIRY HEALTH ECONOMICS

Dairy health performance could change the output from the dairy production system in terms of quality and quantity of production. Moreover, consumers also value good health performance (Dijkhuizen and Morris, 1997). Disease has a negative effect on the conversion process from resources to production, or services from livestock animals. Moreover, disease could decrease consumers' expected value for the output from the animal production system.

Health economics has not been a traditional topic in the core of veterinary science or animal science until recently when people began paying more attention to disease hazards. Animal health economics research started in the 1960's and the early 1970's when governments started eradication programs for some livestock diseases and began recognizing the importance of disease economics (Rushton, 2008). The economic impact of animal disease had seldom been under the spotlight. Veterinarian services did simple cost and benefit analyses using records. Limited by sample size and oversimplification, these analyses was not efficient enough for either macroscopic estimation or dynamic attribution of animal agriculture.

Rushton (2008) summarized the history of animal health economics. People had been in doubt whether animal health economics was a discipline for a long time. However, now, a group of researchers, consultants, and veterinarians are working on the economic impact of diseases. Peter Ellis and Heinz Konigshofer composed the first official document about animal health economics in the mid-1960's based on the previous published animal health yearbook from FAO/WHO/OIE (Food and Agriculture Organization/ World Health Organization/ International Epizootic Office). During the following years, Bill Macallon from USDA (United States Department of Agriculture) estimated several livestock disease costs using more advanced and comprehensive methods. Recently, the majority of the work is being conducted in North America and Europe.

Different from traditional animal health economics, modern health economics emphasizes the interaction between disease and management, and considers multiple technical issues (Dijkhuizen and Morris, 1997). Animal health economics began rapidly developing in the 1980's due to the quick growth in global livestock trade (Otte and Chilonda, 2000).

Dairy health economics focuses on the economic impacts of dairy diseases on the dairy industry based on animal health economics principles. Health issues change dairy cows' performance, which affects the current profit and future value. The economic assessment quantifies the effects of health issues into monetary units; yet, the conservative measurement uses the physical units, for example, milk production loss, or reduced daily weight gain (Otte and Chilonda, 2000). Disease influences profitability through both direct and indirect effects (Dijkhuizen and Morris, 1997, Galligan, 2006).

The direct effect includes visible loss (death, milk production decrease, and slow growth) and invisible loss (poorer reproductive performance, herd demography change, and lower feed conversion efficiency). The indirect effect includes revenue decreases (lower production quality and shorter productive lifetime) and additional costs (veterinarian and drug costs and labor costs). Furthermore, health conditions influence culling policies because of the changes in potential value. In addition, the external factors such as market conditions and government policies also influence the profit of a dairy farm (Seegers et al., 1994, Seegers et al., 2003). Furthermore, the total cost varies among regions, farms, and the animal's purpose for the same disease. For example, both beef and dairy cattle could get mastitis; however, the cost of mastitis in beef cattle is much lower than dairy cows because milk is not the major production from beef cattle.

The total disease cost (C) is the sum of loss (L) from the decreased production and expenditure (E) in the disease management and controlling. The relationship between production loss (L) and control expenditure (E) is not linear in most cases. The decreased rate of production loss from disease control (per unit) is reduced as disease control inputs increase, in agreement with the law of diminishing marginal returns (McInerney et al., 1992).

The mission of dairy health economics is helping health related decision-making on dairy farms, including estimating disease costs, optimizing replacement moment, and evaluation of disease management economics.

Research Methods in Dairy Health Economics

The two main research methods in dairy health economics are the positive and normative approaches (Dijkhuizen and Morris, 1997). The positive approach is also known as ‘empirical modeling’, which analyzes data from observation or designed experiments, such as using DHIA (Dairy Herd Improvement Association) data to estimate milk loss due to mastitis, or evaluate culling risk due to reproductive failure. When NAHMS (National Animal Health Monitoring System) began in the mid-1980’s to collect animal health information, it allowed researchers access to a large national animal health database, enabling researchers to estimate disease impacts. On the other hand, modeling and simulation are essential techniques in the normative approach, which builds models based on results from empirical studies and sets proper further assumptions for modeling-simulation (Seegers et al., 2003). With advanced modeling and simulation techniques, the normative approach is currently the major method for estimating the economic impact of diseases.

To select a proper analysis method for dairy health economics, the first step is to clarify whether the economic analysis should be at the individual, farm, national, or global level. The economic analysis becomes gradually more complex as the viewpoint shifts from the individual to global level. Dijkhuizen and Morris (1997) pointed out that the research method (analyzing or modeling) could change the estimated costs of disease dramatically. Seegers et al. (1994) preferred farm-level modeling because the dairy managers always made decisions at the farm level. Producers’ farm-level decisions aggregate the basic biology facts from the individual cows. For example, when dairy producers are making culling decisions on mastitis-infected cows, they have to consider not only the value of the individual cow, but also the somatic cell count (**SCC**) impact of this cow on the whole-farm bulk tank somatic cell count (**BTSCC**) and changing milk prices.

Cost and Revenue. Cost and revenue are the essential key points and foundation in the dairy health economics. In the dairy industry, the revenue is from milk sales and slaughter. Additionally, some farms sell their extra heifers to keep their herd size stable and make extra profit. On the other hand, the cost in the dairy production system includes feed costs, labor costs, veterinary fees, and replacement costs. The dairy production system is dynamic and the market conditions fluctuate. Thus, the economic analysis should consider the timing of costs and revenues. A common method is adjusting the future cash flow for a discount rate to the current base, allowing the economic comparison and calculation across time (Brealey and Myers, 2000, Galligan and Groenendaal, 2001). Present value (PV) is a common used term to represent current value of future costs or revenue.

$$PV = \frac{FV_t}{\left(1 + \frac{r}{100}\right)^t}$$

Where,

FV_t=the future costs or revenue at time t,

r=discount rate, which is the return of an alternative opportunity

t=the time point in the future

To support decision making in the dairy production system, net present value (**NPV**) is widely used as an extension of PV. Net present value is the sum of the initial investment and PVs across time (Galligan and Groenendaal, 2001), which expresses the difference between the total future net revenue and the current investment amount on the current base (Dijkhuizen and Morris, 1997).

$$NPV = FV_0 + \sum \frac{FV_t}{(1+r)^t}$$

Where,

FV_0=initial investment cost,

FV_t=the future costs or revenue at time t,

r=discount rate, which is the return of an alternative opportunity,

t=the time point in the future, (Galligan, 2006)

Net present value is a common profitability metric of an investment. If NPV is greater than zero, the investment will be profitable in the future, and vice versa.

The annuity value, which adjusts NPV to constant annual revenue, enables compare profits of different management or investment options in same period.

$$AnnuityValue = \frac{NPV}{\frac{1}{r-1} \Big/ [r*(1+r)^t]}$$

Where,

NPV=net present value of calsh flow over t periods

r=discount rate per period,

t=the time point in the future, (Galligan, 2006)

Model and Simulation in Dairy Health Economics. For any resource allocation problem, the equimarginal principle is always the basic and fundamental rule: “A limited input should be allocated among alternative used in such a way that the marginal value products of the last unit used on each alternative are equal” (Kay et al., 1994). The production function curve, which plots the relationship between the output and input, shows the same trend that the output starts decreasing when inputs exceed the optimal point. The law of diminishing marginal returns explains the phenomenon that the marginal production value will eventually start decreasing as additional units of input variables are used (Figure 1.2). Particularly in dairy health economics, the goal is seeking the optimal input point, which indicates the highest profit.

Modeling and simulation have been widely used in disease control, nutrition, reproduction, and genetics in animal science research. As dairy health economics have become increasingly important in recent decades, people have wanted to evaluate the impact of disease and related managing strategies. A great number of modeling techniques have been adopted to provide information and help dairy producers and consultants make better decisions about disease management (Bennett, 1992). Previous studies have claimed that modeling described the behavior and performance of the dairy production system and the impact of diseases by using a set of mathematical equations

(Brown et al., 1981, Bennett, 1992, Bethard, 1997). Mertens (1977) stated that simulation enabled models to take the dynamics of the dairy production system into consideration. Dijkhuizen and Morris (1997) suggested that modeling was the essential tool to understand economics in the dairy production system. Computerization is a key step in the dairy health management, which initially involve data management. Computers started helping with the diseases data collection and management in the 1980s and became an essential tool in dairy health decision making in the early 1990's (Bennett, 1992). With the rapid development in computer hardware and software, researchers began using more advanced and normative modeling methods in the dairy health economics research. Simulation is an essential part in the normative modeling approach, which was an artificial representation of a real-life system including several models with their assumptions (Bethard, 1997). People claimed that simulation should be the terminal joining of modeling research to practical fieldwork (Brown et al., 1981, Bennett, 1992, Bethard, 1997). With computer simulation, creating and validating a large-scale model becomes doable, including Markov Chain Theory, stochastic programming, or dynamic process.

Specified in the dairy production system, computer modeling and simulation are popular tools used in optimizing culling decisions, estimating losses due to reproductive failure, and projecting the disease development with associated costs. Computer-based modeling is useful and helpful for on-farm decision making because a computer model is considered as a simple representation of the dairy production system (Jalvingh, 1992). The dairy production system is different from other economic systems, the cow's lifetime length is not deterministic, and depends on other decisions (for example, culling policies). Culling decisions depend on the performance of both the current cow and replacement cow. The culling principle in dairy farming is replacing the current cow with a young heifer when revenue of the current cow was equal to or lower than maximal annuity of the potential replacement (Dijkhuizen and Morris, 1997).

Economic Consequences of Reproductive Performance

The ultimate goal of a dairy farm is to maximize total profits. Breeding and culling decisions play a critical role in determining farm profitability (Giordano et al., 2012). The culling decision is profit oriented (Monti et al., 1999). Reproduction, milk production, and disease are the top culling risk factors (Millan-Suazo et al., 1989). Replacing the current cow with a new cow can be considered an investment in future farm profitability. Culling decisions should rely on economic principles instead of biological phenomena (Lehenbauer and Oltjen, 1998, Groenendaal et al., 2004). Within herd conditions and input and output prices determine the current and future values of a cow, so culling decisions are also tied to internal and external factors (Dhuyvetter et al., 2007).

The marginal net revenue (**MNR**) approach is often used to model the dairy cow culling decision-making process (Dijkhuizen and Morris, 1997, Groenendaal et al., 2004). With this approach, the expected future profit of the current cow is compared with the expected profit from a replacement cow. The retention pay-off (**RPO**) value is used to compare the future economic profit across time and conditions. The RPO value is widely used to determine optimal culling time. A negative or zero retention pay-off indicates that the current cow should be replaced immediately.

Days open (**DO**) is the major indicator of calving interval, defined as the time between successive calvings. Considerable research efforts have focused on estimating the effects of extended DO on farm profitability. In general, the economic losses due to extended DO increases with the increasing DO. Previous studies have revealed the effects of extended DO on dairy farm profitability through milk loss, culling risk, and associated financial losses. The optimal calving interval has been described as 12 to 13 months to maximize average daily milk production and produce the most replacement cows for the herd (Schmidt et al., 1988). Holmann et al. (1984) reported that a 13-mo CI resulted in maximal net revenue using an empirical analysis. Management practices centered around conception rate (**CR**), heat detection rate (**HDR**), and voluntary waiting period (**VWP**) have a large influence on days open (Meadows et al., 2005). Poor reproduction leads to a higher culling rate and fewer newborn calves and reduced replacement cow availability (Boichard, 1990, Groenendaal et al., 2004, Meadows et al., 2005).

Optimal DO varies by milk production level, parity number, and the availability of replacement cows (Weller et al., 1985, Boichard, 1990, Marti and Funk, 1994, Plaizier et al., 1998, Groenendaal et al., 2004, Meadows et al., 2005, Inchaisri et al., 2010). Primiparous cows need longer days open than multiparous cows to reach maximal production (Weller et al., 1985). Boichard (1990) and Inchaisri et al. (2010) concluded the net economic loss due to extended DO was lower in the primiparous cows than the multiparous cows; whereas Groenendaal et al. (2004) concluded the opposite relationship. Marti and Funk (1994) reported an antagonistic relationship between production and reproduction in that the high-producing cows always had longer DO than the low-producing cows. Yet, a longer DO is more acceptable for a high-producing cow because the high milk production elevates the future profit (Groenendaal et al., 2004), which leads to a higher RPO value and associated culling cost. Cost of DO is considerably higher in the low production cow than average cow, and CDO is lower in the high-producing cow than the average one (Boichard, 1990, Groenendaal et al., 2004, Inchaisri et al., 2010). The improvement of reproductive performance is more important for a cow with poorer reproductive performance and lower production than an average or higher production cow (Oltenacu et al., 1981, Plaizier et al., 1998). Culling rate also impacts the optimal DO because of the changes in the availability of replacement cows (Groenendaal et al., 2004).

Although the high production compensates for the lower reproduction to some degree, the effect of lower fertility is still among the top risk factors of dairy culling (Beaudeau et al., 1995). Gröhn et al. (1997) claimed that culling risk dropped considerably as soon as the cow became pregnant. Rajala-Schultz and Gröhn (1999) reported that a cow with a 305 DO in one lactation had 12 times higher culling risk compared with a cow conceiving within 150d post-parturition.

Several models have quantified the relationships among CDO, CR, and market prices. Higher CR decreases CDO; whereas a higher milk or feed price increases CDO (Boichard, 1990, Plaizier et al., 1998). Cost of DO varies among different studies: $0.50 to $2.00 per d (Holmann et al., 1984), $0.10 to $1.60 per d (Groenendaal et al., 2004), $1.37 per d in 160d DO scenario (Meadows et al., 2005), and $3.19 to $5.14 per d (De Vries, 2006a).

DISEASE ECONOMICS

Common dairy diseases include (but are not limited to) mastitis, lameness, metritis, retained placenta (**RP**), left displaced abomasum (**LDA**), ketosis, and milk fever (**MF**). Robust epidemiological studies have focused on the impacts of disease on dairy cow performance, especially for mastitis, lameness, and reproductive failure that are regularly considered as the most expensive health issues in the dairy industry (Kossaibati and Esslemont, 1997, Juarez et al., 2003).

Mastitis

Mastitis is mostly caused by pathogenic bacteria (*Staphylococcus aureus, Streptococcus agalactiae, etc.*) invading and multiplying in the mammary gland (Harmon, 1994). Mastitis has two stages: subclinical and clinical mastitis. The subclinical mastitis (**SCM**) results in elevated SCC in milk, milk production loss, and milk composition change. Clinical mastitis (**CM**) always has visible symptoms such as clots in milk, swelling in the udder, or fever (Philpot and Nickerson, 2000).

Mastitis is expensive in the dairy industry. Many studies have discussed the monetary impact of mastitis on the dairy farm profit (Seegers et al., 2003, Halasa et al., 2007). The total cost of CM ranged from €102 ($135) to €287 ($379) per case and the prevalence varied among pathogen type, management, seasons, milk production level, and other factors (Halasa et al., 2007).

Early mastitis economics studies used the SCC as the criterion to interpret the severity of mastitis. Recently, the mastitis studies prefer estimating the correspondent mastitis costs specified by pathogen type. Houben (1995) divided total mastitis economic effects into three categories: reduced milk revenue, costs of treatment, and pre-optimal disposal. Halasa et al. (2007) categorized the economic effect of mastitis into ten classes: milk production loss, drugs, discarded milk, veterinary service, labor, production quality decrease, material and investment, diagnostics, culling, and cost from elevating risk of other interrelated diseases.

Health Performance. Mastitis affects milk production by destroying the alveoli in the mammary gland, where milk is produced (Harmon, 1994). In addition, the inflammation in mammary gland would change the milk component such as SCC, sodium, potassium, or casein content. Moreover, the mastitis-infected cows showed a shorter productive lifetime, higher pre-optimal removal risk, and extended DO (Seegers et al., 2003).

Milk Production. The largest economic effects of mastitis was the milk production decrease (Seegers et al., 2003), which also varied among production levels, countries, and regions (Halasa et al., 2007). Abundant studies have been conducted on milk production decrease due to mastitis and associated economic effects. The production loss includes both the quantity and quality changes. The difference is that the milk quality change affects the selling price, while the milk quantity changes the amount of salable milk. In some cases, mastitis generates discarded milk due to the antibiotic used for treatment.

Clinical and subclinical mastitis have different effects on milk production. The average milk production decrease of clinical mastitis was 375 kg (5% of the lactation level, Seegers et al., 2003). On the other hand, the SCM production decrease was considered log-linear related with SCC (Halasa et al., 2007). Hortet and Seegers (1998) summarized a 0.5 kg daily milk production decrease with two-fold increase in crude somatic cell score (**SCS**, 0.4 in primiparous and 0.6 multiparous cows). A recent estimation stated that milk loss due to high SCC in the multiparous cow was greater than the primiparous cow (Hand et al., 2012). High SCC milk loss was correlated with milk production level and SCC in milk; high-producing cows lost more milk than low-producing cows. Moreover, the lactation milk loss varied from165 kg to 919kg, with SCC increasing from 200,000 to 2,000,000 cells/mL (Hand et al., 2012).

Reproductive Performance. Cullor (1990) first explained that mastitis might have a negative effect on reproductive performance because of the harmful effects from the mastitis pathogen endotoxin. Mastitis prolonged the inter-estrus intervals (Moore et al., 1991) and influenced the time of the following breeding actions after the diagnosis (Santos et al., 2004). Clinical mastitis occurring before the first AI service prolonged the period length between calving to first service; CM occurred between first AI to pregnancy increased the number of artificial insemination needed for conception and the days until conception (Barker et al., 1998). Schrick et al. (2001) found the subclinical mastitis had similar effects on reproduction. Risco et al. (1999) analyzed the relationship between the mastitis timing and abortion. These results showed a higher abortion risk if mastitis occurred during the first 45d in gestation than in the following 90 days.

Mortality and Culling Risk. Mastitis affected longevity in both the short-term and mid-term (Seegers et al., 2003). For the short-term effect, the major effect was fatality risk of severe CM infections. The lethality varied among different pathogens. The pathogens with the highest risk of fatality were Gram-negative pathogens, such as Escherichia coli, Klebsiella sp., and Staphylococcus aureus (Seegers et al., 2003). The mid-term effect was the elevated culling risk due to mastitis. Cows with mastitis have higher culling risks than the healthy cows in general (Rajala-Schultz and Gröhn, 1999a). Bar et al. (2008a) analyzed the effects of repeated CM episodes on mortality and culling risk after diagnosis. Clinical mastitis, either the first or the repeated episodes, increased mortality risk after occurrence. In addition, CM could increase the culling risk in the following two months after diagnosis.

Economic Loss. According to numerous studies in mastitis economics, the variation of mastitis cost was very large (Huijps et al., 2008). The variation was generated by different assumptions of pathogen type, lactation stage, and the occurrence of infection. Schepers and Dijkhuizen (1991) reviewed mastitis cost results published since 1970, including research conducted in the U.S., the Netherlands, Canada, and the U.K. Total mastitis costs per cow was \$295, NLG125 (\$74), \$102, and \$40 per case, respectively. Several regional studies analyzed the recorded data from NAHMS and estimated the costs of mastitis. A Michigan study (Kaneene and Scott Hurd, 1990) estimated the total costs of CM at \$35.54 per cow per year, including \$4.54 for prevention per cow per year. Sischo et al. (1990) valued the mastitis costs in California, including the disease occurrence, costs of prevention, and miscellaneous costs. The authors found the majority of prevention costs were from drug usage. An Ohio study (Miller and Dorn, 1990) showed the costs of CM were \$45.22 ± 2.06 per cow per year based on NAHMS data.

Several studies were conducted in Europe during the same time. Kossaibati and Esslemont (1997) calculated the cost of CM in England at £153.28 (\$262.41) per affected cow per year. Fourichon et al. (2001) also studied the dairy farm health control costs in western France. The costs of udder disorder prevention were €26.76 ($31.69) per cow per year. Wolfová et al. (2006) in the Czech Republic also estimated the direct CM costs, including the cost of discarded milk, drugs, veterinary service, labor, and extra maintenance costs for milking equipment and antibiotic usage. The range of average mastitis costs was from €43.63 ($51.67) to €84.84 ($100.47) per cow per year; the total CM cost increased by €62.60 ($74.13) per cow per year with one SD increase in the mastitis prevalence.

Yalcin (2000) compared the costs of SCM between the low (<250,000 cells/mL) and high (≥ 250,000 cells/mL) BTSCC levels in Scotland. For all the herds, the average SCM cost was £140 ($226) per case. Milk production decrease, control and prevent expenditures, and culling costs were the top three cost categories. In the high BTSCC herds, the cost was £217 ($351) per case; in the low BTSCC herds, the cost was £68.90 ($111.40) per case. Milk production decrease was the greatest component in both BTSCC categories. The authors demonstrated that SCM was responsible for most of the economic losses, and milk production reduction was the major mastitis cost, which varied with the level of mastitis in a herd. When mastitis was highly prevalent with a high BTSCC, the milk quality penalty shared a large portion of total mastitis costs.

Dynamic programming (**DP**) algorithms (with Markov processes) are widely used to simulate disease development and find optimal solutions for health issues. Several researchers have adopted DP in mastitis economics. Yalcin and Stott (2000) estimated the economic impact of three high SCC control procedures via a DP model; Stott et al. (2002) also used the same technique for replacement decisions of *Staph. Aureus* SCM. Houben et al. (1994) built a DP model with a multi-hierarchy Markov process, which included more than seven million ‘states’ to describe cow’s condition, to optimize replacement time for cows with CM. In this model, the culling loss due to CM was $83 per cow per year.

Huijps et al. (2009) estimated the costs of early-lactation heifer mastitis costs with a stochastic model. The model simulated the development of heifer mastitis in the early lactation. Returning back to a healthy status, developing into CM with visual symptoms, or staying in SCM stage were the three options for a cow with early-lactation high SCC. The costs of milk production decrease, discarded milk, veterinarian fees, drug, culling, and labor were included in the total costs of CM and SCM. Only milk production loss and culling cost in the early lactation were included in the total costs if the cow was cured. The total heifer mastitis costs were €31 ($43) per, €13 ($18) from the early-lactation elevated SCC; €13 ($18) from the following CM occurrence; and €5 ($7) from the following SCM occurrence.

A series of studies have been conducted in Cornell University in the late 2000’s, focusing on the production (milk production, mortality, and culling) effect of CM and economic impacts of CM using a DP model (Bar et al., 2007, 2008a, Bar et al., 2008b, Bar et al., 2008c, Cha et al., 2011). The average cost of CM was $71 per cow per year ($179 per case), in which the highest loss was from milk production decrease. The higher milk price, milk production level, replacement price, and pregnancy rate would increase the total CM costs positively (Bar et al., 2008b). The economic impact of CM treatment and prevention strategies were also discussed (Bar et al., 2008c). The costs of CM varied across time during productive life; the CM episode number was considered as well. As indicated above, the CM costs could be influenced by milk production level, same as its associated treatment and breeding decisions. A low producing cow with CM infected was recommended to be replaced, even during pregnancy; but a high producing cow was suggested to be treated if infected (Bar et al., 2008c).

Cha et al. (2011) estimated the CM costs, which were classified into three categories: Gram-positive (*Streptococcus* spp., *Staphylococcus aureus*, and *Staphylococcus* spp.), Gram-negative (*Escherichia coli*, *Klebsiella* spp., *Citrobacter* spp., and *Enterobacter* spp.), and others (*Arcanobacterium pyogenes*, *Mycoplasma* spp., *Corynebacterium bovis*, *Pseudomonas* spp., and yeast). Total CM costs were summarized into several categories: treatment cost (include drug costs, labor, discarded milk, culturing costs), fertility decrease, milk loss, and incidence of pregnancy. The authors also conducted sensitivity analysis on different kinds of CM cost to see the relationship with milk price, replacement price, and pregnancy rate. The results showed that the per-case costs of gram-negative CM was $211.03, followed by the gram-positive CM at $133.73, and the other pathogen caused CM were $95.31. In the gram-positive and other pathogen caused CM cases, the highest portion of the total costs was from the treatment costs (51.5% and 49.2%, respectively). The milk loss was the greatest contribution to total costs of gram-negative caused CM case (72.4%). The sensitivity analysis showed that the milk price, replacement price, treatment costs, mastitis incidence, and pregnancy rate all influenced the total CM costs with different impacts. Results showed that all CM costs increase or decrease with a higher or lower milk price, replacement price, treatment costs, and mastitis incidence; however, the correlation with pregnancy rate was the opposite.

A more recent study assessed the costs of pathogen-specific mastitis in Denmark (Sørensen et al., 2010), using SimHerd (Østergaard et al., 2005). The costs ranged from €149 ($213) to €570 ($816) per case. The highest cost was from *Staph. aureus* (€570, $816), followed by CNS (€380, $544), unspecific mastitis pathogenic (€231, $330), *Escherichia coli* (€206, $295), and the lowest were *Streptococcus dysgalactiae* and *Streptococcus uberis* (€149 ($213) and €149 ($213), respectively). An earlier Danish study also calculated the costs and benefit of pathogen-specific mastitis control using the same model (Østergaard et al., 2005).

Those results listed above all focused on the cost of mastitis. However, many other studies studied the costs and benefits of mastitis management strategies, as reviewed by Halasa et al. (2007). McInerney et al. (1992) described the cost and benefit of disease control, using mastitis as an example. Authors also explained the economically optimal level of disease cost where the expenditure on disease control was most effective. They found the minimal cost of mastitis (defined as SCC > 500,000 cells/mL with pathogen presence) with optimal preventive input was £3,006 ($5,633) per year for a 100-cow herd.

Lameness

Lameness is a common disease in the dairy industry. Lameness is the third most expensive dairy disease, following mastitis and reproductive failure (Juarez et al., 2003). Lameness has a very high incidence, even in well-managed farms (Sanders et al., 2009). The prevalence of lameness in the U.S. dairy herd was similar with British data (Esslemont, 1990); the U.S. average prevalence in the freestall housing is around 25%, with a large variation (Cook, 2003, Espejo et al., 2006, Sanders et al., 2009). The prevalence ranged from 1.8% to 39% with the median at 7% according to Kelton et al. (1998). Lameness was a multifactorial clinical foot disorders condition (Sanders et al., 2009, Bruijnis et al., 2010). The major causes include infectious agents, laminitis, injury, or claw lesions. Lameness was the result of both cow factors (i.e., diet, milk production, or under-conditioning) and environmental conditions (i.e., housing type, floor type) (Sanders et al., 2009).

Health Performance. Lameness has a negative effect on herd productivity, welfare, and economics on dairy farms (Cha et al., 2010). The lameness risk was higher in multiparous high-producing cows due to the high metabolic stress and poorer hooves health condition with aging (Barkema et al., 1994, Seegers et al., 1998, Warnick et al., 2001, Juarez et al., 2003).

Milk Production. The influence of lameness on milk production was not clear. Some studies found lameness would decrease milk yield (Rowlands and Lucey, 1986, Warnick et al., 1995, Rajala-Schultz et al., 1999, Warnick et al., 2001); yet, another study conducted by Dohoo and Martin (1984) suggested that milk production of lame cows were greater than the healthy ones. Several other studies found the impact of lameness was not significant or simply negative on milk production. The effect depended on other variables, such as season or measuring time (Sanders et al., 2009).

Reproductive Performance. Many previous studies have demonstrated that lameness reduced the fertility performance in the dairy cows. Barkema et al. (1994) found that lameness prolonged the interval from calving to first service and CR at first service. Some U.S. studies (Sprecher et al., 1997, Hernandez et al., 2001) also found that lame cows had a longer calving period and a greater number of breeding trials before conception. In an earlier U.S. study (Lee et al., 1989), the authors found that the lame cow had 28d longer DO, compared to the healthy one. Researchers have explained the hidden mechanisms. Some studies suggested that lameness could reduce the mounting activities, which influenced heat detection or observation (Lucey et al., 1986, Collick et al., 1989). Some other studies explained it from the nutrition aspect that lameness decreased body condition, which associated with a negative energy balance and finally resulted in a poor fertility performance (Miettinen, 1991, Tranter and Morris, 1991, Ruegg et al., 1992). The third reason may due to the internal hormone disorder, which was firstly caused by the pain or stress due to lameness, then increased the blood cortisol level and inhibited luteinizing hormone surge (Echternkamp, 1984, Nanda and Dobson, 1990). Considering both lower milk production and fertility performance, genetics may also play a role in a changed dairy cattle production system because of lameness (Berger et al., 1981).

Mortality and Culling Risk. Lameness affects culling decisions for several reasons and is one of the top risk factors for culling. Collick et al. (1989) analyzed recorded data from 17 dairy herds in England, and the results showed that lameness had a significant effect on culling risk. Milian-Suazo et al. (1988) found that lameness would increase the involuntary culling rate soon after diagnosis. In addition, researchers also suggested that lameness culling highly depended on the time of diagnosis (DIM or lactation stage) or pregnancy status. Lameness in early lactation resulted in higher culling risk (Dohoo and Martin, 1984). A series of studies conducted by Rajala-Schultz and Gröhn (1999a), b), c) adjusted lameness culling by milk production and pregnancy status. They found lameness increased culling risk throughout the entire lactation (Rajala-

Schultz and Gröhn, 1999a). Even after adjusting for milk production level and pregnancy status, the culling risk was still higher than control cows, but lower than not considering milk production (Rajala-Schultz and Gröhn, 1999c). Several studies found no significant increase in culling risk due to lameness, explained by the complexity of situation. Two French studies (Beaudeau et al., 1994, Beaudeau et al., 1995) failed to find a significant effect of lameness on culling risk under a quota system. Barkema et al. (1994) found a lower culling rate in lame cows than healthy ones in 13 Dutch farms. The authors believed that producers chose to tolerate lameness because of their greater milk yield.

Economic Loss. Several studies estimated the costs of lameness using positive approaches. Kossaibati and Esslemont (1997) reported the costs of common dairy diseases in England. In this study, the lameness costs included treatment costs, labor, discarded milk, reduced milk yield, increased culling risk, extended CI, veterinarian service fees, and extra services. The total costs were £246.22 ($421.53) per average case, £212.60 ($363.97) per digital lameness case, £112.80 ($193.11) per interdigital lameness case, and £391.80 ($670.76) per sole ulcer case. The poor reproductive performance, higher culling risk, and lower marketable milk production were the main reasons for lameness costs.

Enting et al. (1997) calculated the costs of lameness in the Netherlands with a partial budget model. The total costs were summarized as production decrease, longer CI, lost future income, idle production factors, treatment costs, labor costs, decreased slaughter value, and increased occurrence of other diseases. The total costs were NLG229.79 ± 103.30 ($132.43 ± 59.53) per lame cow per year.

In the U.S, a recent evaluation of lameness was $469 per case (Guard, 2008), including the costs of death, culling, veterinarian service and drugs, discarded milk, milk loss, delayed conception, and labor.

With computer simulation (normative modeling approach), researchers made new estimations of lameness costs in the U.S. and Europe. Ettema and Østergaard (2006) used the SimHerd model to calculate the costs of lameness control and prevention in Denmark. The result was €192 ($227) per case with the average Danish dairy condition, and the milk yield reduction due to lameness was the most influential factor on lameness costs.

In the Netherlands, Bruijnis et al. (2010) used a dynamic stochastic model to estimate lameness costs. This model simulated the development of foot disorder, including several different lameness types. This model was dynamic with lameness development in dairy cattle, and the development was divided into three stages: healthy, subclinical or clinical foot disorder, and cull or alive. The total costs were €75.37 ($89.25) per cow per year, including €24.03 ($28.46) for subclinical lameness, and €51.34 ($60.80) for clinical lameness. Among several lameness types, digital dermatitis was the most expensive type at €23.34 ($27.64) per cow per year. The milk production losses and discarded milk were the largest two portions. Probabilities of contracting and recovering from foot disorders were the top two influencing cow factors.

Cha et al. (2010) used a dynamic programming model to value the cost of different types of lameness in the U.S. The average costs per case were $177.62, regardless of the lameness types. The average costs of a sole ulcer, digital dermatitis, and foot rot were $216.07, $132.96, and $120.70 per case, respectively. The authors also found the costs of lameness were greater in the younger cows compared to the older ones;

similarly and the costs were greater in the high-producing cows compared with the average ones. However, among those low-producing cows, the costs were greater for the pregnant cows, compared to the open ones.

Metabolic Diseases

Metabolic diseases are also called the 'transition diseases' because their peak manifestation is during the 'transition period' (three weeks before to three weeks after calving). Metabolic disease was always caused by multiple metabolic systems breaking down, due to the conflict of high-production stress and management (including nutrition, breeding policy, and husbandry) (Payne, 1972, Mulligan and Doherty, 2008). Although the majority occurs during the transition period, the metabolic diseases remained detrimental to the cattle's productivity and health for the entire lactation (Mulligan and Doherty, 2008). Metabolic disease was also considered as consequence of genetic selection for 'higher efficiency' dairy cattle (Drackley, 2006), thereby giving the metabolic disease another name, the 'production disease.'

Metabolic disease is always caused by the imbalance between the nutrient intake (from feed intake) and demand (milk production, pregnancy, body metabolism, and body growth), especially the calcium content (Grummer, 1995). In addition, Mulligan and Doherty (2008) found that immunosuppression appeared around calving, which also led to digestive disturbance after calving, which could intensify insufficient nutrient intake.

Metabolic disease is not only one disease; it is a typical categorical name of many common dairy diseases manifesting during the transition period. The common metabolic diseases include milk fever (**MF**), metritis, ketosis, displaced abomasum (**DA**), and retained placenta (**RP**). As the metabolic diseases relate with etiology, the interrelationship among several diseases was more important in research than the individual disease separately (Mulligan and Doherty, 2008). The over-conditioned cows were more risky in metabolic disease commonly. The over-conditioned cows had four times higher MF risk than the normal cows (Houe et al., 2001), which led to an increase in the risk of dystocia and RP, and increased immunosuppression (Houe et al., 2001). Immunosuppression was also considered as a main reason for RP (LeBlanc et al., 2006). Ketosis and MF were related to each other and both of them are related with RP via multiple etiological pathways (Mulligan and Doherty, 2008). Most metabolic diseases were responsible for the milk production decrease, poorer reproductive performance, and higher culling risk (Rajala-Schultz and Gröhn, 1999a, Rajala-Schultz et al., 1999, Fourichon et al., 2000, Wilson et al., 2004).

The economic evaluation of metabolic diseases is very necessary for producers to determine the best option for disease control and prevention to maximize farm profit (Miller and Dorn, 1990). As a side effect of genetic selection of ‘higher efficiency’ dairy cattle, dealing with the metabolism disease is an essential point in the dairy cattle husbandry, welfare, and farm profitability(Mulligan and Doherty, 2008). In general, the costs of LDA, RP (and metritis), MF, and Ketosis were $494, $315, $275, and $231 per case, respectively (Guard, 2008).

Metritis. Metritis was defined as uterine inflammation due to mild infection due to bacteria invasion (Sandals et al., 1979, Bartlett et al., 1986, Bellows et al., 2002). Metritis had a detrimental effect on milk production, fertility, and culling, especially for reproductive performance. Previous studies found that cows with metritis (and RP) had a poorer reproductive performance including a longer open period, lower CR, lower pregnancy rate at first service, and increased services per conception (Sandals et al., 1979, Bartlett et al., 1990, Gröhn and Rajala-Schultz, 2000, Gilbert et al., 2005). Furthermore, metritis increased the cost of drugs and veterinarian services (Bartlett et al., 1986). Antibiotic treatment was required in some cases and led to associated milk withdrawal for antibiotic residual. A Michigan study estimated the cost of metritis was at $106 for one lactation with metritis (Bartlett et al., 1986). A more general study claimed that metritis costs $4.70 per dairy cow inventory (Bellows et al., 2002).

Retained Placenta (RP). Retained placenta is a reproductive disease. Retained placenta occurs right after parturition and affected the subsequent lactation (Joosten et al., 1988). A common definition of RP was the presence of fetal membranes 24 hours or later post-calving period, or fetal membrane retained for more than 6 hours (Laven and Peters, 1996). Retained placenta and metritis had a complex correlation. RP was widely considered as a predisposing factor to metritis (Sandals et al., 1979, Markusfeld, 1984, Bartlett et al., 1986, Drillich et al., 2001). The incidence of RP ranged from 3 to 12% following a normal parturition; however the incidence increased to 20 to 50% if the cow had suffered an abnormal calving or a reproductive tract infection (Bellows et al., 2002). According to the results estimated by Kossaibati and Esslemont (1997), the direct cost of RP was £83.25 ($142.52), including treatment cost (£6.25, equaled to $10.70) and reduced milk production (£77.00, equaled to $131.82). In addition, the associated longer CI (£66.00, equaled to $112.99), increased culling risk (£143.22, equaled to $245.19), and increased vulvar discharge risk (£5.82, equaled to $9.96) were included in the total costs (£298.29 per average case, equaled to $510.68).

Displaced Abomasum (DA). Among all DA cases, 80 to 90% happened on the left side, which was named as left displaced abomasum (**LDA**). The LDA is widely considered as a nutritional disease, defined as the abomasum filled with gas or filled and subsequently trapped by the descending rumen to the left side of abdominal cavity (Coppock, 1974, Markusfeld, 1986). Coppock (1974) discussed about three main types of causative reasons of LDA: a). Genetic selection trend of dairy cows with larger rumen volume; b). mechanical pressure from rumen and uterus during gestation; and c). abomasal atony due to the occurrence of other metabolic diseases. The older, larger, high-producing cows are at a higher risk for LDA; the LDA risk will also be greater if the cow has suffered or is suffering other metabolic diseases (i.e., ketosis, metritis, or MF) (Coppock, 1974, Markusfeld, 1986). The average annual LDA incidence ranged from 1.4% to 5.8% (Shaver, 1997). Miller and Dorn (1990) estimated the costs of LDA in Ohio at $7.54 ± 0.81 per cow per year. The total costs include costs of pre-optimal removal from herd (died, culling, and stillbirth), body weight loss, labor, carcass disposal, milk loss, drugs, and veterinary service fees. Milk loss ($3.40 ± 0.44) was the greatest part in the total LDA costs. Yet, treatment costs were considered high in total LDA costs, ranging from $100 to $200 (Shaver, 1997). Geishauser et al. (2000) suggested the cost of LDA ranged from $250 to $400, depending on whether surgery was conducted to cure the cow.

Ketosis. Ketosis results from a negative energy balance or starvation (Beem, 2003), especially a glucose imbalance (Baird, 1982). The worldwide incidence of subclinical ketosis was 8.9% to 34%; and the incidence of clinical ketosis was 2% to 15% (Baird, 1982, Beem, 2003). Clinical ketosis generally occurs between the 2^{nd} to the 7^{th} week in lactation with typical symptoms, such as lost appetite, rapid body weight loss, sweet smell of breath, head down (Baird, 1982). Both the clinical and subclinical ketosis affected the health condition and the potential maximal milk yield in the subsequent lactation. Subclinical ketosis appeared with slight decreases in milk production. Varga (2004) summarized ketosis costs at $140 for treatment, and the total cost at $2,520 per year for a 120-cow farm. Another study estimated the costs of subclinical ketosis at $78 per case (Geishauser et al., 2000). A Canadian study estimated the costs of ketosis at 200 Canadian dollars per case (Duffield and Herdt, 2000).

Milk Fever (MF). Milk fever is also as known as ‘hypocalcaemia’ and is characterized by clinical and subclinical stages. Milk fever was caused by insufficient plasma calcium soon after parturition. The demand of calcium would be much higher than the normal calcium concentration during the dry period when the cow started milking after calving (Horst et al., 1997). Due to the rapidly elevated calcium demand, dairy cows always suffer mild MF around calving by adapting calcium from intestines and bones, which could be cured by treating with calcium solutions (Horst et al., 1997, Kossaibati and Esslemont, 1997). In the severe case, the huge gap between the calcium supply and demand will result in the clinical symptoms, including appetite loss, twitching, inhibition of defecating and urination, eventual coma, and even death (Horst et al., 1997).

Milk fever had a strong inter-relationship with the presences of several other common metabolic diseases, including RP, metritis, DA, ketosis (Mulligan and Doherty, 2008). High-producing cows suffer a higher risk of MF. The prevalence of subclinical hypocalcaemia (33%) was much higher than the clinical cases (5%), especially in the older cows (Roche, 2003, Mulligan and Doherty, 2008). Milk fever decreased the productive life of dairy cows by 3.4 yr. on average (Horst et al., 1997)

In an Ohio survey study (Miller and Dorn, 1990), MF cost $7.67 ± 0.91 per cow per year. The total costs included the costs of pre-optimal removal (died, culling, or stillbirth), body weight loss, labor, carcass disposal, milk loss, drugs, and veterinarian service fees. Pre-optimal removal ($4.33 ± 0.59) took the highest portion of the total MF costs. The British estimation (Kossaibati and Esslemont, 1997) summarized MF cases into three severe degrees: mild (87%), severe (5%), and fatal (8%). The MF costs were weighted by the possibility of three categories. The results showed the direct cost of MF at £59 ($101) per average case, including costs of treatment, labor, reduced milk production, and veterinarian service fees. Besides, cost of fatality (£2,014.60 per fatal case, equaled to $3,448.99) was included in the total costs (£220 per average case, equaled to $376.64).

SUMMARY

The up-to-date estimation of disease costs is important for the dairy industry. Understanding the economic impacts of dairy diseases could help improve farm profitability (Guard, 2008). Dairy producers and veterinarians could use the disease cost data in on-farm decision-making, such as culling, treatment, or early dry-off. Whole-farm resource allocation would also benefit from disease cost results, The contribution of each cost category could help allocate disease control or expenditure. Disease cost data would also be useful and essential for the dairy companies with their marketing strategies and production research investments.

Both cow performance and market condition change disease cost. Obviously, disease affected the cow's health condition directly. The detrimental effects included milk production decrease, milk quality change, shorter productivity life (pre-optimal culling or mortality), extended CI, and reduce fertility. Besides the direct effects, disease also had indirect economic costs for producer, such as the treatment costs (drug costs and veterinarian service fees), labor, discarded milk due to medical withdrawal period after treatment, and other miscellaneous costs. Many previous studies used empirical analysis to find the incidence of diseases, relationship between disease and productive performance, and national- or global-level disease impact on animal agriculture business.

Agricultural market prices have tremendous volatility, which affect the supply-demand relationship, disease occurrence, policy changing, and global trading. Although difficult to predict future market prices at the producer level, the variation should be considered in disease costs calculation and disease management. Market prices such as replacement price and milk price could easily affect the total disease costs by changing costs and revenues.

Using the results from the empirical analysis of disease effects, many models were built to estimate the disease costs. Moreover, for some metabolic diseases, little comprehensive normative research has been conducted to estimate the total economic cost and the correlation with internal and external factors. A flexible generic model including costs of several common dairy diseases is needed to estimate the national average disease cost and show the relationship between market prices, cow's health performance, and total disease costs.

To take the large variation of dairy health economics into consideration, much research has focused on stochastic models with Monte Carlo simulations (Allore et al., 1998, Østergaard et al., 2005, Huijps et al., 2009, Bewley et al., 2010, Bruijnis et al., 2010). Stochastic models with Monte Carlo simulation emulate the real-life of dairy cows and calculate the variation of results (Sørensen, 1990). This technique enables model to be flexible in adapting to the health performance and market prices.

The objective of this thesis was improving a farm-level stochastic model with Monte Carlo simulation to assess new estimations of common clinical dairy disease costs. This stochastic model uses pseudorandom number generator to control the selected stochastic distributed variables (Sørensen, 1990). The total disease costs were categorized into seven classes: treatment, labor, culling, death, milk loss, discarded milk, and extended days open (**DO**) cost. Seven clinical dairy diseases were included in this model: mastitis, lameness, metritis, ketosis, milk fever, left displaced abomasum, and retained placenta. As a secondary objective, this model also estimated the cost of days open with flexibility in herd performance and market condition.

Figure 1.1. The basic structure of the dairy production system included resources, products, and people. (Adapted from Galligan (2006), modified for the dairy production system)

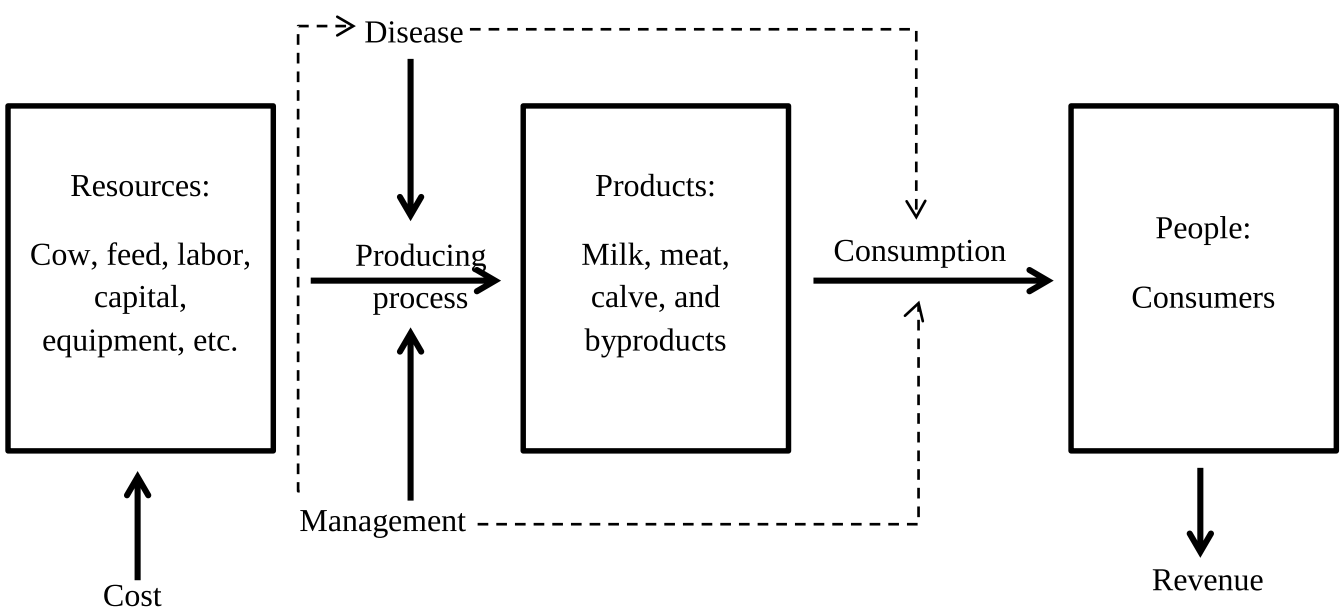
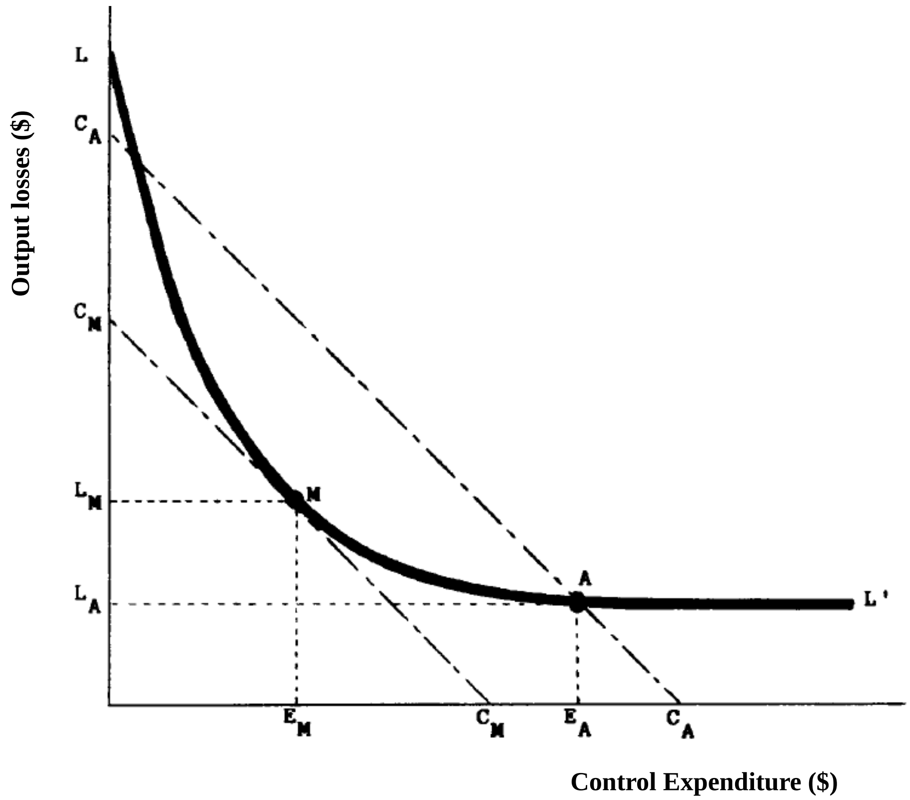


Figure 1.2. The relationship between output losses (L) and control expenditures (E), adapted from McInerney et al. (1992)



CHAPTER TWO. Stochastic Simulation of the Economics of Dairy Cow Culling and Reproductive Performance

INTRODUCTION

The ultimate goal of a dairy farm is to maximize total profits. Breeding and culling decisions play a critical role in determining farm profitability. The culling decision is profit oriented (Monti et al., 1999). Reproduction, milk production, and disease are the top culling risk factors (Millan-Suazo et al., 1989). Replacing the current cow with a new cow can be considered an investment in future farm profitability. Culling decisions should rely on economic principles instead of biological phenomena (Lehenbauer and Oltjen, 1998, Groenendaal et al., 2004). The herd conditions and input and output prices determine the current and future values of a cow, so culling decisions are also tied to internal and external factors (Dhuyvetter et al., 2007).

The marginal net revenue (**MNR**) approach is often used to model the dairy cow culling decision-making process (Dijkhuizen and Morris, 1997, Groenendaal et al., 2004). With this approach, the expected future profit of the current cow is compared with the expected profit from a replacement cow. The retention pay-off (**RPO**) value is used to compare the future economic profit across time and conditions. The RPO value is widely used to determine optimal culling time. A negative or zero retention pay-off indicates that the current cow should be replaced immediately.

Days open (**DO**) is the major indicator of calving interval (**CI**), defined as the time between successive calvings. Considerable research efforts have focused on estimating the effects of extended DO on farm profitability. In general, the extended DO loss increases with the elevating DO. Previous studies have revealed the effects of extended DO on dairy farm profitability through milk loss, culling risk, and associated financial losses. The optimal calving interval has been described as 12 to 13 months to maximize the average daily milk production and produce the most replacement cows for the herd (Schmidt et al., 1988). Holmann et al. (1984) reported that a 13-mo CI resulted in maximal net revenue using an empirical analysis. Management practices centered on conception rate (**CR**), heat detection rate (**HDR**), and voluntary waiting period (**VWP**) have large influences on DO (Meadows et al., 2005). Poor reproduction leads to a higher culling rate and fewer newborn calves and reduced replacement cow availability (Boichard, 1990, Groenendaal et al., 2004, Meadows et al., 2005).

Optimal DO varies by milk production level, parity number, and the availability of replacement cows (Weller et al., 1985, Boichard, 1990, Marti and Funk, 1994, Plaizier et al., 1998, Groenendaal et al., 2004, Meadows et al., 2005, Inchaisri et al., 2010). Primiparous cows need longer days open than multiparous cows to reach maximal production (Weller et al., 1985). Boichard (1990) and Inchaisri et al. (2010) concluded the net economic loss due to extended DO was lower in the primiparous cows than the multiparous cows; whereas Groenendaal et al. (2004) concluded the opposite relationship. Marti and Funk (1994) reported an antagonistic relationship between production and reproduction in that the high-producing cows always had longer DO than the low-producing cows. However, a greater DO is more acceptable on a high-producing cow because the high milk production increased the RPO value by elevating the future profit, which indicated a higher culling cost (Groenendaal et al., 2004). Cost of DO (**CDO**) is considerably higher in the low production cow than average cow, and CDO is lower in the high-producing cow than the average one (Boichard, 1990, Groenendaal et al., 2004, Inchaisri et al., 2010). The improvement of reproductive performance is more important for a cow with poorer reproductive performance and lower production than an average or higher production cow (Oltenacu et al., 1981, Plaizier et al., 1998). Culling rate also impacts the optimal DO because of the changes in the availability of replacement cows (Groenendaal et al., 2004).

Although high production compensates for lower reproduction to some degree, the effect of lower fertility is still among the top risk factors of dairy culling (Beaudeau et al., 1995). Gröhn et al. (1997) claimed that culling risk dropped considerably as soon as the cow became pregnant. Rajala-Schultz and Gröhn (1999) reported that a cow with 305 DO in one lactation had 12 times higher culling risk compared with a cow conceiving within 150 d post-parturition.

Several models have quantified the relationships among CDO, CR, and market prices. Higher CR decreases CDO; whereas a higher milk or feed price increases CDO (Boichard, 1990, Plaizier et al., 1998). Cost of DO varies among different studies: $0.50 to $2.00 per d (Holmann et al., 1984), $0.10 to $1.60 per d (Groenendaal et al., 2004),

$1.37 per d in a 160 d DO scenario (Meadows et al., 2005), and $3.19 to $5.14 per d (De Vries, 2006a). The objective of this research is to describe a farm-level stochastic model for calculating the daily cow performance, RPO, and CDO using stochastic market prices and herd performance.

MATERIALS AND METHODS

Model overview

This farm-level stochastic, Monte Carlo simulation model was first described by Bewley et al. (2010a). The model was constructed in Microsoft Excel 2010 (Microsoft, Seattle, 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, CR, HDR, RHAM, and AFC. This model was designed to describe and examine a cow's value with flexibility 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) into a daily-based model.

Farm Level Model

Humphry et al. (2005) and Bewley et al. (2010) discussed advantages of a herd-level model compared to a cow-level model. Comparing a farm-level to a cow-level model of bovine viral diarrhea, Humphry et al. (2005) claimed the herd-level model was easier to operate and more user-friendly. Dairy producers often have more herd level performance data available than individual cow data. An individual cow-level model may be more accurate in scientific research; however, a herd-level model may be more appropriate for producer decision-making.

Model Input

This model was constructed with the flexibility for users to input their farm-level parameters as inputs instead of default parameters. For demonstration purposes, default input variables were collected from published literature or from Dairy Records Management Systems (May 21st, 2013, **DRMS**, Raleigh, NC) (Table 2.1). Financial parameters are listed in Table 2.2 adjusted to 2013 values for inflation. Rolling herd average milk production, HDR, CR, and AFC were modeled stochastically using data from DRMS; Table 2.3 shows the simulated values including mean, SD, and 5% to 95% range.

Average Cow Simulation

This farm-level model used an 'average cow' to represent all cows in the herd (Bewley et al., 2010). As a whole farm, herd size changes with culling rate and the herd structure was steady, which were two key assumptions in this model. In all lactations, calvings were evenly distributed across the year. The life cycle of the average cow was determined deterministically by age at first calving, calving interval, and dry period length. Productive lifetime was set as six parities, which meant all cows were programmed to be culled on the last day of the 6th parturition. The life cycle of a cow is shown in Figure 2.1. All daily production and reproduction data were calculated based on the methodology described in Bewley et al. (2010).

Stochastic Prices Module

Agricultural market prices are characterized by considerable dynamic variation. 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 2013. Market prices were predicted based on historical price variation and future price baseline data. The historical milk, corn, soybean, and alfalfa prices for 1971 to 2012, the slaughter price for 2009 to 2012, and the replacement price for 1971 to 2009 were collected from the Understanding Dairy Markets website (http://future.aae.wisc.edu/) (Gould, 2013). The slaughter prices for 1970 to 2008 were defined from the historical prices data from the USDA-National Agricultural Statistics Service (**USDA-NASS**) values for 'beef cow and cull dairy cows sold for slaughter' (USDA-NASS, 2009). The replacement prices for 2010 to 2012 were collected from the Agriculture Prices quarterly report by the USDA-NASS (USDA-NASS, 2012). Baseline market prices were obtained from the Food and Agricultural Policy Research Institution's 2013 US Baseline Briefing Book: projections for agricultural and biofuel markets FAPRI (2013) except replacement heifer price. To obtain the replacement-heifer price baseline, a regression analysis was conducted between historical replacement price and slaughter price between 1990 and 2012. The final equation was as follows:

$$\text{Replacement price} = 29.47 \times \text{Slaughter price} - 274.46 \times \text{Year} - 57456.06$$

Where, Replacement price = Market Replacement cow price (per cow)

Slaughter price =Market slaughter price (per kg)

Year = Counter of years, set 1990 as year 1

Market price for year i (P_i) was first logarithm converted to $\mathbf{LOGP_i}$ and a predicted price ($\mathbf{LOGEP_i}$) was calculated according to the regression coefficients between $LOGP_i$ and $LOGP_{i-1}$. All the residual terms ($\mathbf{r_i}$) between $\mathbf{P_i}$ and $\mathbf{EP_i}$ (Convert $LOGEP_i$ back to standard dollar) were sorted in ascending order and their associated probability of observing each r_i was assumed to be equal across years. An empirical distribution was built via @Risk using all r_i and their associated cumulated probabilities, with the 'minimal' and 'maximal' values determined by multiplying the smallest and greatest r_i by 1.0001. By using the parameters above, this @RiskCumul distribution enabled the use of historical variation to predict future prices. In the last step, the predicted stochastic market price was the combination of deterministic future baseline price and the error term from correspondent @RiskCumul distributions. To make this prediction closer to reality, a correlation matrix among all six types of market prices was applied to the @RiskCumul distribution to avoid unrealistic extreme predictions. Market prices for the most recent ten years (2003 to 2012) were used in estimating the cost of days open (**CDO**), in addition to the 2013 market condition. These average market conditions were derived from the past ten-year historical prices, including mean, 2.5%, and 97.5% that were fit into a PERT distribution through @Risk. Being a special version of Beta distribution, the PERT distribution allowed skewness and was defined by the minimum, mean, and maximal values (Bewley et al., 2010).

Revenues and Costs

Revenues and costs depend on the quantity of input and output and their associated market prices. Daily revenue included milk, calf value, and slaughter value. Daily costs included feed, routine veterinary service, breeding, and financial disposal losses. The financial disposal losses was the cost generated after the involuntary culling. The model assumed individual herd conditions would not affect global market prices. Daily revenues and costs were calculated from daily productivity data and market prices. The revenue from milk, slaughter, and calves and the cost from breeding, feed, and routine veterinary were all calculated using methodology described in Bewley et al. (2010)

Retention Pay-off Module

Retention pay-off 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 present cow's future profit was used to determine the optimal replacement moment. The optimal replacement time was considered as the time of maximal NPV (Brealey and Myers, 2000). In dairy cattle culling decision-making, the optimal culling time occurs when the future marginal net revenue from the present animal is the same as the maximal annuity of expected net revenue from the average replacement animal (Dijkhuizen and Morris, 1997).

Dijkhuizen and Morris (1997) also defined RPO as the extra profit between keeping a cow until the next optimal replacement moment and replacing the cow with a new average replacement heifer immediately, accounting for the discount rate and the survival probability. The RPO also represented the extra amount of money to spend on disease or reproductive failure control (Groenendaal et al., 2004). The optimal replacement moments (ORM) appeared when RPO was ≤ 0.

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 body weight difference and financial disposal loss due to base involuntary culling risk (Groenendaal et al., 2004, Bewley et al., 2010).

$$MNR_i = Revenue_{milk,i} + Revenue_{calf,i} + Revenue_{slaughter,i}$$

$$- Cost_{feed,i} - Cost_{mortality\ disposal,i} - Cost_{veterinarian,i} - Cost_{breeding,i}$$

Where,

MNR=Marginal net revenue,

$Revenue_{milk,i} = Price_{milk} \times$ Daily milk $production_i$,

$Revenue_{calf,i} = 0$ or calf value (only at calving),

$Revenue_{slaughter,i} = Price_{slaughter} \times (BW_i - BW_{i-1})$,

$$\text{Cost}_{\text{feed},i} = \text{Price}_{\text{feed}} \times \text{DMI}_i,$$

$$\text{Cost}_{\text{mortality disposal},i} = \text{Probability}_{\text{death},i} \times \text{Financial disposal cost},$$

$$\text{Cost}_{\text{veterinarian},i} = \text{Average daily routine veterinarian cost}$$

$$\text{Cost}_{\text{breeding},i} = 0 \text{ or daily breeding costs (after voluntary waiting period).}$$

Performance of a replacement cow was the same as the average cow due to the farm-level model setting. The economic opportunity of the replacement cow was calculated in terms of maximal average discounted net revenue or ‘maximal annuity net revenue (**ANR_{max}**). The $ANR_{max}$was the highest ANR value from the following day to the end of productive life (end of 6th parity), so ANR_{max} was dynamic across time and the optimal replacement moment appeared at each time ANR equaled to the closest ANR_{max}.

$$\text{ANR}_i = \frac{r \times \left[\sum_1^j \frac{(p_i \times \text{MNR}_i)}{(1+r)^i} \right]}{1 - \frac{1}{(1+r)^{\sum_i^j p_i \times m_i}}}$$

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)

According to the definition, RPO was the summation of daily differences between closest ANR_{max} and daily MNR until the soonest optimal replacement. Final RPO for day i was set as the cumulated differences between following daily MNR (MNR_j) and ANR_{max}, accounting for the survival probability.

$$RPO_i = \frac{\sum_{i+1}^{ORM}\left[p_j \times \left(MNR_j - ANR_{max}\right)\right]}{\left(1+r\right)^j}$$

Where,

RPO_i = Retention pay-off value of the present cow in day i

ANR_{max} = Maximal ANR value of the replacement cow

p_j = Probability of surviving until the end of day j

ORM = Optimal replacement moment (d)

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

Cost of Days Open

The CDO was calculated in this model using the RPO value. The methodology was adapted from Groenendaal et al. (2004) by comparing the same-DIM RPO values for different DO scenarios. The shortest DO (60 d) scenario assumed conception the day after VWP; the longest was 300 d (model input). In this model, the CDO was calculated as the same-parity first day of lactation RPO (**FDRPO**) values across various DO scenarios. This method was firstly described and used in Groenendaal et al. (2004). The shortest DO scenario (60 d) was selected as the baseline in different DO comparisons. The average daily CDO was calculated by dividing the total CDO over the DO difference between two scenarios. For example, the CDO of a primiparous cow conceived at the 300 DIM was calculated as the difference between the first parity FDRPO of the 60 d DO scenario (baseline) and the 300 d DO, resulted in \$521.03. The average daily CDO divided the CDO value (\$521.03) over 240 d (the difference between 300 d and 60 d), resulted at \$2.16 per d.

The CDO was calculated using the following equation.

$$CDO_{m,\,n,l} = FDRPO_{n,l} - FDRPO_{n+m,\,l}$$

Where, $CDO_{m,n,l}$ = Cost of m day(s) delayed conception

$FDRPO_{n,l}$ = RPO value on the 1st day in lactation of a cow with n d DO, in parity l

$FDRPO_{n+m,l}$ = RPO value on the 1st day in lactation of a cow with n+m d DO, in parity l

Simulation

Simulations were conducted to calculate CDO and RPO values with the stochastic variables of interest, including the stochastic factors (RHAM, PR, 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

After each simulation, @Risk conducted a multiple regression analysis as the sensitivity analysis between the stochastic factors and outputs to test the effects of selected stochastic factors (including the RHAM, PR, AFC, milk price, feed price, replacement heifer price, and slaughter price) on the RPO, CDO and first optimal replacement moment (**FORM**). Sensitivity analysis results were plotted in tornado graphs and spider graphs. The tornado graph showed the regression coefficient of each factor in the multiple regression analysis or the change in corresponding output with one SD increase in each factor. In addition to the tornado graph, the spider graph was used to present the effect of each factor on the output. The spider graph depicted each stochastic factor on the x-axis with 10% intervals from the associated PERT distribution, and plotted the corresponding output as the dependent variable. The spider graph showed the changing trend in the output with various sampled stochastic factor values.

RESULTS AND DISCUSSTION

Stochastic Parameters

The predicted market prices for 2013 are listed in Table 2.4. The 2013 market prices were unusual compared with historical data (Figures 2.3 and 2.4). The unusual market condition appeared as the high slaughter and feed price and the low replacement cow price. The high grain prices, high demand in beef market and the sufficient replacement cow market explained the 2013 unusual market condition. Market prices from the past ten years (2003 to 2012) were used to better reflect market dynamics across time. The descriptive statistics of the market prices (milk, feed, replacement cow, and slaughter) from 2003 to 2012 are presented in Table 2.4.

Retention Pay-off

Different from simply subtracting a slaughter cow price from replacement cow price to calculate culling cost, the retention pay-off value projected the potential profit of a cow over her immediate slaughter value. The RPO-based culling cost modeling approach compares the expected MNR of a cow to the economic opportunity (future expected value) of a replacement cow (Dijkhuizen and Morris, 1997, Groenendaal et al., 2004, Bewley et al., 2010). As a profitability index, a RPO less than zero indicated that immediate culling would be a better option than keeping the cow any longer because the future net profit was lower than her immediate slaughter value. Additionally, the RPO value also represented the maximum amount of extra money (i.e., disease treatment) a producer could spend to stay profitable on an individual cow or at the farm-average level. Retention pay-off value was widely used in dairy farm decision-making.

The RPO value and the optimal replacement moment (**ORM**) were positively correlated because a higher RPO represents higher profitability and culling cost, which would defer ORM. Assigning greater MNR to early productive life (led to higher RPO) would shorten the period before the maximal annuity net revenue at the first optimal replacement moment (**FORM**). Sensitivity analysis of both herd performance and market prices were conducted on the RPO and the FORM. Although many herd performance affect the RPO value, this model only examined AFC, PR (including HDR and CR), and RHAM.

The daily RPO of an average cow is depicted in Figure 2.2, separate for the 2013 market condition and the past ten-year market condition. In general, the RPO value showed the similar pattern in each parity, regardless of the market condition. The peak RPO appeared right before parturition and decreased gradually after calving until reaching the lowest RPO value in mid-lactation. After the lowest point, RPO started to increase when approaching the next parturition. The highest RPO value appeared on the day before the 3rd parturition under both market conditions. The RPO value under the past ten-year average market condition was higher than the RPO value under the 2013 market condition in the first two parities. However, the difference was progressively reducing since the 3rd parities. This result demonstrated that the RPO value were more sensitive to the market prices in the early productive life (Bewley et al., 2010).

Described by previous studies, a higher replacement price could increase RPO value; whereas a higher milk price, feed price, and slaughter price had the opposite effects (Groenendaal et al., 2004, Bewley et al., 2010). Compared to historical conditions, the 2013 market condition had relatively high slaughter price and feed price and low replacement price. This unusual combination of market conditions explained the comparatively low RPO value in this model (Figure 2.2). Under the 2013 market condition, the FORM showed up at 199 DIM in the first parity, which was much earlier than previous results (Groenendaal et al., 2004, Bewley et al., 2010, Heikkilä et al., 2012). In each parity, the lowest RPO value in each mid-lactation fell below zero, which led to an ORM in each parity. The negative RPO values indicated that the cow's future profit would be less than her immediate slaughter value, replacing with a young cow would be the better option other than keeping the cow for any longer. The effects of each stochastic factor on the FDRPO in each parity are depicted in Figure 2.5. The relationships between the daily RPO and market prices and the relationships between daily RPO and herd performance in the first 860 d after the first calving under the 2013 market condition were further described (Figures 2.6 and 2.7).

Market factors had different effects on FDRPO depending on parity number and lactation stage (Figure 2.5 and 2.6) under the 2013 market prices. Across all parities, a higher replacement cow price would increase the FDRPO, whereas a higher slaughter price would decrease the FDRPO (Figure 2.5). A greater replacement cow price increased RPO value by elevating the cost of purchasing a new cow to replace the current one. A greater slaughter price decreased RPO because higher slaughter revenue increased income and compensated for a part of the culling cost. The influence of replacement cow price and slaughter price were greatest in the first parity then progressively decreased (Figure 2.5 and 2.6). The replacement price and the slaughter price determined the first parity FDRPO largely with high regression coefficients. The replacement cow price was only included in the calculation on the first parity FDRPO calculation where the market value of this cow switched from a replacement cow value to her slaughter value, as defined by the slaughter price (Bewley et al., 2010). The milk price was not related to the FDRPO in the first parity (Figure 2.5). However, the effect of the milk price became negative after the first several days in the first parity (Figure 2.6) until the end of first parity when the effect became positive. In early productive life, a higher milk price increased revenues and decreased the cost of culling. Later, the higher milk production, along with the peak milk production, elevated a cow's potential value and increased the culling cost. A higher feed price would decrease the FDRPO slightly across all parities (Figure 2.5), because a higher feed price reduced the daily MNR and resulted in a lower daily RPO.

Herd performance also influenced the RPO (Figure 2.5 and 2.7) and the relationships were sensitive to parity and lactation stage. In agreement with Bewley et al. (2010), the higher RHAM and the AFC would decrease the RPO whereas the higher PR would increase the RPO (Figure 2.7). In the first parity, the later AFC decreased the RPO value because the feed intake of a relatively older cow was greater, which decreased the

MNR and daily RPO. This effect decreased as the animal aged. Greater RHAM led to a higher RPO in a cow's early productive life, which resulted in lower daily RPO values and a shorter FORM (Figure 2.7). The effect of RHAM was similar to milk price. As the animal was approaching peak milk production, her potential value would be higher with greater RHAM, which led to the higher RPO and culling cost. Higher PR was weakly correlated with the first parity FDRPO (r = 0.003, Figure 2.5). However, this effect was negative in later parities due to differences in lactation persistency. In addition, the effect of PR varied according to lactation stage (Figure 2.7). An early pregnancy would decrease daily milk production and shorten the total lactation period, resulting in a lower total milk production (Capuco et al., 2003). A greater PR decreased calving interval that made the same-day closer to the next parturition and increased the culling cost.

In the original model by Bewley et al., (2010), the higher replacement price and feed cost extended the FORM and the higher milk price and slaughter price reduced the FORM. This research showed similar results, and the effects of each stochastic parameter on the FORM were depicted in the spider graph (Figure 2.8 and 2.9) and tornado graph (Figure 2.10). Only higher replacement cow price would extend the FORM. The higher RHAM, slaughter price, milk price, PR and the later AFC would reduce the FORM. These relationships explained that the FORM was much earlier under the current market conditions with a high slaughter price and a relatively low replacement cow price. The feed price was not related with FORM so that higher feed price would not change the FORM but decrease the RPO by shrinking the daily MNR.

Ideally, the average cow should be culled at the FORM (the 199 DIM in the first parity under 2013 market condition). However, the model continues to calculate the RPO value after the FORM to see the RPO pattern in the rest of the productive life until the end of the end of the 6th parity. In reality, most producers would prefer not to cull the cow at her FORM during the middle of the first parity. Abundant first parity culling would decrease total milk production at a macro-level and elevate milk price, but production would be lowered with cows never reaching maturity. In addition, a large increase in dairy culling at the industry level would change both slaughter and replacement cow prices at the market level.

Groenendaal et al. (2004) indicated the MNR method had a disadvantage that the variation of inputs had hardly been modeled. However, in this model, the stochastic approach was used to cover this limitation. Key variables were fit into individual distributions and the value was drawn from the distribution randomly in each iteration. Therefore, this model captured the variation of the selected factors.

Cost of Days Open

Market Condition in 2013. This model estimated the CDO in the 1st, 2nd, 3rd, 4th, 5th, and 6th parity separately. A sensitivity analysis was also conducted to examine the effect of market prices and herd performance on CDO. Costs of days open were calculated as the difference among the same-parity FDRPO under various DO length scenarios. The shortest DO (60d), in which the cow conceived at the day after VWP, and the longest DO was 300d.

Figure 2.11 shows the FDRPO values in all DO scenarios in each parity; and Figure 2.12 shows the CDO values in each parity. In this CDO calculation, the FDRPO in the shortest DO scenario was used as the baseline in each parity. The FDRPO increased with a longer open period and reached the maximal value ($380.65) with a 198 d DO period (Figure 2.11). This result represented that before a cow reached the FORM, a relatively late pregnancy had higher future profit than an earlier FORM. The FDRPO value stayed the same when the conception time occurred after the FORM. If a cow failed to get pregnant before the FORM under the 2013 market conditions, the FDRPO would be the same. The reason was that the performance and the cumulative MNR were the same before the FORM and she was programmed to be replaced then.

The CDO values were negative and decreasing with extended DO (Figure 2.12) under the 2013 market condition. Cost of days open reached the smallest value (-$75.61) if the cow failed to conceived before her optimal culling. This result was partially explained by the 2013 market conditions. The high slaughter price and the low replacement cow price reduced the RPO and the FORM. The other reason was from lactation persistency, especially in the first parity. According to lactation persistency, the daily milk production was lower if a cow was pregnant or longer in pregnancy than a cow that was not pregnant or shorter in pregnancy on the same day (Capuco et al., 2003). The cow was programmed to be replaced at the FORM, and the relatively longer DO assigned a greater MNR to the period before the FORM due to the greater milk production before culling. As a result, the FDRPO was higher in a longer DO scenario than shorter one when both conceived before FORM under the 2013 market condition.

Although the results were estimated under unusual market condition, the changing trend of the RPO and the CDO still demonstrated that the decision not to breed a cow was the most profitable choice; a late pregnancy would increase the future profit. Furthermore, under the 2013 market conditions, not to breed a cow before the programmed culling would be the most profitable choice.

Long-term Market Conditions. As discussed above, the market prices influenced RPO, FORM, and associated CDO greatly. Market conditions in 2013 are abnormal compared to the historical prices. Thus, models also used the average conditions across a ten-year period (2003 to 2012). During this period, the milk price (mean ± SD) was \$0.36 ± 0.04 per kg, feed price was \$0.17 ± 0.04 per kg, replacement cow price was \$1,609.85 ± 159.37 per cow, and slaughter price was \$1.29 ± 0.21 per kg. The FORM appeared 1,055 days after the first calving (the 190 DIM in the third parity) and the RPO values were higher than the ones in 2013 in the first two parities (Figure 2.2).

In the first parity, the lowest CDO was -\$37.69 with 113 d DO and highest was \$521.03 with 300 d DO; the average daily CDO varied from -\$1.37 to \$2.16 (Figure 2.13). In the second parity, the lowest CDO was -\$35.81 with 105 d DO and highest was

$667.20 with 300 d DO; the average daily CDO varied from -$1.54 to $2.78 (Figure 2.14). Demonstrated by previous studies (Skidmore, 1990, Groenendaal et al., 2004, De Vries, 2006b), the first parity CDO was lower than in the second parity because of lactation persistency. These results were close to the results from other studies (Holmann et al., 1984, Groenendaal et al., 2004, Meadows et al., 2005), but lower than De Vries (2006b)

Figures 13, 14, and 15 show the FDRPO, CDO, and average daily CDO under the average market condition for the first, second, and third parity, respectively. From the shortest DO to the longest DO length, FDRPO started to increase then decrease with DO length extending in the first two parities. Under the average market conditions, the highest FDRPO appeared with a 113 d DO in the first parity and the highest FDRPO appeared with a 105 d DO in the second parity. Consequently, the 113 DIM and the 105 DIM were the optimal conception time in the first and second parity, respectively. These results also demonstrated that the first parity cow needs a longer time to reach her optimal breeding time (Weller et al., 1985). The lowest FDRPO appeared with the longest DO length. In the third parity, the cow reached her FORM at 190 DIM. If a cow was not pregnant before 190 DIM in the third parity, the FDRPO values were same, regardless when conceived after the FORM. Cost of days open reflected the trend with negative values in the shorter DO scenario then the CDO became positive with the longer DO. The longest DO scenario had the highest CDO and average daily CDO. De Vries (2006b) used a similar approach that defined the difference on the same-day RPO between a pregnant and a non-pregnant cow. The CDO in this model can be considered as another form of the pregnancy value. A CDO less than zero indicated that pregnancy would not increase the future profit (Groenendaal et al., 2004). In a DO scenario with negative CDO value, a pregnancy impeded the cow to attain the maximal profit. The results under the average market conditions demonstrated that the shortest DO may not be the most profitable breeding decision. Results from this model were in agreement with the statement from Gröhn and Rajala-Schultz (2000) that the proper length of DO with a certain extended open period allowed a cow to reach her maximal value.

Sensitivity Analysis**.** The sensitivity analyses were conducted on the CDO under the average market condition to test the effects of the market prices and the herd performance. Because the FORM appeared during the third parity that cows were programmed to be replaced, only the first and second parity CDO were in this analysis under the average market condition. The tornado graph (Figure 2.16) shows the change in CDO with one standard deviation increase in each stochastic factor. In general, the market prices and herd performance had the inverse effect on the CDO and FDRPO because of the model methodology. In the first parity, if the RHAM, PR, and milk price increased by one standard deviation, the CDO would decrease by $27.95, $17.26, and $13.92, respectively. On the other hand, if the feed price, slaughter price, and AFC increased by one standard deviation, the CDO would increase by $11.44, $2.72, and $0.69, respectively.

Interestingly, a greater slaughter price increased the first parity CDO whereas decreased the second parity CDO. The greater replacement price had the opposite effect of slaughter price on the CDO value in the first two parities separately. However, the correlations were low between the CDO and the slaughter price (r = 0.05), and between the CDO and the replacement price (r =-0.02) in the first parity.

In agreement with previous results (Oltenacu et al., 1981, Marti and Funk, 1994, Groenendaal et al., 2004, De Vries, 2006b) that extended DO had a greater impact with a higher CDO value on a low-producing cow than on a high-producing one. The higher PR decreased CDO by shortening the extended open period, similar to that reported by De Vries (2006b). A higher milk price decreased the CDO because the later conception cow had a higher FDRPO because of lactation persistency. However, a greater feed price increased CDO because of the lower FDRPO in later conceived cow. The replacement price and the slaughter price affected the second parity CDO by influencing the FDRPO. A higher replacement price or a lower slaughter price would increase the culling cost, which indirectly elevated the pregnancy value (De Vries, 2006b) and the economic losses with a non-pregnant cow. The effects of the interaction between herd performance and market factor were not included in this model; however, those interactions could be very interesting for future research and useful in realistic on-farm decision making. Although the practical breeding decisions and culling decisions depended on multiple factors, this model could help the managers be aware of the change in cows’ future value in different herd or market situations.

CONCLUSIONS

The RPO and CDO values were greatly impacted by the market conditions and herd performance. The milk price and the feed price had short-term immediate effects on the RPO and the CDO, whereas the replacement cow price and the slaughter price had comparative long-term effects. The effects of herd performance and market prices depended on the lactation stage and the parity number. This model estimated a cow's profitability, replacement costs, and cost of extended days open. The earliest conception may not be most profitable, and the optimal conception time depended on the other internal and external factors. This model could help adjust the breeding and culling decisions with flexibility in the market condition and the cow's performance. In addition, this model could be applied for further dairy economics research, such as disease cost estimation or the reproductive program comparison.

Table 2.1. Farm performance parameters used in stochastic modeling of dairy cow culling and reproductive performance economics

Variable	Value	Source
Number of milking cows	170.20	DairyMetrics
Heifers (0 to 12 months as a percent of total herd)	42.0%	DairyMetrics
Heifers (≥ 13 months 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 (**DNB**)	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, J Dairy Sci 88:298
Weaned heifer death rate	1.8%	NAHMS (2007)
Age at first calving (mo.)	26.20	DairyMetrics
Days dry (d)	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)

Table 2.2 Financial inputs used in stochastic modeling of dairy cow culling and reproductive performance economics

Variable	Value	Source
Interest rate	10.00%	Giordano et al. (2012)
Discount rate	8.00%	Hyde and Engel (2002)
Tax rate	35.00%	Boehlje (2005)
Heifer calf value	$ 400	Dhuyvetter et al. (2007)
Bull calf value	$ 100	Dhuyvetter et al. (2007)
Yearly veterinary costs	$ 61.61	Groenendaal et al. (2004)[1]
Semen costs (per straw/unit)	$ 18.48	De Vries (2004)[1]
Dry cow feed price ($/kg 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)

[1] Adjusted for inflation to 2013 dollars.

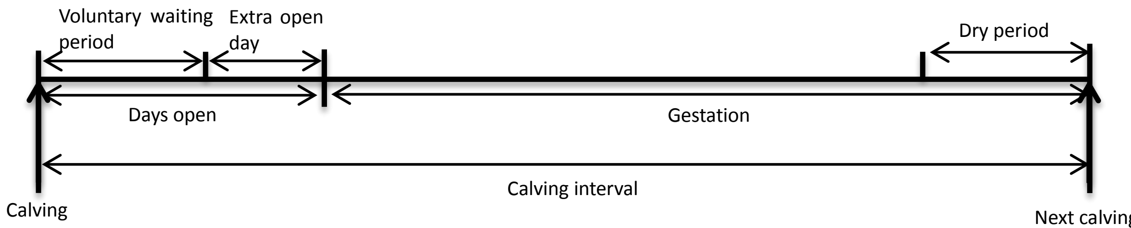
Table 2.3. Simulated cow performance metrics used in stochastic modeling of dairy cow culling and reproductive performance economics

	Mean	SD	Range (5% to 95%)
Rolling average herd milk production (RHAM, kg/cow/yr.)	9,682.53	1880.48	7,765.25 to 12,904.02
Age at first calving (AFC, mo.)	26.18	2.84	23.15 to 30.79
Heat detection rate (HDR, %)	44.09%	17.74%	23.45% to 72.60%
Conception rate (CR, %)	41.86%	13.01%	27.71% to 63.44%

Table 2.4. Predicted 2013 market prices and mean market prices for 2003 to 2012

	2013 market prices	Mean market prices for 2003 to 2012
Milk ($ per kg)	$0.45 ± 0.05	$ 0.36 ± 0.04
Feed ($ per kg)	$0.23 ± 0.04	$ 0.17 ± 0.04
Replacement cow ($per cow)	$1,648 ± 194	$ 1,610 ± 159
Slaughter ($ per cow)	$1.83 ± 0.24	$ 1.29 ± 0.21

Figure 2.1. A cow's life between successive calvings, including days open (DO) and gestation [1,2,3,4,5,6]



[1]Calving interval: the period between two successive calvings

[2]Voluntary waiting period (VWP): time between calving and the first insemination (Miller et al. (2007)

[3]Gestation: pregnancy period, set as 280 d in this model

[4]Dry period: non-lactating period at the end of pregnancy

[5]Days open: the period between calving and conception

[6]Extra days open: days between the voluntary waiting period and conception

Figure 2.2. The retention pay-off value from the 1st parity to the end of the 6th parity, with the 2013 market condition and the past ten-year (2003 to 2012) average market condition

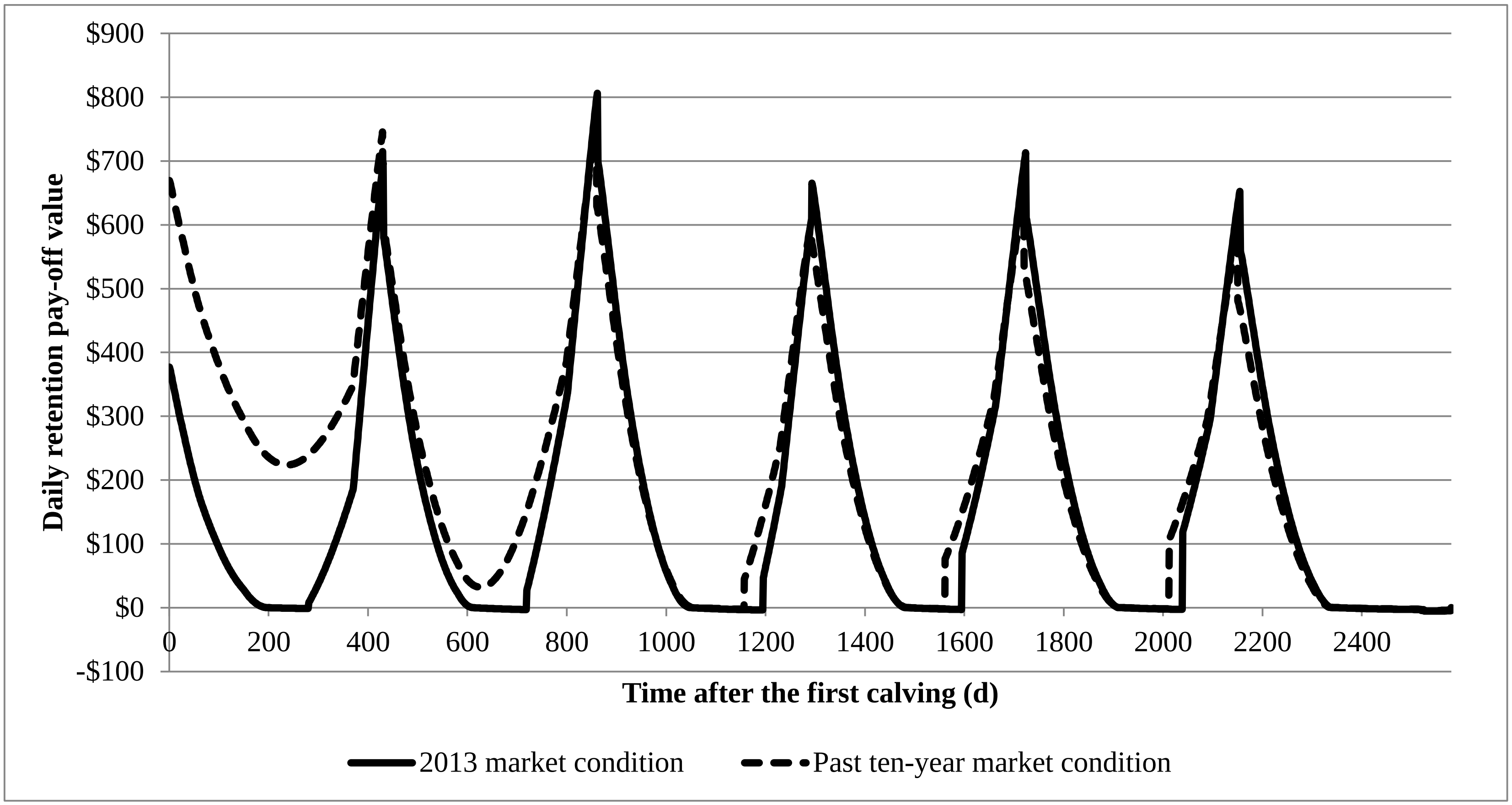
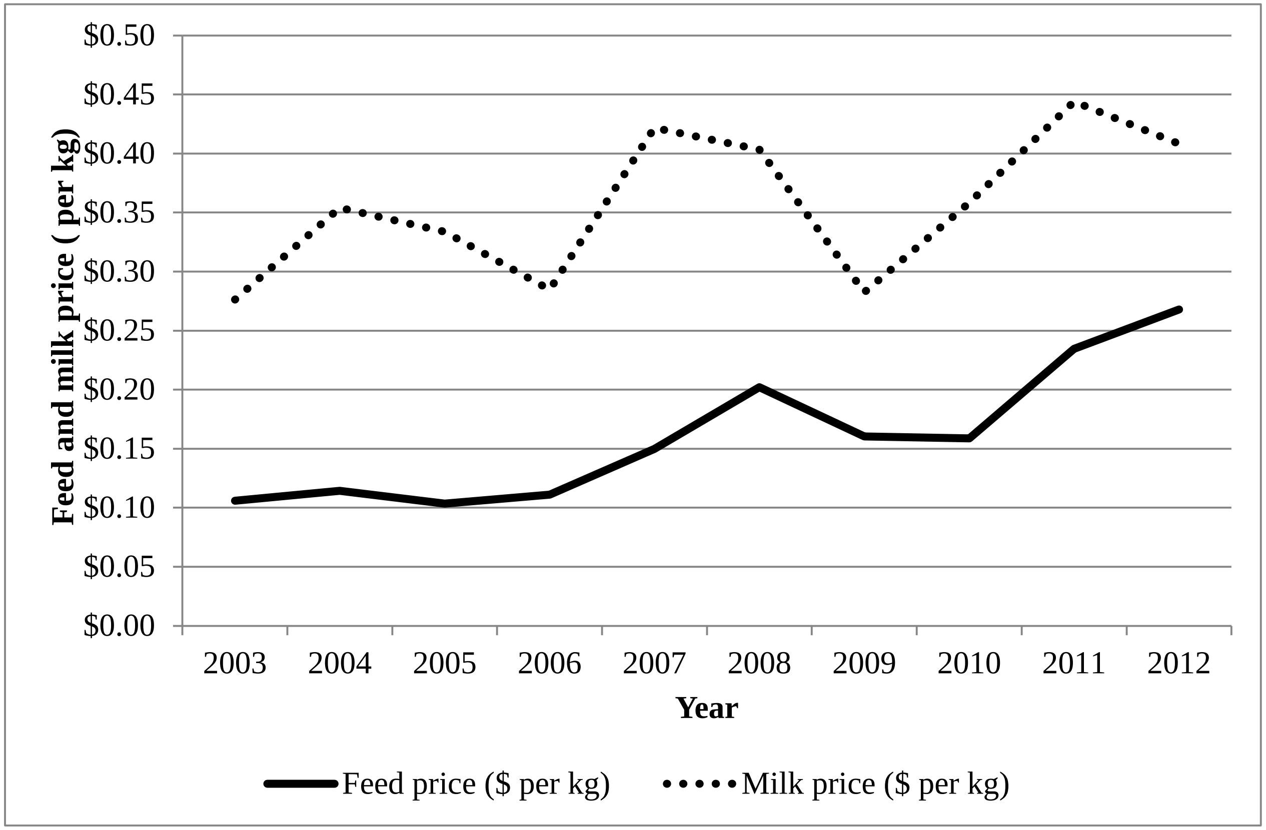


Figure 2.3. Historical milk and feed prices (2003 to 2012), collected from "Understand Dairy Markets" website (Gould, 2013)[1] .



[1]The feed price was calculated based on the corn, soybean, and alfalfa price, using an equation from Bailey and Ishler (2007)

Figure 2.4. Historical replacement cow and slaughter price (2003 to 2012) collected from "Understand Dairy Markets" website (Gould, 2013) and the USDA-NASS statistics reports (USDA-NASS, 2009, 2012)

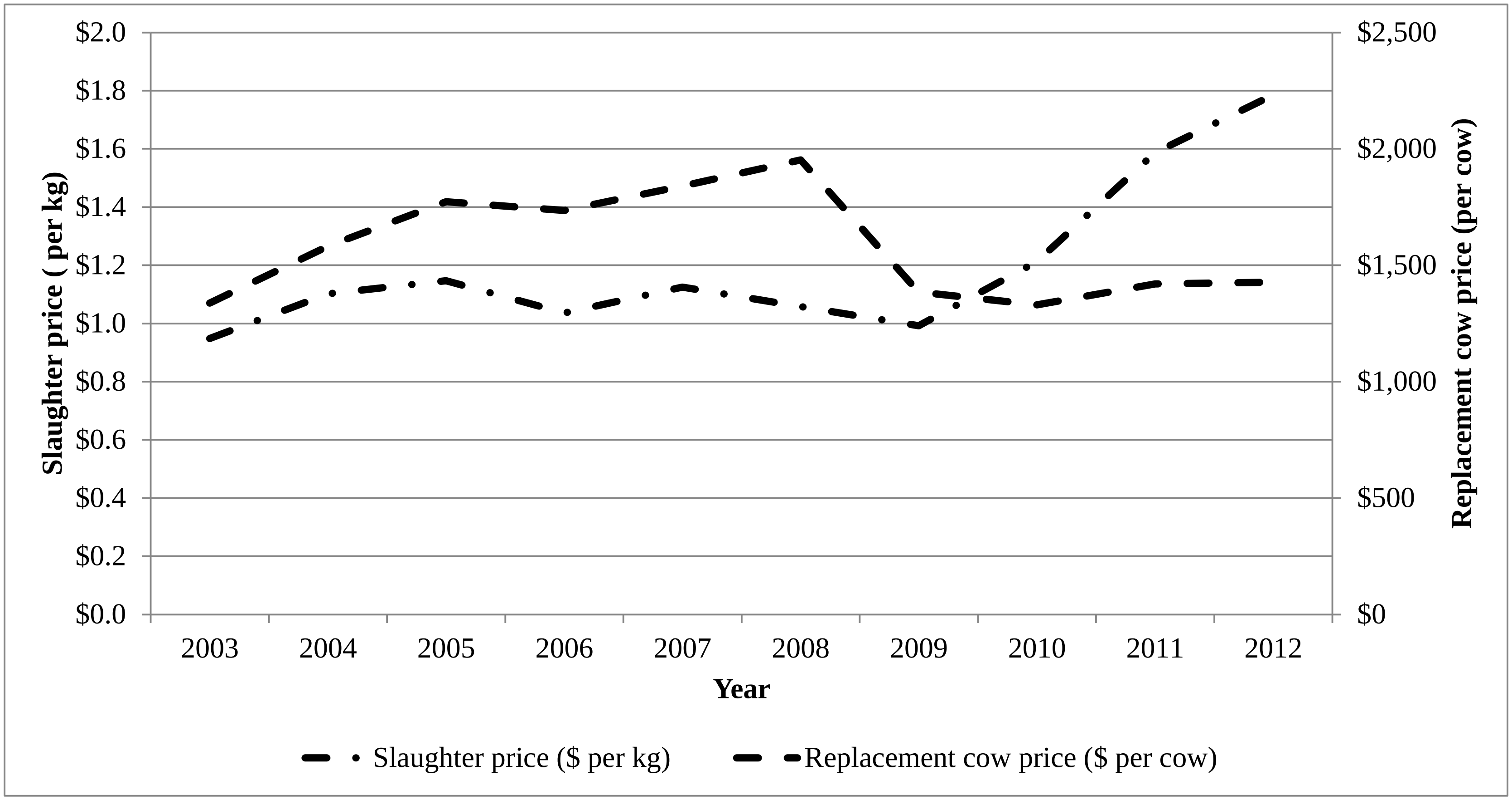


Figure 2.5. Regression coefficients for the effects of milk price, feed price, slaughter price, replacement cow price, rolling herd average milk production (RHAM), pregnancy rate (PR), and age at first calving (AFC) on the first retention pay-off value (FDRPO) in each parity

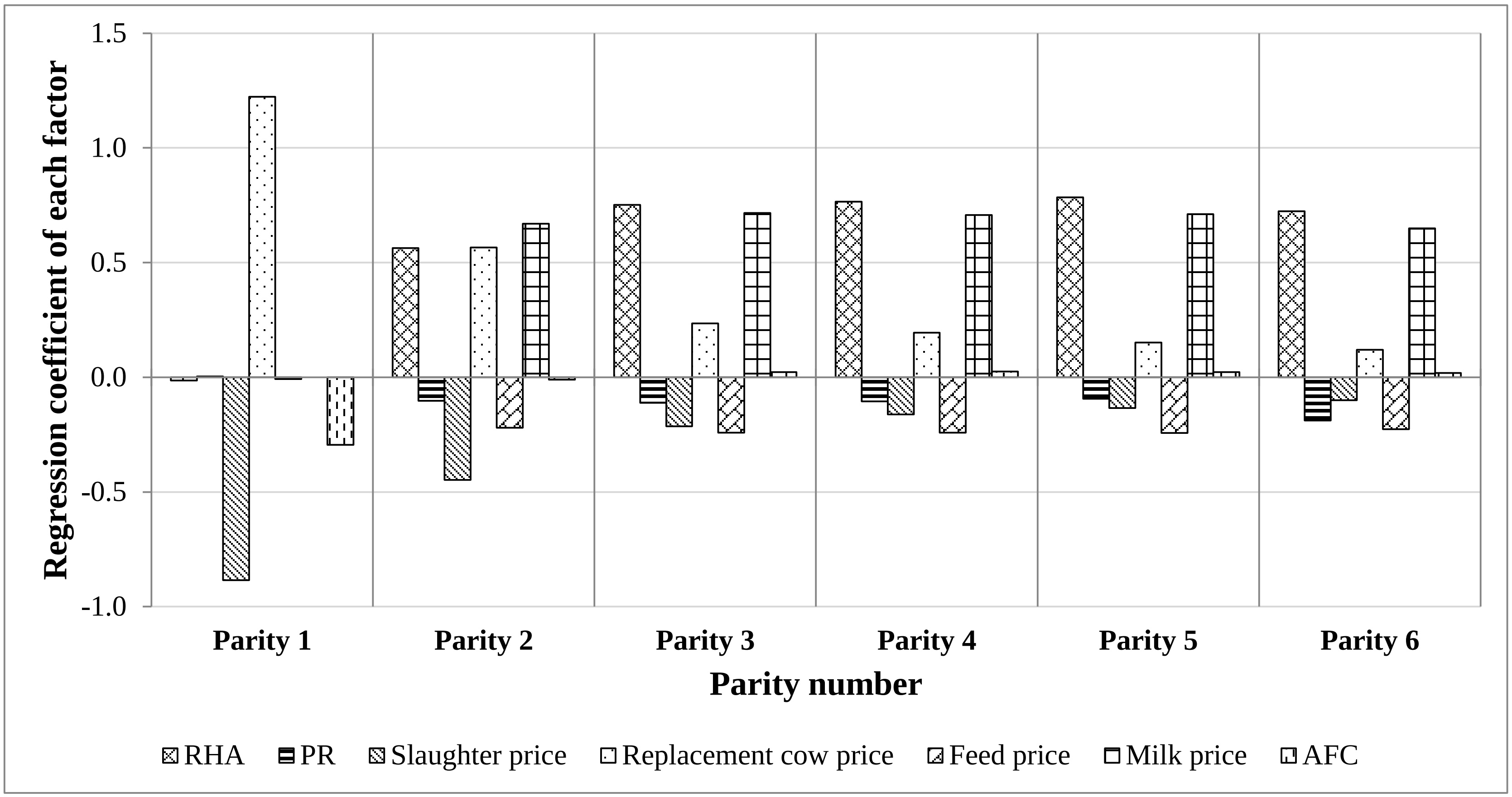


Figure 2.6. Relationship between milk price, feed price, slaughter price, replacement cow price, and the daily retention pay-off (RPO) value in the first 860 days after first calving

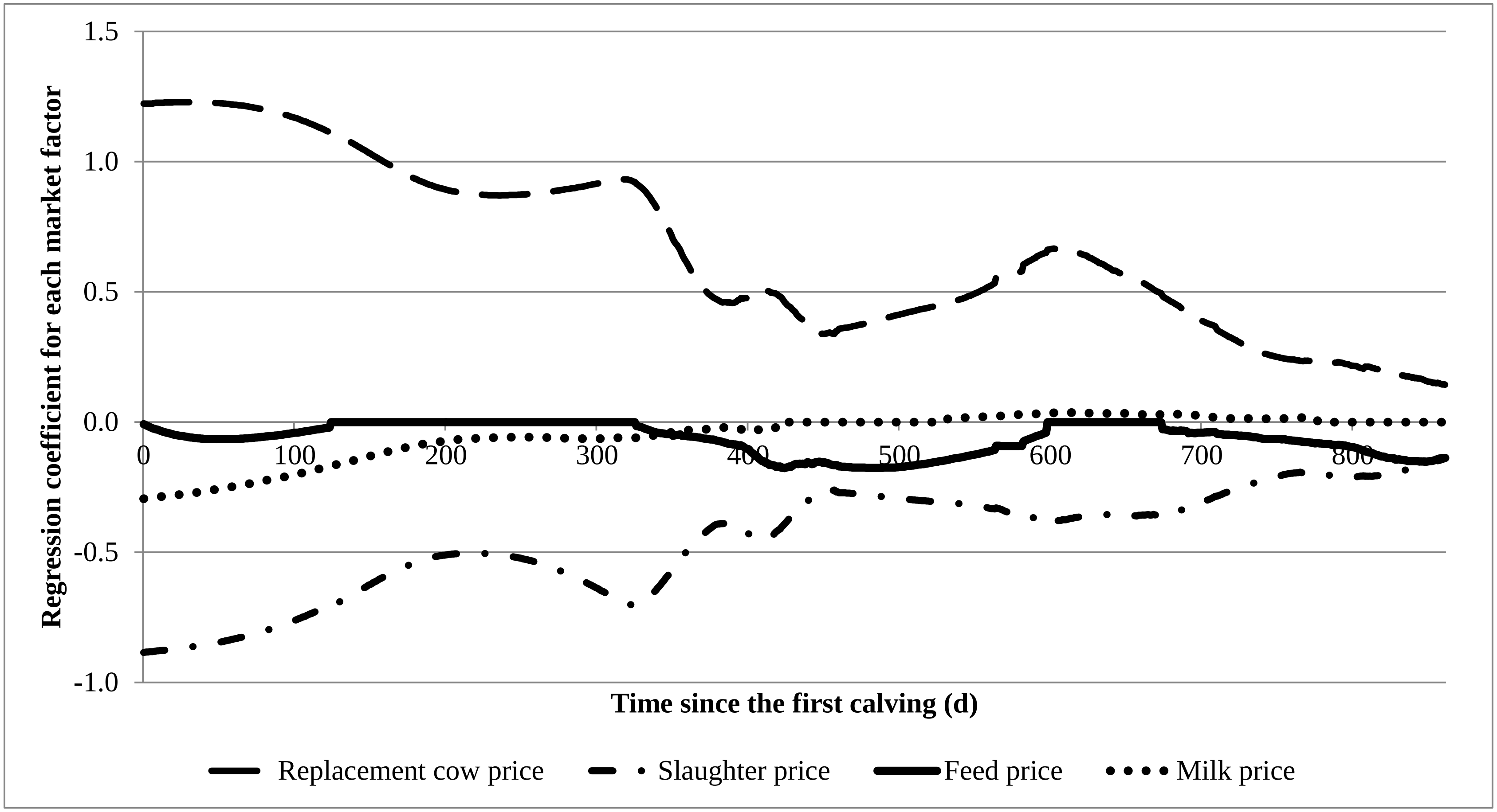


Figure 2.7. Relationship between rolling herd average milk production (RHAM), pregnancy rate (PR), age at the first calving (AFC) and retention pay off value (RPO) in the first 860 days in milk

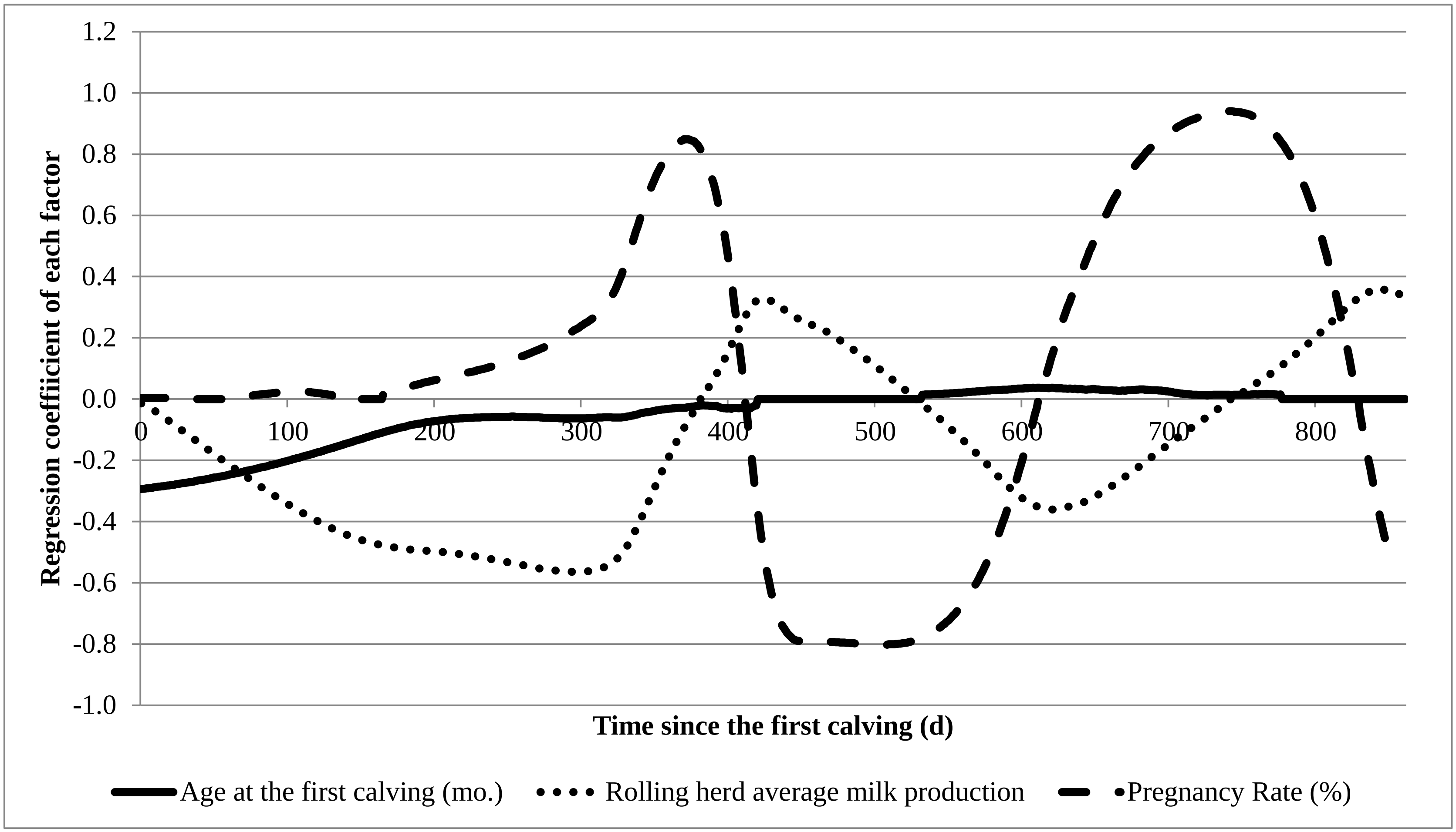


Figure 2.8. Relationship between milk price, feed price, slaughter price, replacement cow price, and first optimal replacement moment

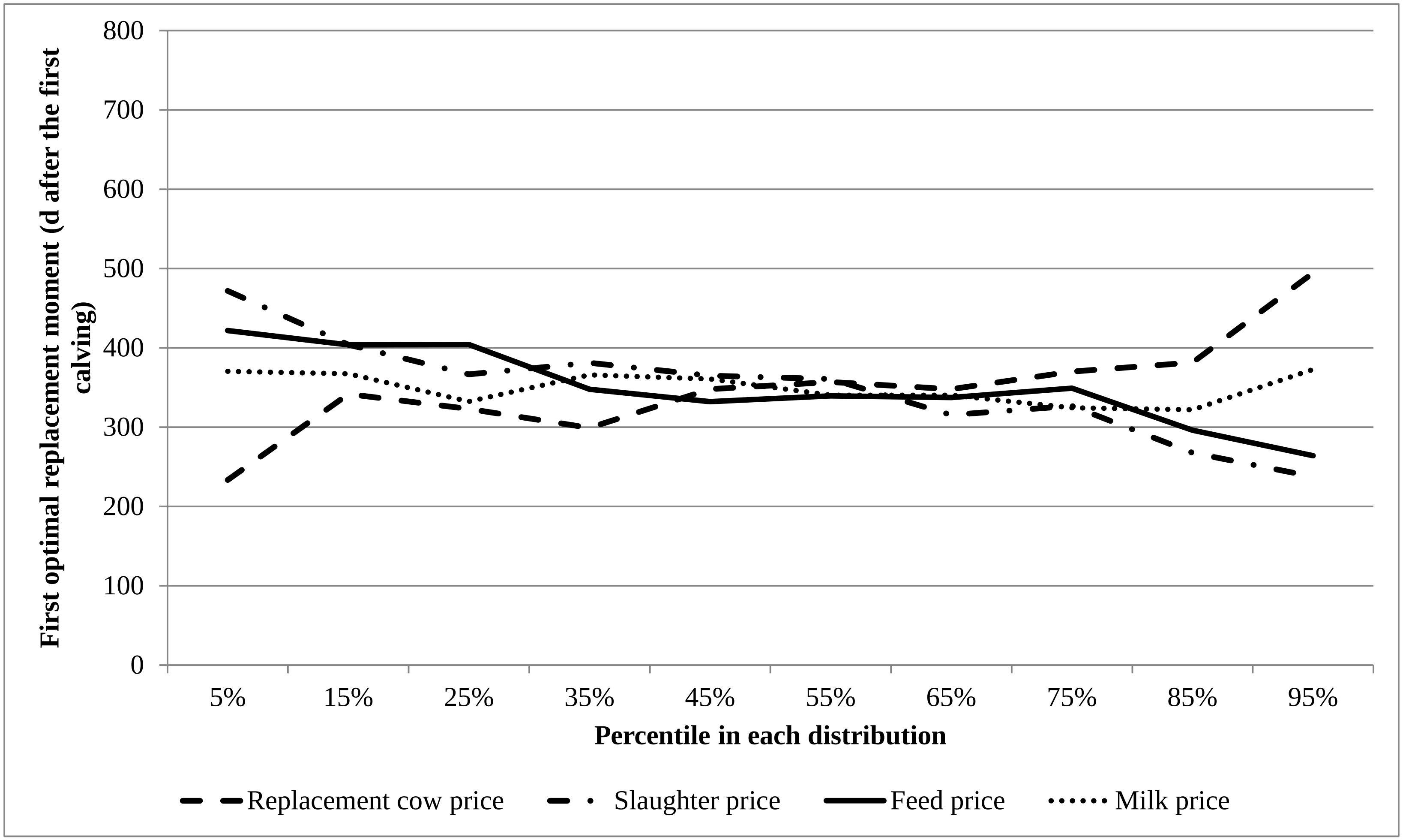


Figure 2.9. Relationship between rolling herd average milk production (RHAM), pregnancy rate (PR), age at the first calving (AFC), and first optimal replacement moment

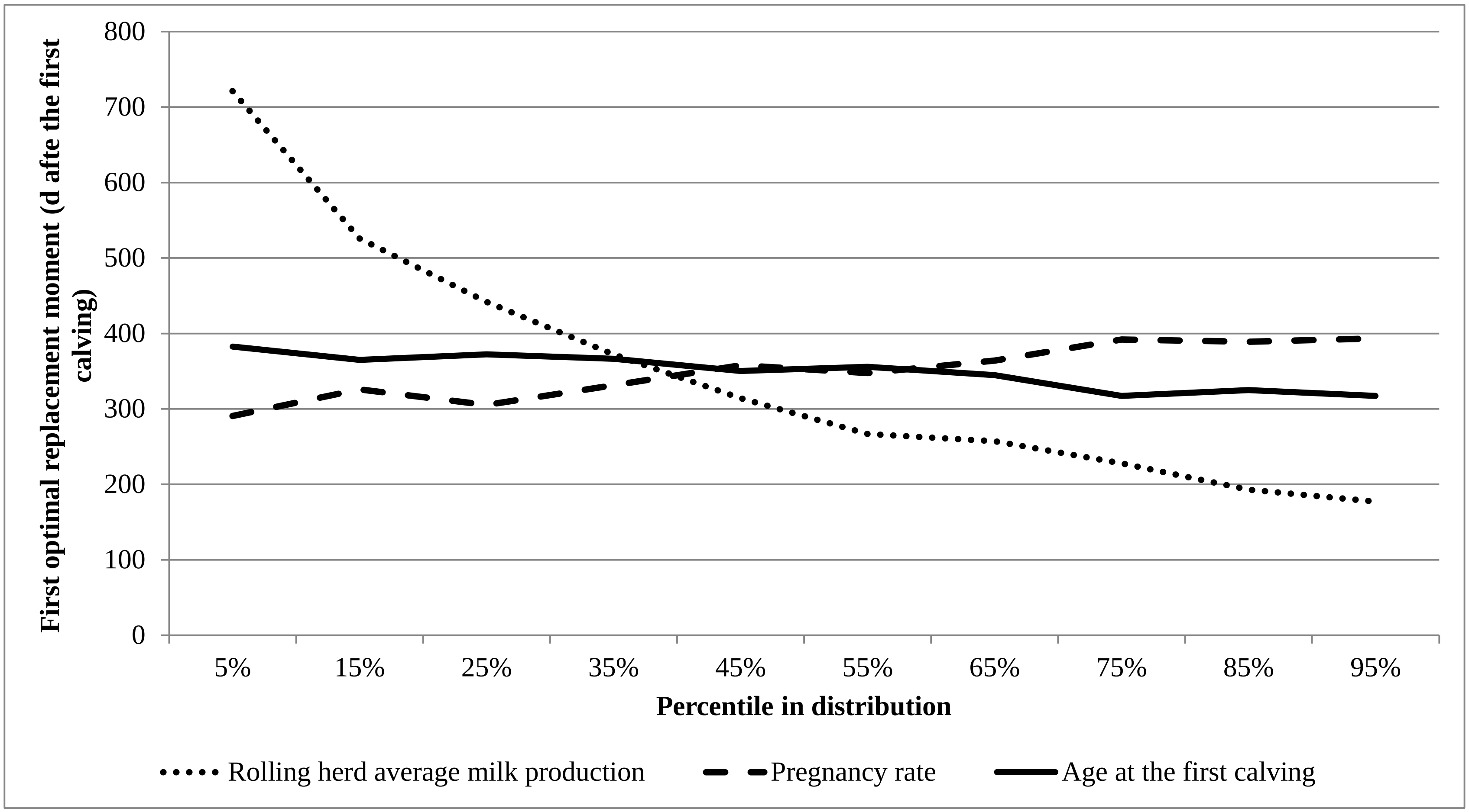
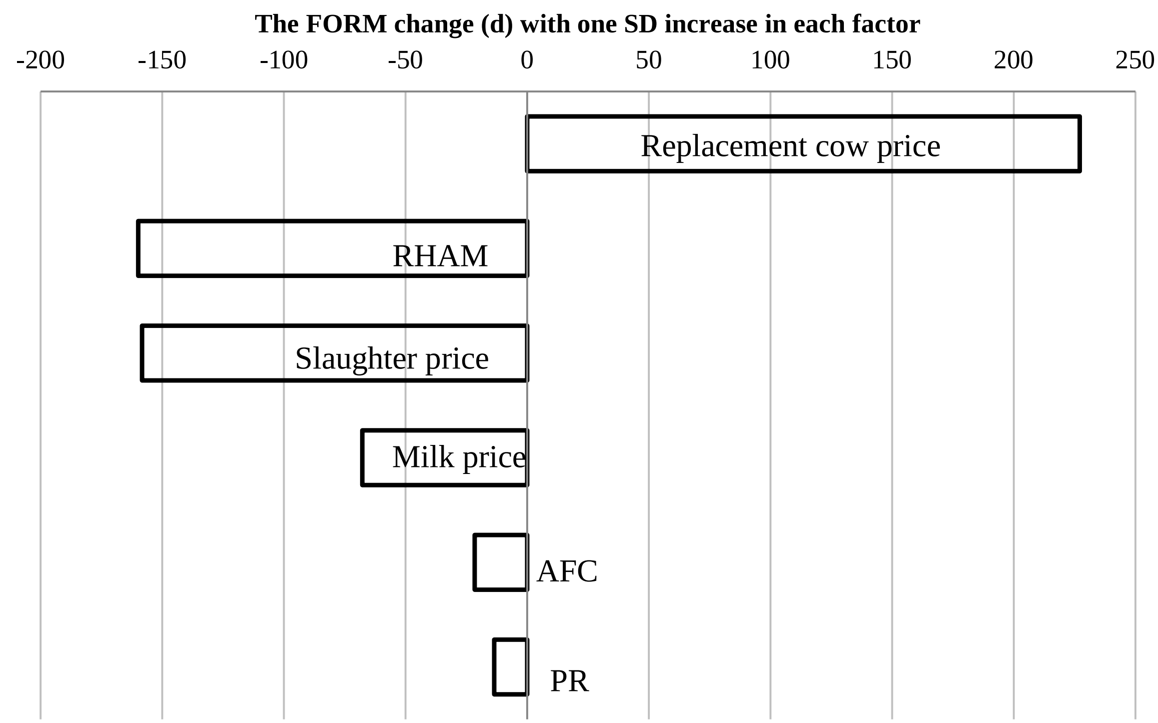


Figure 2.10. Relationship between the first optimal replacement moment (FORM) changes (d) with one SD increase in milk price, slaughter price, replacement price, rolling herd average milk production (RHAM), pregnancy rate (PR), age at the first calving (AFC) [1]



	PR	AFC	Milk price	Slaughter price	RHAM	Replacement cow price
FORM change with one SD increase in each factor	-14	-22	-68	-158	-160	227

[1] The feed price was not related with the FORM

Figure 2.11. Retention pay-off (RPO) values on the first day in lactation with different days open length in each parity

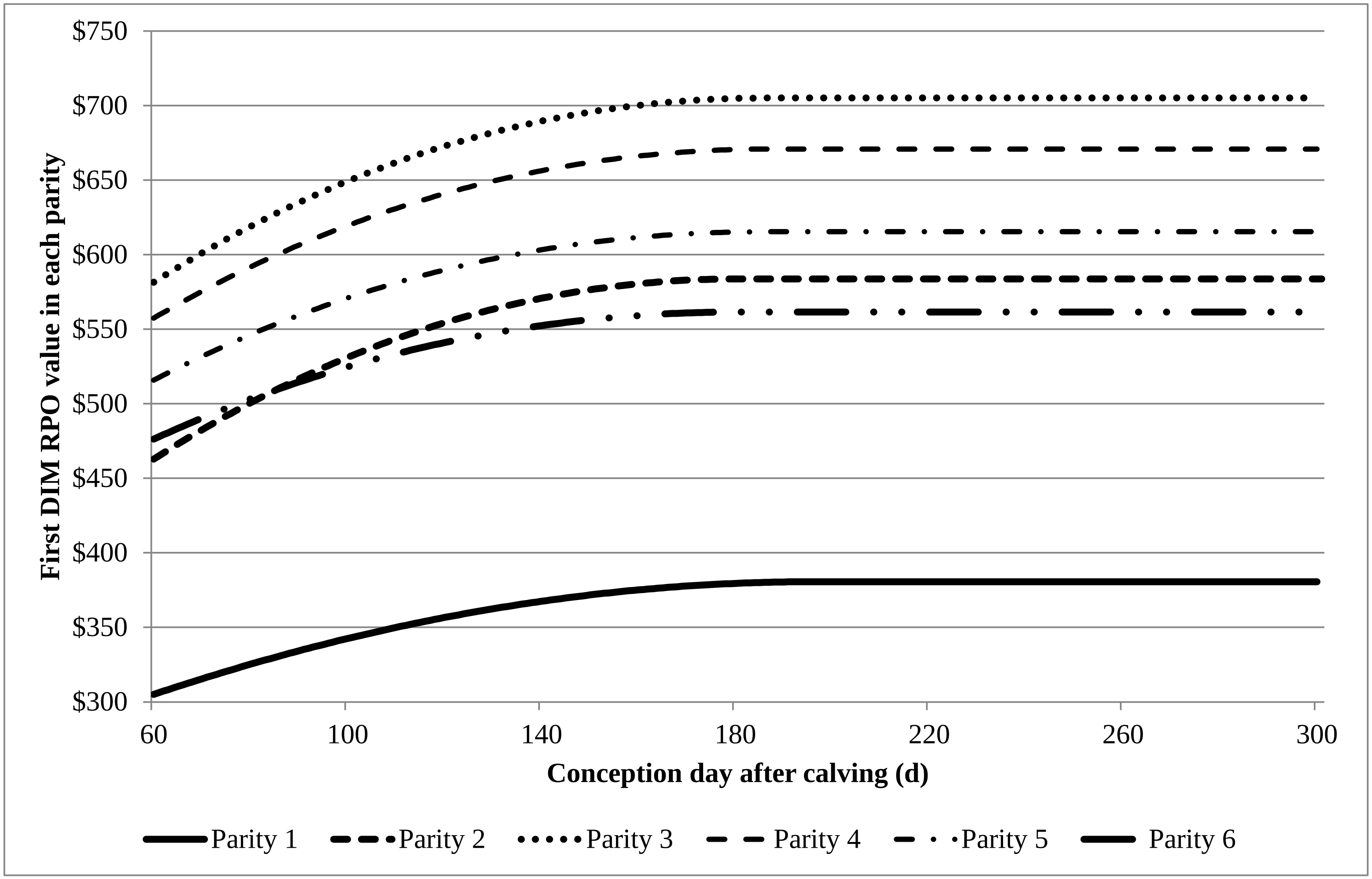


Figure 2.12. Cost of days open with different open days length in each parity under the 2013 market condition

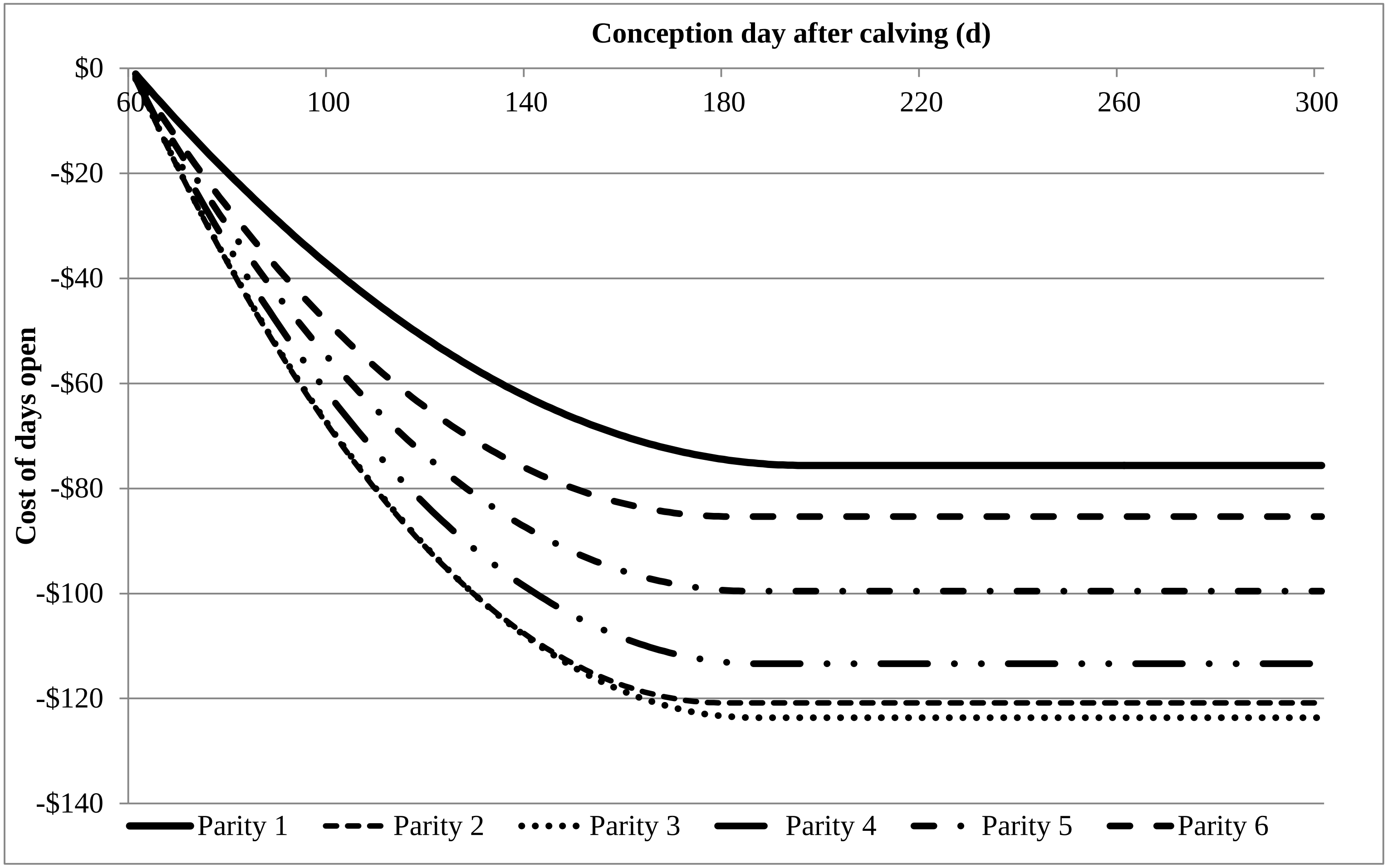


Figure 2.13. First day of lactation RPO value (FDRPO), cost of days open (CDO), and average daily CDO value with different open day lengths in the first parity with the past ten-year (2003 to 2012) average market condition

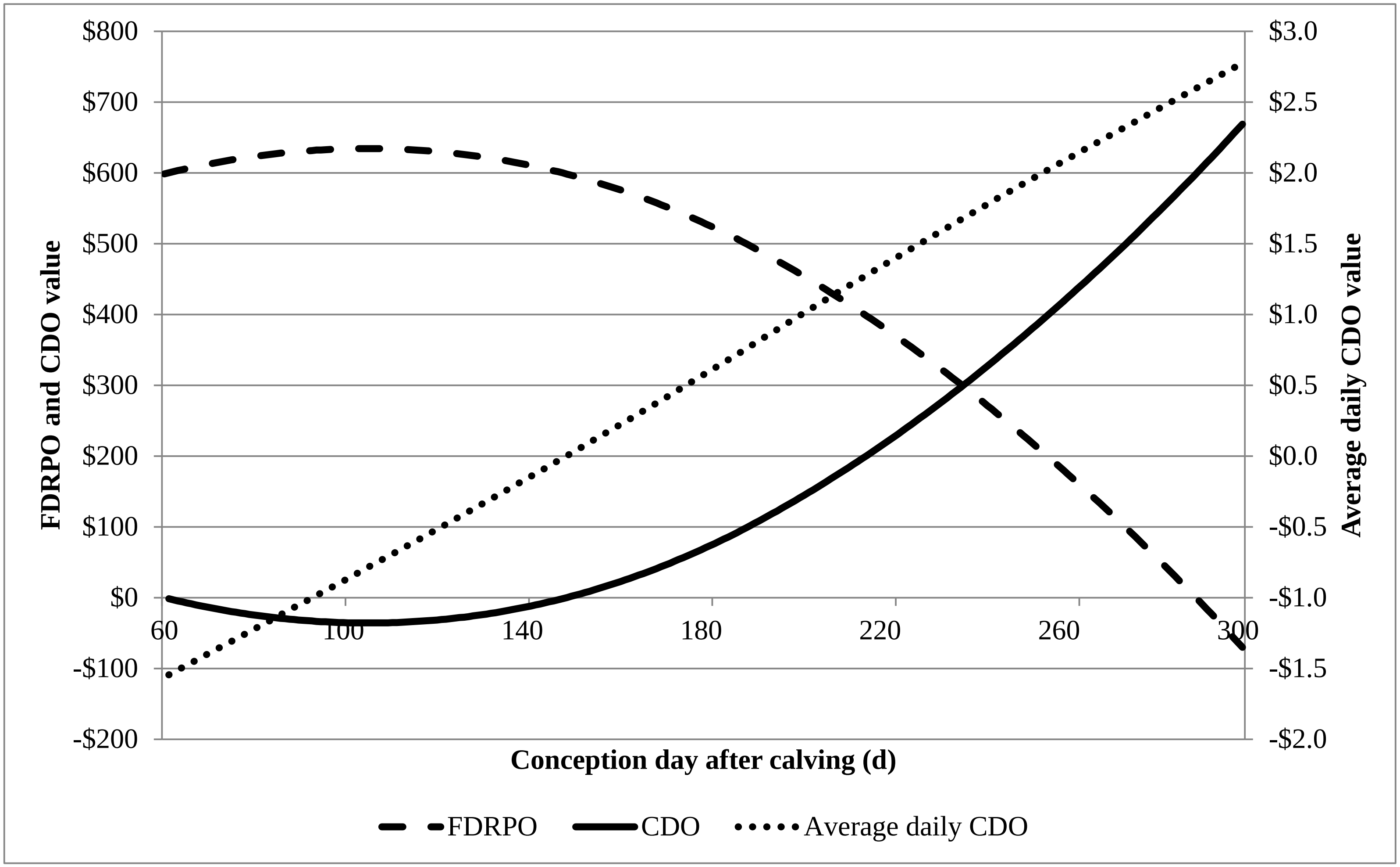


Figure 2.14. First day of lactation RPO value (FDRPO), cost of days open (CDO), and average daily CDO value with different open day lengths in the second parity under the past ten-year (2003 to 2012) average market condition

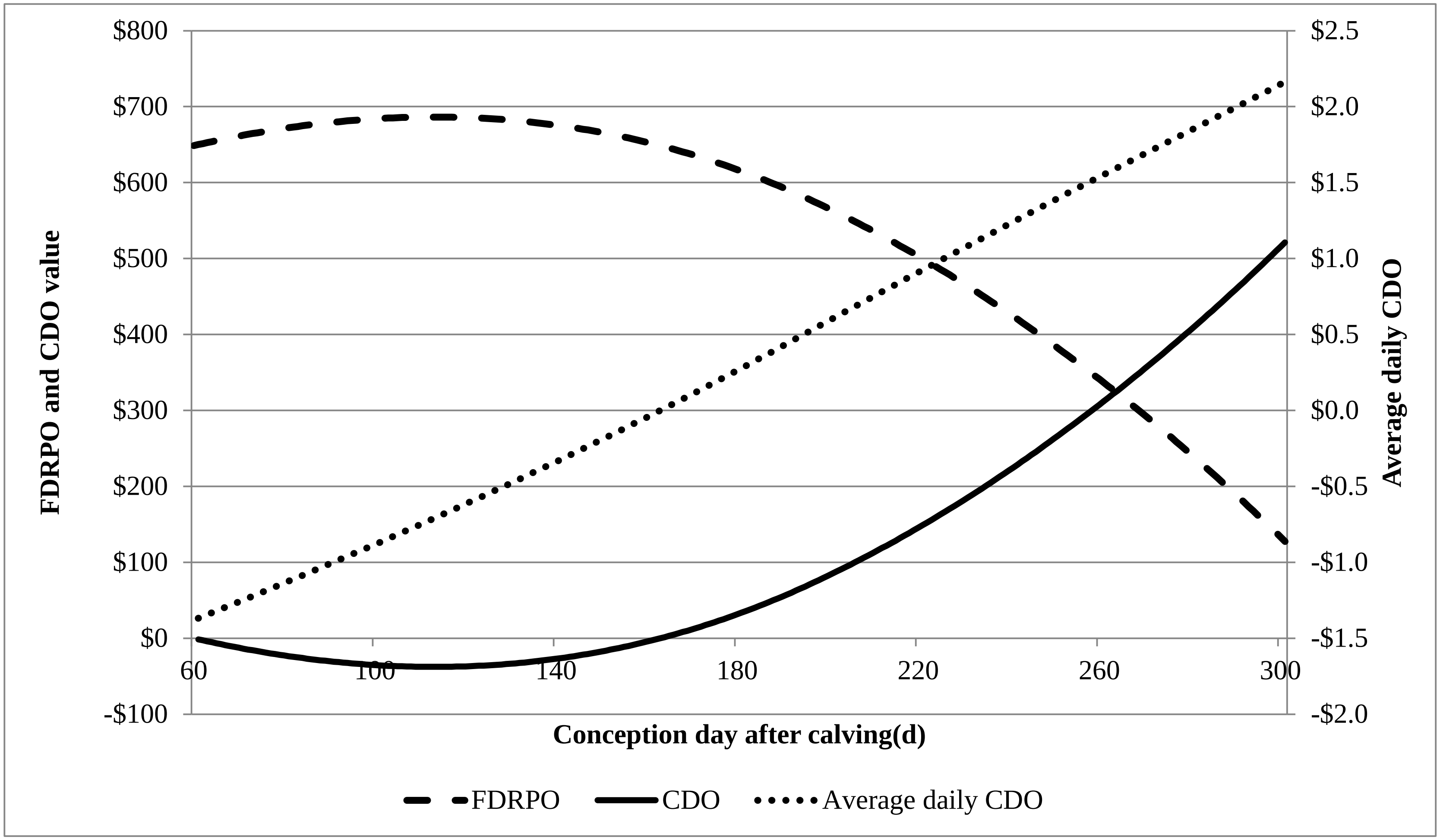


Figure 2.15. First day of lactation RPO value (FDRPO), cost of days open (CDO), and average daily CDO value with different open day lengths in the third parity under the past ten-year (2003 to 2012) average market condition

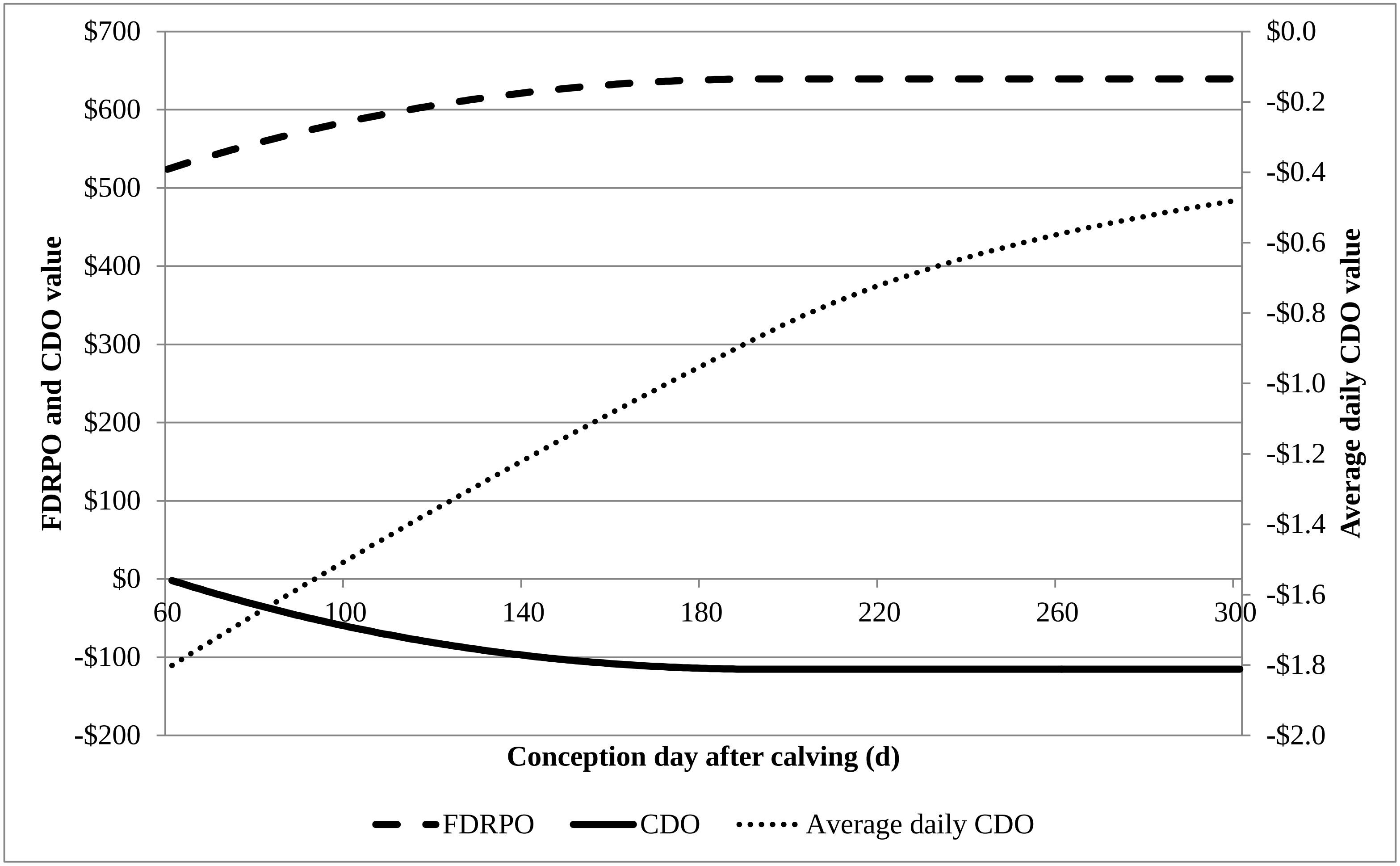
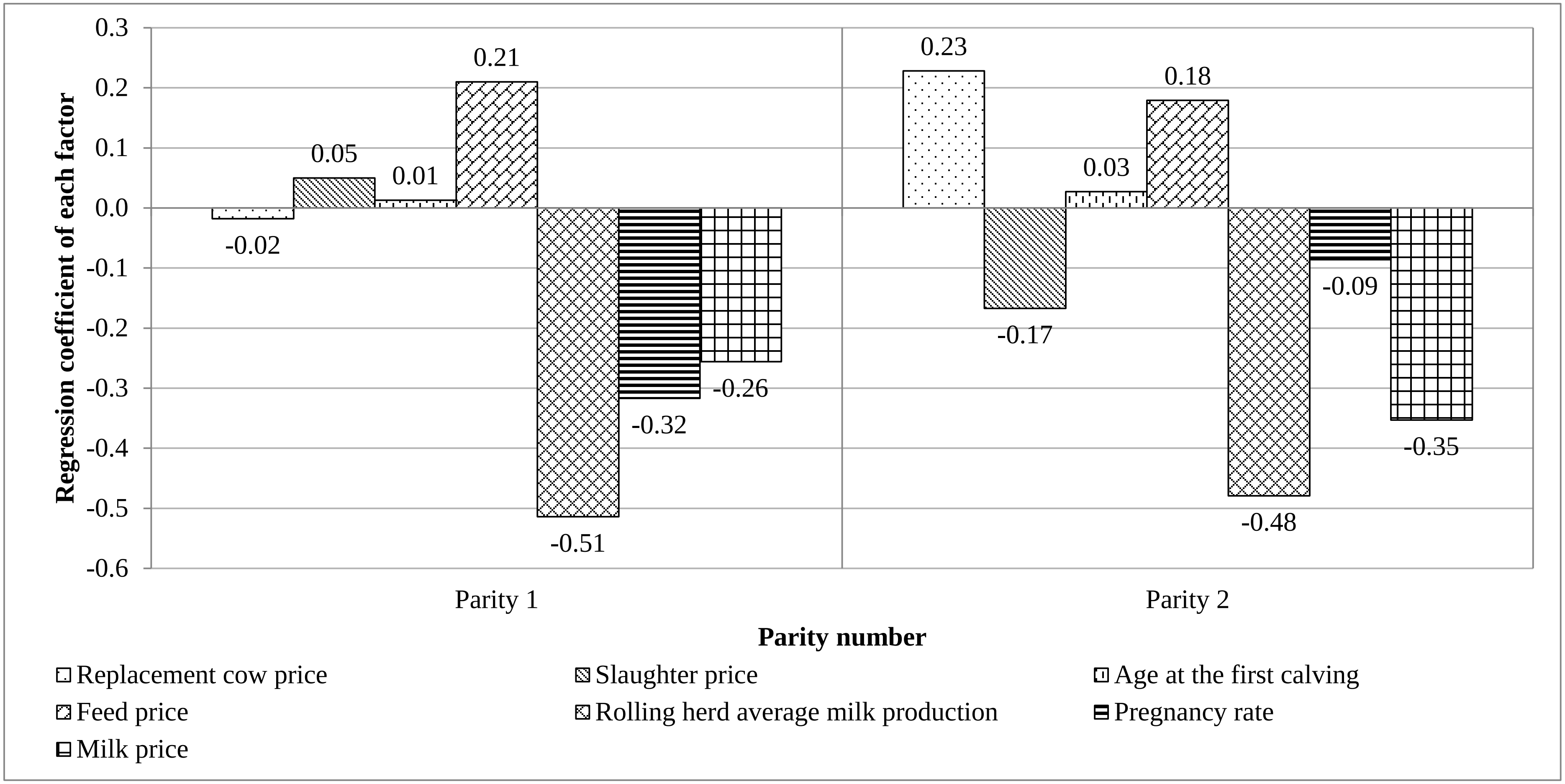


Figure 2.16. Relationship between cost of days open and milk price, feed price, slaughter price, replacement cow price, rolling herd average milk production (RHAM), pregnancy rate (PR), and age at the first calving (AFC) in the first two parities under the past ten-year average market condition



CHAPTER THREE. Common Clinical Dairy Disease Treatment Cost Survey

INTRODUCTION

Estimation of disease costs is important for the dairy industry. Understanding disease costs and their individual components could help improve farm profitability (Guard, 2008). Dairy producers, veterinarians, and advisors can use disease cost data to support prevention and treatment decisions. Whole-farm resource allocation may also improve allocation of disease control expenditures (Otte and Chilonda, 2000). Furthermore, disease cost estimates are also useful and essential for dairy-related companies in marketing and product research investment strategies.

The total cost of dairy disease includes milk production loss, pre-optimal removal cost, reproductive failure, labor costs, and veterinary and treatment costs (Dijkhuizen and Morris, 1997, Galligan, 2006). The veterinary and treatment costs rely on the treatment decisions made by the producer or the veterinarian. The labor costs depend on how much time is spent treating the disease and the value of a producer's time.

Although many studies have focused on disease control and prevention, few have estimated veterinary service fees and treatment costs. Guard (2008) provided a set of treatment cost estimates for several common dairy diseases, combining the results from published literature and practical experience. Several other studies investigated antibiotic usage to harvest detailed results about treatment proportion, length, and antibiotic types (Zwald et al., 2004, Sawant et al., 2005, Pol and Ruegg, 2007). The general dairy disease treatment cost has a wide range because of the large variation and uncertainty in treatment and control strategies. Computerized modeling and simulation are an effective method to capture the information and associated variation from experts' experience. The objective of this research was to estimate common dairy disease treatment costs using survey data. The results were used as the veterinary and treatment cost and labor costs in estimation of total disease cost in Liang et al. (2013b) .

MATERIALS AND METHODS

An online survey was employed to collect data from dairy veterinarians, industry consultants, researchers, hoof trimmers, and producers. This survey was conducted through SurveyMonkey® (Palo Alto, CA). Seven common clinical dairy diseases were included in this survey: mastitis, metritis, ketosis, lameness, milk fever (**MF**), left displaced abomasum (**LDA**), and retained placenta (**RP**). Four questions were listed in this survey for one clinical case of each disease (Table 3.1), inquiring about veterinarian service rate ($ per h), treatment cost per clinical case ($ per case),veterinarian treatment and diagnosis time (min. per case), and producer treatment and diagnosis time (min per case) per clinical case. Participants answered the questions by selecting an option from a pull-down list of individual question for each disease. In the dollar related questions, the range of answer options was from $0 to $300 with a $5 interval. In the time related questions, the range of answer options was from 0 min to 60 min with a 5 min interval.

Microsoft Excel® 2010 (Microsoft, Seattle, WA) was used to analyze the orginial survey responses in terms of the mean, SD, 2.5 percentile, and 97.5 percentile. PERT distribution was used for further simulation of each disease, specified for each question's responses by using the mean, 2.5 percentile, and 97.5 percentile from the survey responses as the mean, minimum, and maximum. Within the same disease, a correlation among four question responses were applied on those four PERT distributions to avoid the extreme and unrealistic simulated results. The distribution fitting and simulation were conducted with Microsoft Excel® 2010 (Microsoft, Seattle, WA) and @Risk Monte Carlo simulation add-in 6.0 (Palisade Corp., Ithaca, NY). In each simulation, 10,000 iterations and Latin Hypercube sampling were used with a static seed of 31,517 to ensure all simulations provided repeatable resutls.

RESULTS AND DISCUSSION

One hundred and thirty seven people started the survey by clicking the website link and forty-seven of them completed the survey (completion rate 34.3%). The results showed considerable variation among all the respondents. Table 3.1 shows the descriptive analysis results, including the mean, SD, and 2.5 percentile value and 97.5 percentile value. Table 3.2 shows the simulated results after 10,000 iterations, including the mean, SD, and 90% range (from the 5 percentile to 95 percentile).

The stochastic model and Monte Carlo simulation enable the model to utilize the variation in responses. Defined by the mean, 2.5 percentile, and 97.5 percentile of the original responses, the distribution was able to describe the responses and avoid the extreme outliers. A large number of interations made the simulated result more precise than the original survey responses. 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 ($34.60 per h), which was adjusted for inflation from 2009 farm manager wages ($ 29.21 per h, United States Department of Labor, 2009). The simulated results of the veterinary cost, drug cost, and producer labor cost are listed in Table 3.2.

The veterinary costs combined the veterinary time and the associated service rate. Left displaced abomasum had the greatest veterinary cost ($83.47 ± 29.76 per case), followed by lameness, milk fever, metritis, ketosis, mastitis, and retained placenta (Figure 3.1). Left displaced abomasum also had the highest treatment cost ($114.79 ± 62.91 per case), followed by lameness, retained placenta, metritis, milk fever, mastitis, and ketosis (Figure 3.2). In addition, LDA had the highest producer labor cost ($16.59 ± 8.85), followed by lameness, MF, ketosis, RP, mastitis, and metritis (Figure 3.3). Overall, LDA had the greatest total veterinary and treatment cost and producer labor cost. Although the LDA is not the most common disease with an incidence at 2% to 7% in dairy farms (Shaver, 1997), LDA treatment includes omentopexy, toggle-pin fixation, and rolling other than injection and sample culturing (Stengärde and Pehrson, 2002, Guard, 2008). As LDA treatment was more complicated than other common diseases, the related labor cost was higher for the postoperative care.

As shown in Figure 3.1, 3.2, and 3.3, lameness had the second greatest treatment, drug, and producer labor costs. Lameness is a universal disease in dairy farms with high incidence. Treatment of lameness included trimming, medical treatment, etc. Although lameness is second highest in the veterinary cost, it was less than half of LDA ($33 vs. $83).

Another finding from this survey was that the variation of all the responses was high. The cost was relatively subjective according to the treatment and control plan of individual producers and veterinarians. On the cow side, the pathogen type, severity, age, production, and presence of other diseases would influence treatment decisions. The decision maker, the producers and veterinarians, always have personal preferences for diagnosis and treatment. The farm size, location, and management could also affect disease treatment. Furthermore, this survey assumed the labor wage equal to the national farm manager salary however, dairy producers may self-estimate their time at different values, which could change the producer labor cost in both directions.

CONCLUSIONS

Multiple factors influenced disease treatment and labor costs. The variation in results demonstrated the substantial diversity in dairy disease diagnosis, treatment, drug, and labor costs. Results from this survey provided data for further research on disease economics.

Table 3.1. The descriptive analysis results from original survey responses for each survey question, including the mean and SD.

	How much money will the producer spend to treat the disease per case? ($)	The veterinarian hourly service rate ($ per h)	How much time does the average veterinarian spend in minutes to diagnose and treat one case of this disease?	How much time does the average producer spend in minutes to diagnose and treat one case of this disease?
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
Milk fever	30.87 ± 42.71	93.25 ± 48.59	18.04 ± 14.36	20.48 ± 12.34

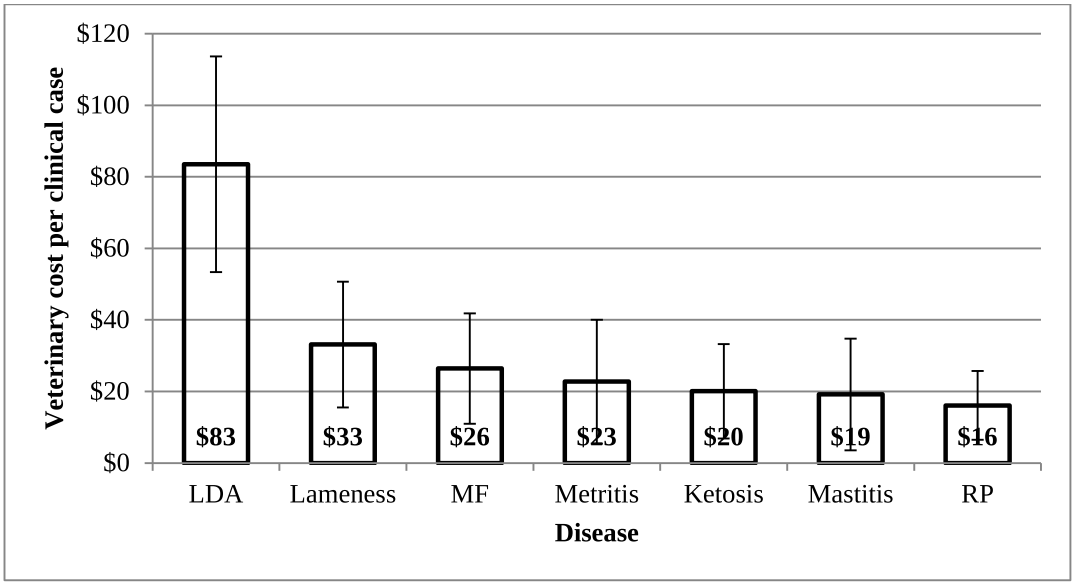
Table 3.2. Simulated veterinary cost, treatment cost, and producer labor cost for each disease, including the mean and SD. The mean, 2.5 percentile, and 97.5 percentile data from the survey responses were fit into a PERT distribution and a 10,000 iteration simulation was conducted on this distrbution to estimate the final costs.

	Mean ± SD		
	Veterinary cost[1] ($)	Treatment cost ($)	Producer labor cost[2] ($)
Mastitis	19.61 ± 15.59	56.93 ± 27.20	12.34 ± 6.14
Metritis	22.75 ± 17.19	67.33 ± 30.96	10.37 ± 4.65
Ketosis	20.06 ± 13.01	32.25 ±19.34	12.64 ± 6.24
Left displaced abomasum	83.47 ± 29.76	114.79 ± 62.91	16.59 ± 8.85
Retained placenta	16.06 ± 9.74	69.00 ± 40.25	12.51 ± 6.30
Lameness	33.11 ± 17.81	71.02 ± 45.01	13.80 ± 6.25
Milk fever	26.39 ± 15.54	57.68 ± 38.24	13.31 ± 6.12

[1]The veterinary cost was the combination of veterinary service and the assoicated hourly rates.

[2]The producer labor cost was the product of producer diagnosis and treatment time and the average producer hourly wage ($34.60 per h)

Figure 3.1. Simulated veterinary cost per clinical case for each disease[1,2,3]. The mean, 2.5 percentile, and 97.5 percentile data from the survey responses were fit into a PERT distribution and the a 10,000 iteration simulation was conducted on this distrbution to estimate the veterinary costs.

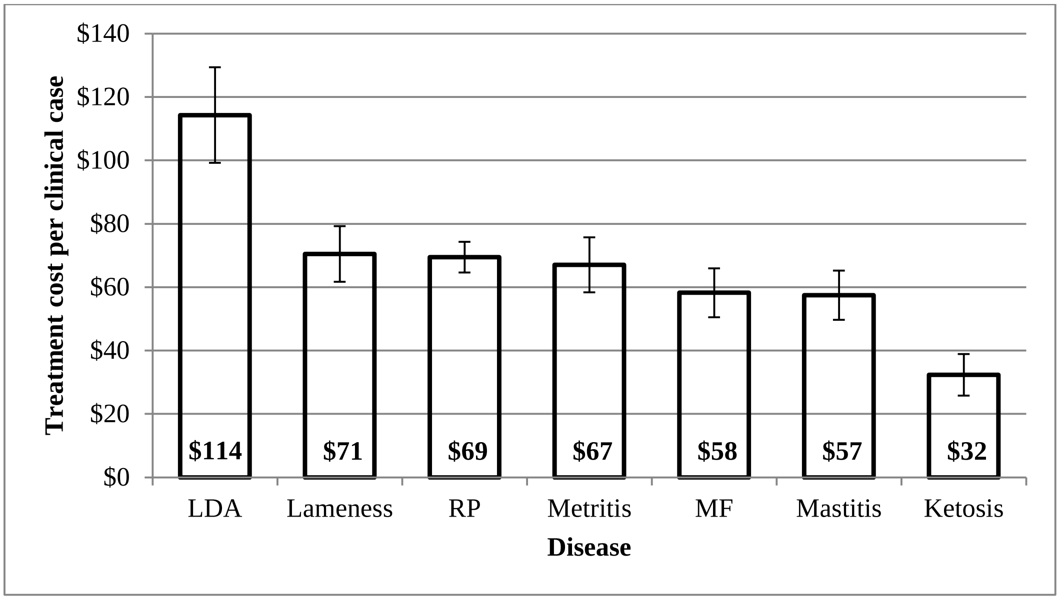


[1]LDA = left displaced abomasum

[2]RP = retained placenta

[3]MF = milk fever

Figure 3.2. Simulated treatment cost per clinical case for each disease[1,2,3]. The mean, 2.5 percentile, and 97.5 percentile data from the survey responses were fit into a PERT distribution and the a 10,000 iteration simulation was conducted on this distrbution to estimate the treatment costs.

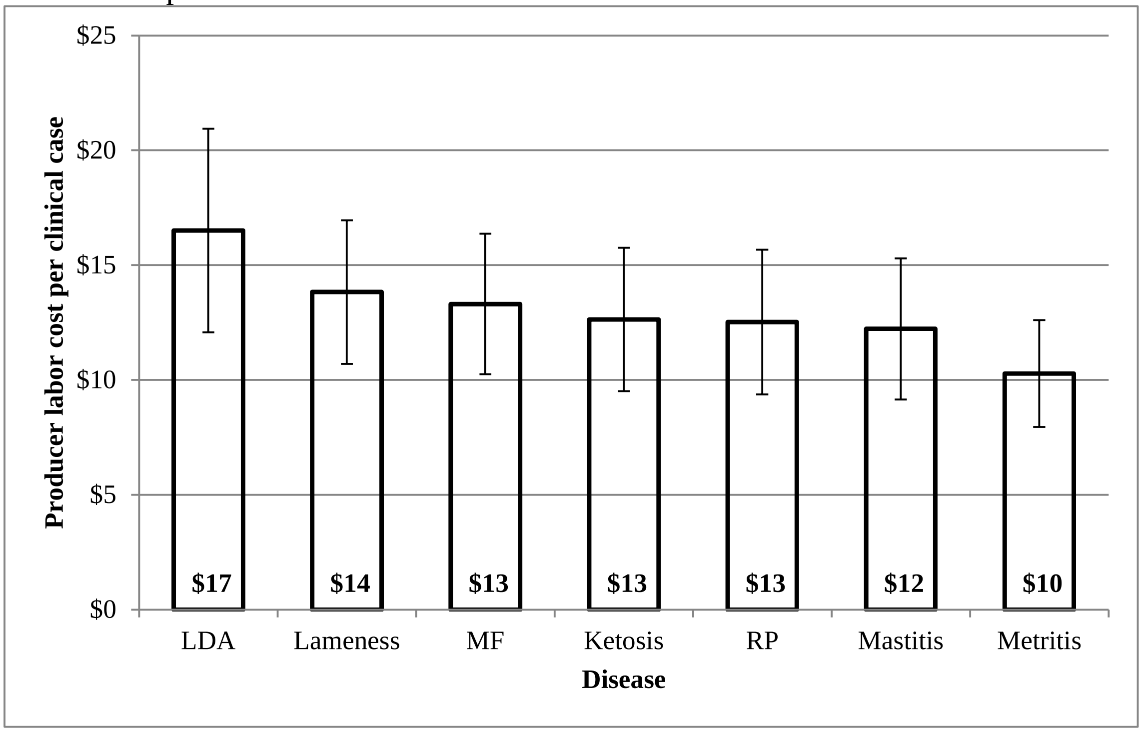


[1]LDA = left displaced abomasum

[2]RP = retained placenta

[3]MF = milk fever

Figure 3.3. Simulated producer labor cost per clinical case for each disease[1,2,3]. The mean, 2.5 percentile, and 97.5 percentile data from the survey responses were fit into a PERT distribution and the a 10,000 iteration simulation was conducted on this distrbution to estimate the producer labor costs.



[1]LDA = left displaced abomasum

[2]RP = retaiend placenta

[3]MF = milk fever

CHAPTER FOUR. Estimating the U.S. Clinical Dairy Disease Costs with a Stochastic Simulation Model

INTRODUCTION

Cow health influences dairy farm profit and alters biological mechanisms and productivity (Dijkhuizen and Morris, 1997, Galligan, 2006). Different diseases have different effects on cow health and economic losses. Disease affects a dairy cow's productivity, including feed intake and efficiency, physiological processes, production, reproduction, and pre-optimal removal (Dijkhuizen and Morris, 1997).

Dairy health economics focuses on the fiscal impacts of dairy disease on the dairy industry using animal health economics principles. Health issues change dairy cow performance, which affects current profits and the future value of a cow. In addition, the external factors such as market conditions and government policies also influence the profit of a dairy farm (Seegers et al., 1994, Seegers et al., 2003).

Different from the conservative physical measuring of animal health performance, the economic assessment of health performance helps resource allocation (Otte and Chilonda, 2000). Disease influences profitability through direct and indirect effects (Dijkhuizen and Morris, 1997, Galligan, 2006). The direct effects include visible losses (death, milk production decrease, and slow growth) and invisible losses (poorer reproductive performance, herd demography change, or lower feed converting efficiency). The indirect effects include revenue decreases (lower production, reduced product quality, and shorter productive life) and additional costs (veterinarian and drug costs and labor costs). Furthermore, health conditions influence culling policy because of the changes in potential value.

Common dairy diseases included (but are not limited to) mastitis, lameness, metritis, retained placenta (**RP**), left displaced abomasum (**LDA**), ketosis, and milk fever (**MF**). Robust epidemiological studies have focused on the impacts of disease on dairy cow performance, especially for mastitis, lameness, and reproductive failure that were generally considered as the most expensive health issues in the dairy industry (Kossaibati 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 varied largely in different studies. Halasa et al. (2007a) summarized the cost of mastitis ranging from €102 ($135) to 287 ($379) per case. The top two cost categories were decreased milk production and treatment (Seegers et al., 2003, Cha et al., 2011, Heikkilä et al., 2012).

Lameness is a general name of foot or leg disorder condition caused by multiple factors, including infectious agents, laminitis, and lesions (Sanders et al., 2009). Lameness influences the dairy cow's productivity, welfare, and profitability (Cha et al., 2010). Kossaibati and Esslemont (1997) estimated the average cost of a lameness case at ₤246.22 in the U.K., ranging from ₤112.80 to 391.80 according to the lameness type. A recent U.S. estimation showed the average costs at $177.62 per case, ranging from $120.70 to $216.07 for different disorders.

Retained placenta and metritis have a complex correlation. Retained placenta is widely considered as a predisposing factor for metritis (Sandals et al., 1979, Markusfeld, 1984, Bartlett et al., 1986). A common definition for RP is the presence of fetal membranes 24 h or later after parturition or fetal membrane retained for more than 6 h (Laven and Peters, 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, which appear as a longer calving interval (Gröhn and Rajala-Schultz, 2000, Bellows et al., 2002, Gilbert et al., 2005). Moreover, metritis needed an antibiotic treatment in some cases and increased culling risks (Bartlett et al., 1986, Rajala-Schultz and Gröhn, 1999a, Pol and Ruegg, 2007). Guard (2008) estimated the total cost of retained placenta and metritis at $315 per case.

Left displaced abomasum is the predominant type of displaced abomasum in the U.S. (80% to 90%, Coppock, 1974). Left displaced abomasum appears when the abomasum is filled with gas and subsequently trapped by the descending rumen to the left side of abdominal cavity (Coppock, 1974, Markusfeld, 1986). Miller and Dorn (1990) claimed that the cost of milk loss was the largest portion in the total LDA costs. Shaver (1997) stated that the cost of veterinary and treatment highly influenced on the total cost, which was projected at $334 per case, with the treatment cost ranging from $100 to $200. Geishauser et al. (2000) suggested the cost of LDA varied from $250 to $400 per case, depending on whether surgery was needed.

Ketosis occurs with negative energy balance, especially glucose imbalance (Baird, 1982, Beem, 2003). The incidence of clinical ketosis ranges from 2% to 15% (Beem, 2003). Ketosis decreased milk production and increased the culling cost (Gröhn et al., 1998, Rajala-Schultz and Gröhn, 1999a, Rajala-Schultz et al., 1999). In addition, necessary treatment generated another portion of costs, which was valued at $1.17 per cow per year in Varga (2004) and $5 per case in Guard (2008). Duffield and Herdt (2000) estimated the total ketosis cost at $138 per case; Guard (2008) provided a cost of $232 per case.

Milk fever is also known as 'hypocalcaemia', caused by insufficient plasma calcium soon after parturition (Horst et al., 1997, Kossaibati and Esslemont, 1997). The prevalence of subclinical MF was 33% and the clinical stage was 5% (Mulligan and Doherty, 2008). Milk fever reduced the productive life of dairy cows by 3.4 yr. (Horst et al., 1997). In addition, MF caused milk production decreases (Rajala-Schultz et al., 1999, Wilson et al., 2004). Miller and Dorn (1990) summarized that the pre-optimal removal cost was the greatest part of total MF cost. The total cost was estimated at $220 per case on average (Kossaibati and Esslemont, 1997).

The objective of this chapter is to introduce a farm-level stochastic model with Monte Carlo simulation, in order to estimate the common dairy disease costs in the U.S. with flexibility in farm and market conditions. The relationship among farm conditions, market prices, and the total disease costs were further analyzed in this model.

MATERIALS AND METHODS

Basic Model

The basic farm-level stochastic model with Monte Carlo simulation was described by Bewley et al. (2010). The model was constructed in Microsoft Excel 2010 (Microsoft, Seattle, 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), conception rate (**CR**), heat detection rate (**HDR**), rolling herd average milk production (**RHAM**), and age at the first calving (**AFC**) (Table 4.1). The 2013 market prices used in this model that the mean ± SD of milk, feed, replacement cow, and slaughter were $0.45 ± 0.05 per kg, $0.23 ± 0.04 per kg dry matter, $1,648 ± 194 per cow, and $ 1.83 ± 0.24 per kg, respectively (Liang et al., 2013c). This model was constructed with the flexibility for users to input their farm-level parameters into this model as inputs instead of default parameters. All default model inputs were listed in Liang et al. (2013c).

Disease Cost

Seven common clinical dairy diseases were included in this model: mastitis, metritis, lameness, ketosis, LDA, RP, and MF. The total cost of each disease was summarized into seven categories: veterinary and treatment cost, milk production decrease, culling cost, discarded milk due to antibiotic use, death loss, cost of extended days open (**CDO**), and labor costs All the costs were estimated for clinical cases in each disease. Each disease cost category was calculated individually and then summed to find the total costs for each disease. The total disease costs for primiparous and multiparous cows were calculated separately.

Veterinary and Treatment Cost. This model used the veterinary and drug cost data from the common dairy disease treatment cost survey results, discussed in Liang et al. (2013a). Veterinary and treatment costs were assumed equal across parities.

Producer Labor Cost. In addition to the veterinary service time, producers also spent time on disease diagnosis and treatment. The cost of producer labor was the product of disease caused producer time input and hourly labor wage. The former was collected from the survey results (Liang et al., 2013a) and the latter was collected from the United States Department of Labor website (2009, $29.17 per hour), then adjusted for inflation into the 2013 value at $34.17 per hour. Producer labor cost was also assumed to be equal across all parities.

Disease Incidence and Timing. Described as the 'tip' of the disease economic impact 'iceberg,' the cost of clinical disease underestimated the total disease prevalence and fiscal loss, as most disease remained in a subclinical form (Dohoo, 1993, Bewley et al., 2010). The variation of disease incidence was huge depending on the geography, herd size, age, production, and management. Admitting the uncertainty in disease incidence, the default disease incidence rates were collected from Wilson et al. (2004), which also provided milk loss data (Table 4.2). As disease incidence varied across parities, disease incidence rates were separated for the first, second, and later parities. Future users could replace the default numbers with actual farm data.

Disease timing also varied at different DIM during the same parity. For example, RP and milk fever only happened within the first two weeks 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 by the lactation curve and RPO changes.

Milk Loss. Milk loss was the unrealized milk production decrease owing to disease effects. Due to the sickness, this portion of milk had never been produced. However, discarded milk (due to antibiotic use) was the non-salable part of milk production. The decreased milk production led to a feed intake reduction. The value of the saved feed was caculated based on a ratio of the average daily feed intake and average daily milk production, separated for the primiparous and multiparous cows.

The disease-caused milk production reduction was calculated in this model separately for the primiparous cows and multiparous cows, based on the milk loss data published by Wilson et al. (2004). The 95% confidence interval (ranging from 2.5 percentile to 97.5 percentile) 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.

Although in some diseases, the milk production was reported higher after the occurrence, the production increase was not considered in this model and calculated as no change in milk yield. Rather than disease stimulating elevated milk production, high-producing cows were more susceptible to disease. After recovering from the disease, the high-producing cow would return to a high milk yield level because of the better potential genetic merit.

The total milk reduction was calculated weekly. Milk production decrease data were specified for the 1st, 2nd, 3rd, 4th, and later weeks post 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 was generated during the antibiotic treatment period and the following milk withdrawal period (if needed). Antibiotics were used only for mastitis, metritis, and lameness. The antibiotic treatment lengths, the proportion of antibiotic treatment cases over all clinical cases, and the type of antibiotics were collected from Pol and Ruegg (2007). To summarize each disease antibiotic use at the farm level, Pol and Ruegg reported antibiotic usage using defined daily doses (**DDD**) per cow per year as the unit. Specified for disease, antibiotic type and associated treating methods (intramammary or parenteral). The treatment period quotient of the total DDD over the daily dosage, limited by each antibiotic product specified for the treating method. The treatment period length of each antibiotic was then converted from days per cow per year to days per clinical case. The following milk withdrawal period of each drug was collected from the Food Animal Residue Avoidance Databank (**FARAD**, www.farad.org), focusing on lactating cows. The total milk discarded period was the period length of antibiotic treatment plus following milk withdrawal (if accurred). 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.

Culling and Death. The culling and death costs were calculated using the methodology described in Bewley et al. (2010).

Reproduction. In this model, the detrimental effects of disease on reproduction were reflected in an extended days open (**DO**). The change of DO fit into separate stochastic PERT distribution for each disease using the mean and 95% range reported in a meta-analysis study on the effect of disease on reproductive performance (Fourichon et al., 2000). The CDO was calculated for the 1^{st}, 2^{nd}, 3^{rd}, 4^{th}, 5^{th}, and 6^{th} parity individually. The cost of extended DO was the the 1^{st} day in lactation RPO (**FDRPO**) difference between an average cow and a disease affected cow, detailed description in Liang et al. (2013c)

$$CDO_{k,l}=FDRPO_{average,l}-FDRPO_{k,l}$$

Where,

$CDO_{k,l}$=cost of extended DO due to disease k in parity l,

$FDRPO_{average,\ l}$=an average cow's RPO on the 1st day in lactation in pariy l

$FDRPO_{k.l}$ =RPO on the 1st day in lactation in pariy l of a cow with disease k

In this model, CDO was reported for primiparous and multiparous cows; the latter one was the weighted CDO 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, PR, 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 resutls.

Sensitivity Analysis

After each simulation, @Risk conducted a multiple regression analysis as the sensitivity analysis between the stochastic factors and outputs to test the effects of selected stochastic factors (including the RHAM, PR, AFC, milk price, feed price, replacement heifer price, and slaughter price) on each disease cost separately. The resutls of sensitivity analysis were plotted in tornado graphs and spider graphs. The tornado graph showed the regression coefficient of each factor in the multiple regression analysis or the change in correspondent output with one SD increase in each factor. In addition to the tornado graph, the spider graph was used to present the effect of each factor on the output. The spider graph had each stochastic factor on the x-axis with 10% interval from the associated PERT distribution, and plotted the correspondent output as the dependent variable. The spider graph showed the changing trend in the output with different sampled stochastic factor value levels.

RESULTS AND DISCUSSION

Total disease costs of each disease are listed in Table 4.3, separated for primarparous and multiparous cows. In general, disease costs were greater for multiparous cows 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 4.3). For example,the largest contributor to total mastitis cost was decreased milk production, however, the contributor to total LDA cost was veterinary and treatment.

Compared to Guard (2008), the veterinary and treatment costs were much higher in most diseases. In this model, the per-case veterinary and treatment cost data collected from Liang et al. (2013a) was not adjusted for the veterinarian visiting frequency. Neither related with other cost categories nor stochastic factors, the costs of veterinary and treatment contributed to the total disaease costs separately and would not impact the further sensitivity analysis results. Users could replace the default veterinary and treatment costs with their own data to customize the disease 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 counterparts from previous epidemiological studies. Liang et al. (2013c) found that a dairy cow's RPO value was low under the 2013 market condition with a high slaughter price and low replacement price. As a consequence, the RPO-based culling costs and CDO were lower in general than in previous estimates.

Mastitis

The average mastitis cost was \$309.93 ± 74.54 per case in primiparous cows and \$340.08 ± 80.14 per case in multiparous cows. Total mastitis costs were in the range given by Halasa et al. (2007) (\$3.8 to \$360 per clinical case) and higher than the results from Bar et al. (2008), Guard (2008), Bewley et al. (2010), Bar et al. (2008b), and Cha et al. (2011).

The cost of reduced milk production was the largest portion of total costs, contributing \$135.68 ± 44.24 (PRIMIPAROUS COWS) and \$137.88 ± 39.94 (multiparous cows) to the total costs. This result demonstrated the statement from Seegers et al. (2003) that milk production decrease was the major economic loss caused by mastitis. For all parities, the cost of producer labor was \$12.13 ± 6.18 per case, and the cost of veterinary and treatment was \$77.13 ± 32.58 per case, based on the results from Liang et al. (2013a). Cha et al. (2011) and Heikkilä et al. (2012) have addressed that the cost of milk loss and treatment were the two most expensive cost categories in total mastitis costs.

The milk discard period due to antibiotic use and the following milk withdrawal was 4.36 ± 2.42 d, and the associated discarded milk loss was \$63.18 ± 39.38 per case in primiparous cows and \$79.65 ± 48.42 per case in multiparous cows. The different discarded milk cost acoss parities was due to the higher daily average milk production in multiparous cows. The cost of discarded milk in this study was higher than the estimations from Østergaard et al. (2005), Bar et al. (2008b), and Guard (2008), in which the discarded milk period data was assumed from experts' experience. Although the antibiotic usage data in this model was 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.

The death cost was $11.43 ± 1.65 per case in primiparous cows and $12.23 ± 1.71 in multiparous cows, explained by the greater body weight of aging animal. Culling cost was $9.18 ± 5.88 (primiparous cows) and $17.30 ± 6.34 (multiparous cows). Mastitis related cost of extended days-open was $1.20 ± 2.36 (primiparous cows) and $3.17 ± 3.86 (multiparous cows). Costs of culling and extended days-open were based on the daily RPO value. Compared to earlier studies (Bar et al., 2008b, Guard, 2008, Cha et al., 2011), the CDO was lower, possibly because of the 2013 market condition discussed in Liang et al. (2013c). In addition, the mastitis caused extended days-open was comparatively short, ranging from -0.9 to 1.6 d, (Fourichon et al., 2000)

Lameness

The total lameness costs were $179.37 ± 66.51 (primiparous cows) and $217.66 ± 66.29 (multiparous cows) per case. This estimation was close to Ettema and Østergaard (2006) and Cha et al. (2010), but lower than Enting et al. (1997), Kossaibati and Esslemont (1997), and Guard (2008). The greatest portion in total lameness cost was from veterinary and treatment cost ($102.67 ± 54.48 for all parities), which was much higher than previous estimations (Guard, 2008). This difference may due to the different definition the respondents refered to when they were taking the survey. Some people mentioned hoof trimming as part of the lameness treatment cost, which would elevate the estimation (Liang et al., 2013a).

The culling costs were \$22.43 ± 12.17 (primiparous cows) and \$49.09 ± 17.85 (multiparous cows) per lameness case. The costs of extended days open were \$8.52 ± 11.12 (primiparous cows) and \$3.50 ± 4.33 (multiparous cows). Both of the RPO-based costs were lower than Guard (2008), which might be explained by the different culling cost calculation approach and 2013 market conditions. 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 was high across different lameness types. Other studies also claimed that lameness could extend the calving interval greatly through different aspects, such as harder heat detection (Lee et al., 1989, Barkema et al., 1994).

The milk production decrease caused by lameness valued \$19.62 ± 16.41 (primiparous cows) and \$31.43 ± 15.58 (multiparous cows), lower than the cost of \$169 per case from Guard (2008). Researchers have been debting about the effect of lameness on milk production that some studies showed a significant detrimental influence (Rajala-Schultz et al., 1999, Warnick et al., 2001) whereas other studies failed to find the impact or stated a positive effect on milk production (Dohoo and Martin, 1984, Sanders et al., 2009). The interaction of disease incidence and milk production was not included, which explained incompatible results that high-producing cows had a higher lameness risk than a low-producing cow. In addition, the high feed price reduced a part of the economic loss of milk production.

The simulated average milk withdrawal period was 0.12 ± 0.65 d. the discarded milk costs were \$1.68 ± 9.23 (primiparous cows), and \$2.11 ± 11.56 (multiparous cows), close with the result from Guard (2008). Instead of using the 96% antibiotic usage probability on foot infection reported in Pol and Ruegg (2007), five percent from Guard

(2008) was selected and applied in this model for antiobiotic usage possibility in lameness. The producer labor cost was $13.87 ± 6.38 per case. The missed slaughter values for on-farm death were $10.58 ± 1.52 (primiparous cows) and $11.01 ± 1.54 (multiparous cows).

Metritis

The total metritis costs were $175.77 ± 49.76 (primiparous cows) and $191.22 ± 52.00 (multiparous cows), higher than $106 in Bartlett et al. (1986). The veterinary and treatment cost was $89.09 ± 39.12 and the labor cost was $10.32 ± 4.80 per case. The simulated average milk withdrawal period was 2.62 ± 1.51 d, and the discarded milk valued $38.07 ± 24.50 (primiparous cows) and $47.96 ± 30.00 (multiparous cows). The costs of decreased milk production were $2.79 ± 1.42 (primiparous cows) and $7.71 ± 2.95 (multiparous cows). the culling costs were $6.21 ± 2.40 (primiparous cows) and $15.16 ± 5.62 (multiparous cows). The missed slaughter value was $15.43 ± 2.26 in the primiparous cows and $16.67 ± 2.33 in the multiparous cows.

Retained Placenta (RP)

The total RP costs were $145.97 ± 49.99 (primiparous cows) and $213.10 ± 57.70 (multiparous cows), lower than the esitmation of $319 per case from Shaver (1997). The cost associated with veterinary and treatment was $84.95 ± 43.32 and the cost of producer labor was $12.36 ± 6.40. The fiscal losses due to milk production decrease were $40.40 ± 20.80 (primiparous cows) and $112.30 ± 35.95 (multiparous cows). The costs of extended calving interval were $8.26 ± 10.45 (primiparous cows) and $3.52 ± 4.15 (multiparous cows).

Retained placenta caused 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 (1999a) who indicated that RP was not a major risk factor in involuntary culling. With a strong 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 ($321 in the primiparous cows and $404 in the multiparous cows) were higher than $315 in Guard (2008). However, RP and metritis costs were calculated separately in this model, not considering the interrelationship between RP and metritis.

Left Displaced Abomasum (LDA)

The average LDA costs per case was $404.73 ± 100.05 (primiparous cows) and $555.79 ± 116.79 (multiparous cows). The greatest portion was from the cost of veterinary and treatment at $197.87 ± 70.59 per case, fell in the range ($100 to $200 per case) given by Shaver (1997). The need of surgery to treat LDA case may explain the high cost associated with 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 ($141.02 ± 64.31 for primiparous cows, $235.78 ± 75.97 for multiparous cows). This result was in agreement with Miller and Dorn (1990) that cost of milk loss was high in the total cost of LDA. Due to the high culling risk related with LDA, the culling cost was $23.20 ± 12.73 in primiparous cows and $79.62 ± 29.29 in multiparous cows. Costs of on-farm death were $20.58 ± 3.01 in primiparous cows and $22.06 ± 3.08 in multiparous cows. Costs of extended DO were

$5.43 ± 9.00 (primiparous cows) and $3.31 ± 4.10 (multiparous cows). The labor cost was $16.63 ± 9.03 per case.

Ketosis

The total ketosis cost was $79.64 ± 24.45 in the primiparous cows and $91.83 ± 24.11 in the multiparous cows, much lower than the previous estimation at $232 per case (Guard, 2008). The greastest difference was from the milk production loss portion. This model projected the milk loss cost at $0.83 ± 0.58 (primiparous cows) and $5.59 ± 1.74 (multiparous cows) per case, however, the milk production loss was $91 per case in Guard (2008). Based on the results from Wilson et al. (2004), ketosis affected cows had a higher milk production after the occurrence, demonstrating that the ketosis incidence was greater in high-producing cows (Baird, 1982) who eventually showed a‘better-than-average’ milking ability after recovering from ketosis.

The veterinary and treatment cost was $52.26 ± 21.00, and the producer labor cost was $12.66 ± 6.47 per case. Those two categories were higher than the estimation from Guard (2008) ($15 and $5, respectively), but lower than the $170 per cow treatment cost from Varga (2004). The culling cost for ketosis were $4.30 ± 1.75 (primiparous cows) and $12.59 ± 4.71 (multiparous cows), and the death costs were $5.11 ± 0.74 (primiparous cows) and $5.46 ± 0.76 (multiparous cows).

Milk Fever(MF)

Milk fever was assumed to occur only in the multiparous cows. The total cost of MF was $166.26 ± 45.88 per case. As a farm level result, which considered all severity degrees, this value was in agreement with Kossaibati and Esslemont (1997) that the cost of MF was \$85.6, \$263.65, and \$3,615 for a mild, severe, and fatal case, respectively. The largest portion was from the veterinary and treatment cost at \$85.19 ± 43.14 per case. As MF caused a higher on-farm mortality risk and a greater culling risk (Horst et al., 1997), the costs of culling and death were \$15.12 ± 5.60 and \$44.08 ± 6.14 per case, respectively. Miller and Dorn (1990) stated that pre-optimal removal took the majority portion in the total MF cost. This model partially demonstrated it with condition that the culling cost was the second highest portion in the MF cost after the veterinary and treatment cost. The milk production decrease valued \$5.07 ± 1.91 and labor cost was \$13.34 ± 6.22 per case. In addition, the cost of extended days open was \$3.35 ± 3.95 per case.

For all diseases (except MF), the total costs in the multiparous cows were higher than in the primiparous cows due to the higher average daily milk production (29.75 kg per day vs 30.52 kg per day), the greater daily RPO value, and the elevated body weight, all those changes associated with the greater milk losses, discarded milk value, culling cost, and on-farm death cost.

Sensitivity Analysis

Market Price. Figure 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, and 4.7 showed the effects of market price on the total cost of each disease in the primiparous cows and multiparous cows, respectively (only multiparous cows for mf). Market prices consistently impacted the total disease costs except MF. The higher replacement price and milk price would increase the disease cost; the higher slaughter price and feed price would decrease the disease cost. In the MF case, a higher slaughter price would increase the total cost because of the high on-farm mortality risk (4%, Guard, 1998) that increased the on-farm death cost. Associated with the replacement cost, the replacement price and slaughter price had a higher impact in the primiparous cows than in the multiparous cows, because the replacement price and slaughter price were used only in the first-day rpo calculation in the primiparous cows when a cow's market value switched from the replacement cow value to the slaughter value (Liang et al., 2013c). The influence of increased milk price and feed price was greater in the multiparous cows than in the primiparous cows due to the higher milk production loss and discarded milk amount (if applicable). Moreover, the higher feed price could compensate to a part of the cost of decreased milk production because of the related lower feed intake. The higher slaughter price decreased the culling cost, which resulted in a lower mastitis cost.

For example in mastitis, with one SD increase in the milk price, replacement cow price, feed price, and slaughter price, the total mastitis cost would change by $46.87, $6.11, -$33.76, and -$5.03 per case in the primiparous cows (Figure 4.1). This result was in agreement with Bar et al. (2008b) that the higher milk price or replacement cow price would increase mastitis cost. Heikkilä et al. (2012) found a similar result that a higher milk price or a greater replacement cost would increase the clinical mastitis cost in Denmark.

Market prices had consistant influences on lameness cost (Figure 4.2). One SD increase in the replacement cow price increased the per-case lameness cost by $25.09 in the primiparous cows and $7.81 in the the multiparous cows. One SD increase in the milk price would increase the per-case lameness cost by $15.80 in the multiparous cows. One SD increase in the slaughter price reduced the per-case lameness cost by $13.81 in the primiparous cows. One SD increase in the feed price decreased the per-case lameness cost by $6.27 in the primiparous cows and $14.53 in the the multiparous cows.

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

Herd Performance. The sensitivity analysis was conducted on three herd performace factors: RHAM, PR and AFC. The effects of herd performance on the total cost of each disease were showed in Figure 4.8 to 4.14, separately. The PR impacted on the disease cost by changing the calving interval length and the related performance. The AFC changed the time to start milking in a cow's life 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 CDO, and milk losses. Lacking the quantified milk loss data based on milk production level, the RHAM impacted the milk losses through changing the saved feed value, which was calculated based on the daily feed efficiency.

The same herd performance factor had different effects on different diseases and parities. The impacts of herd performance were greater in the multiparous cows than primiparous cows, and might be explained that a multiparous cows cow was aging and approaching her maturity with a better production. Another potential reason was that the 90% range of RHAM was large (Table 4.2). The greater variation in RHAM led to the greater changing range in disease costs. Furthermore, some disease (i.e., retained placenta and left displaced abomasum) had larger influence on production and reproduction in the multiparous cows than primiparous cows. The greater disease impacts enhanced the sensitivity of the total disease cost on the herd performance

Interestingly, a higher RHAM decreased the total costs of ketosis and lameness in the primiparous cows (Figure 4.9 and 4.13). The RHAM related only with discarded milk costs, milk losses, and culling cost. In the primiparous cows, the total costs of ketosis and lameness both had relatively larger portions from culling cost, compared to the milk production decrease and discarded milk costs (in lameness). In the RPO-based culling cost, a higher milk production would reduce the disease-caused culling cost (Liang et al., 2013c). As a result, the higher milk production decreased the total costs of the disease that had a relatively higher culling risk and lower decreased milk production after occurrence.

Compared to the previous disease economic studies, this model included the variation in the cow and market factors, which enabled the model to estimate the flexible disease cost under different conditions. Although LDA had the greatest costs in this study, considering the correspondent incidence, the monetary impact should not be overestimated on the farm level. One limitation of this model was that the interrelationships between diseases were not included. In reality, the correlation between diseases could change disease incidence and affect the farm profit. The proportion of each cost category and the epidimiological sensitivity of total disease costs were more important than the actual number of disease costs.

CONCLUSIONS

This model estimated the common dairy disease costs under 2013 market conditions with flexible model input. Disease costs were expensive and influenced considerably by herd performance and market factors largely. The sensitivity of diseases costs were more important than the actual numbers for practical dairy management.

Table 4.1. Simulated herd performance, including mean, SD, and 95% range (5% to 95%), based on the data collected from DairyMetrics (2013).

	Mean	SD	Range (2.5% to 97.5%)
Rolling average herd milk production (RHAM, kg/cow/yr.)	9,682.53	1880.48	7,765.25 to 12,904.02
Age at the first calving (AFC, mo.)	26.18	2.84	23.15 to 30.79
Heat detection rate (HDR, %)	44.09%	17.74%	23.45% to 72.60%
Conception rate (CR, %)	41.86%	13.01%	27.71% to 63.44%
Pregnancy rate (PR, %)	18.41%	9.62%	8.22% to 36.94%

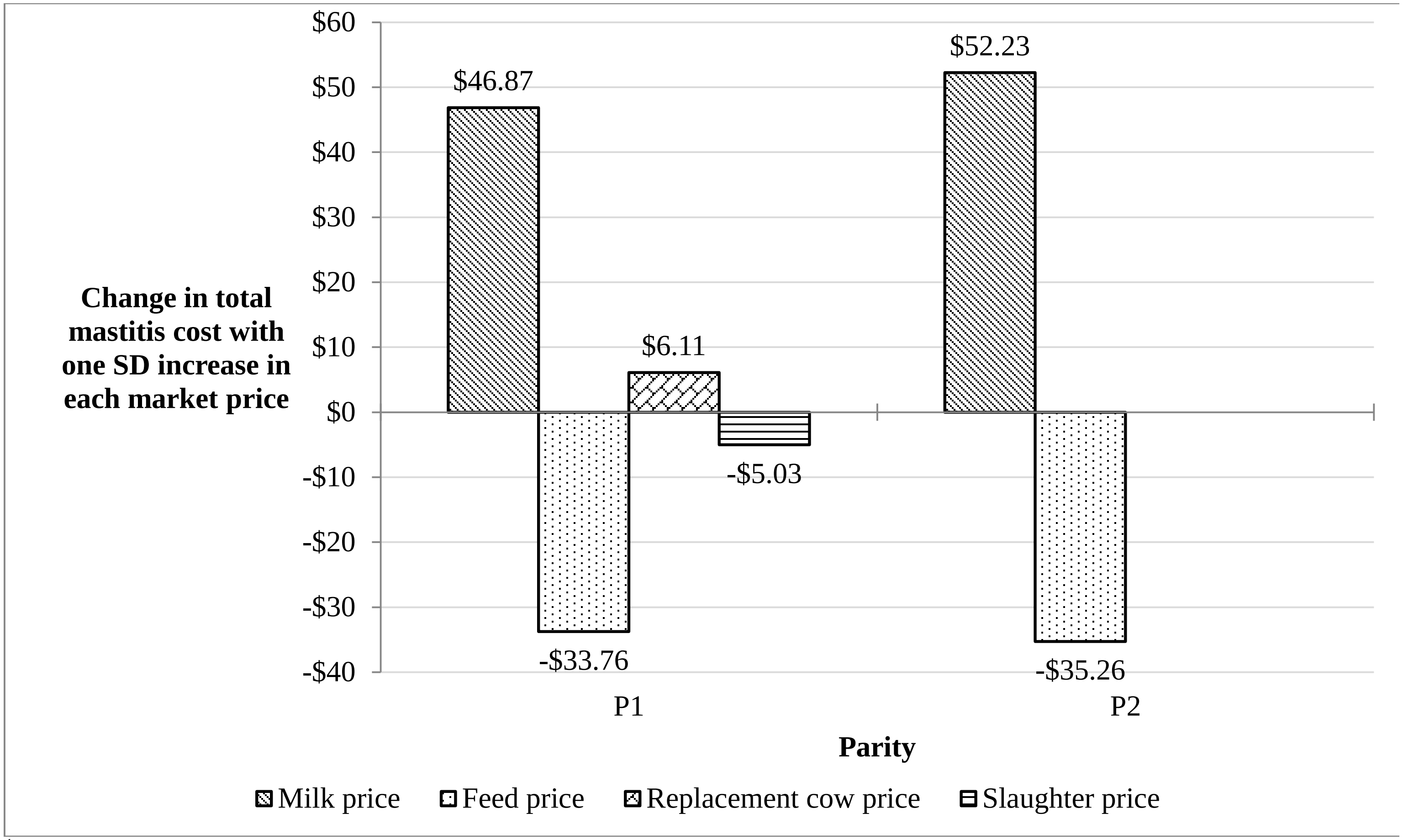
Table 4.2. Disease incidence collected from Wilson et al. (2004) and separated for the first, second, and later parities.

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%
Milk fever	N/A	5.20%	5.20%

Table 4.3. Mean ± SD of total disease costs and the contribution from each category separated the primiparous cows (P1) and multiparous cows (P2)

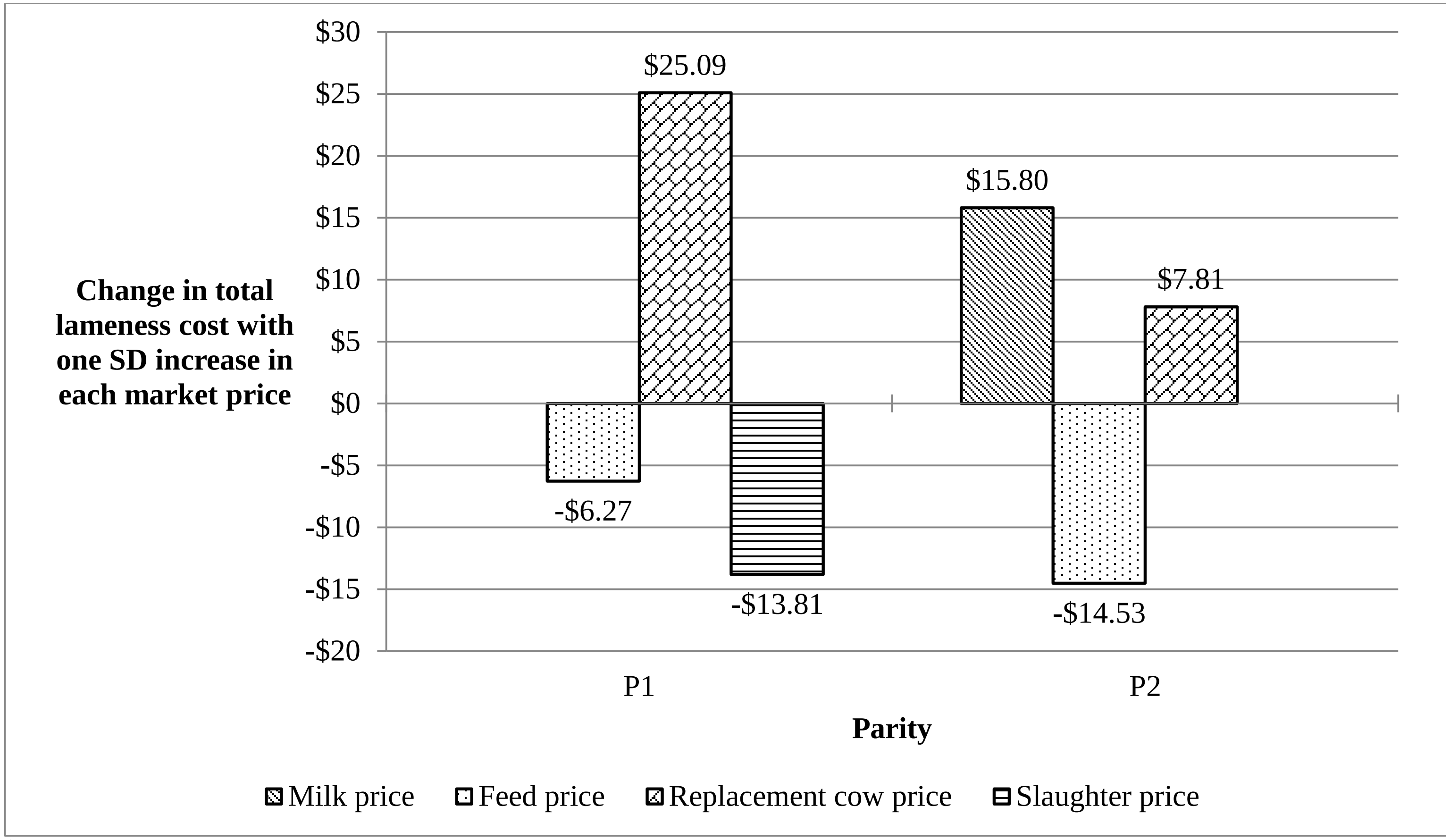
		Veterinary and treatment	Labor	Discarded milk	Decreased milk production	Culling	Extended days open	Death	Total costs
Mastitis	P1[1]	$77.13 ± 32.58	$12.13 ± 6.18	$63.18 ± 39.38	$135.68 ± 44.24	$9.18 ± 5.88	$1.28 ± 2.36	$11.43 ± 1.65	$309.93 ± 74.54
	P2[2]			$79.65 ± 48.42	$137.88 ± 39.94	$17.30 ± 6.34	$3.16 ± 3.86	$12.23 ± 1.71	$340.08 ± 80.14
Lameness	P1	$102.67 ± 54.48	$13.87 ± 6.38	$1.68 ± 9.23	$19.62 ± 16.41	$22.43 ± 12.17	$8.52 ± 11.12	$10.58 ± 1.52	$179.37 ± 66.51
	P2			$2.11 ± 11.56	$31.43 ± 15.58	$49.09 ± 17.85	$3.50 ± 4.33	$11.01 ± 1.54	$213.68 ± 66.29
Metritis	P1	$89.09 ± 39.12	$10.32 ± 4.80	$38.07 ± 24.54	$2.79 ± 1.42	$6.21 ± 2.40	$13.86 ± 17.41	$15.43 ± 2.26	$175.77 ±
	P2			$47.96 ± 30.00	$7.71 ± 2.95	$15.16 ±5.62	$4.18 ± 5.15	$16.67 ± 2.23	$186.33 ±
Retained placenta	P1	$84.95 ± 43.32	$12.36 ± 6.40	N/A	$40.40 ± 20.80	N/A	$8.26 ± 10.45	N/A	$145.97 ± 49.99
	P2			N/A	$112.30 ± 35.95	N/A	$3.52 ± 4.15	N/A	$213.13 ± 57.70
Left displaced abomasum	P1	$197.87 ± 70.59	$16.63 ± 9.03	N/A	$141.02 ± 64.031	$23.20 ± 12.73	$5.43 ± 9.00	$20.58 ± 3.01	$404.73 ± 100.05
	P2			N/A	$235.78 ± 75.97	$79.62 ± 29.29	$3.31 ± 4.10	$22.06 ± 3.08	$555.27 ± 116.79
Ketosis	P1	$52.26 ± 21.00	$12.66 ± 6.47	N/A	$0.83 ± 0.58	$4.30 ± 1.75	$4.49 ± 6.19	$5.11 ± 0.74	$79.65 ± 24.45
	P2			N/A	$5.59 ± 1.74	$12.59 ± 4.71	$3.20 ± 3.77	$5.46 ± 0.76	$91.83 ± 24.11
Milk fever	P2	$85.19 ± 43.14	$13.35 ± 6.22	N/A	$5.07 ± 1.91	$15.12 ± 5.60	$3.35 ± 3.95	$44.08 ±6.14	$166.16 ±45.88

Figure 4.1. The relationship between market prices and the total mastitis cost in the primiparous and multiparous cows[1, 2]



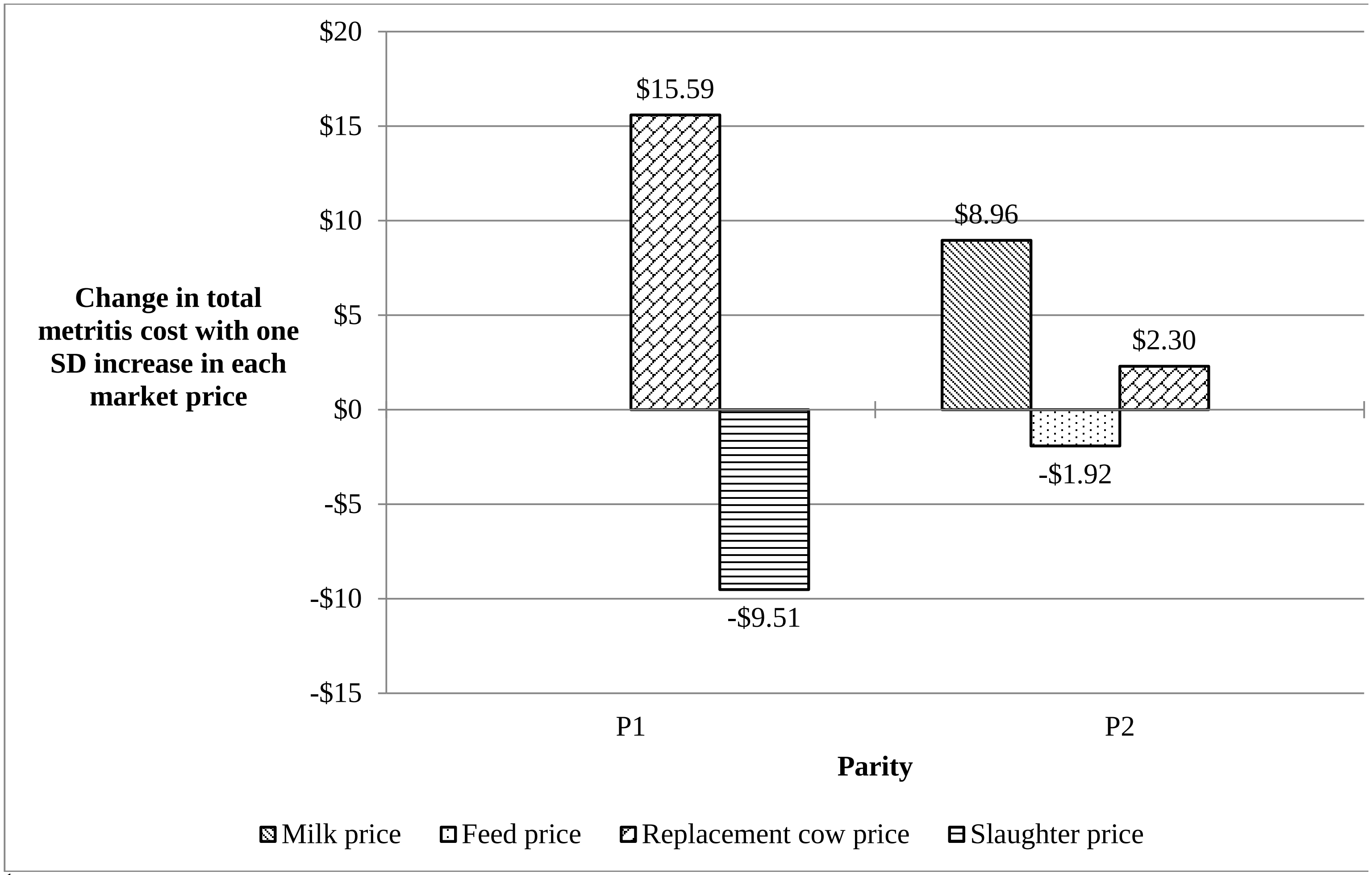
[1]P1: the primiparous cows
[2]P2: the multiparous cows

Figure 4.2. The relationship between market prices and the total lameness cost in the primiparous and multiparous cows[1, 2]



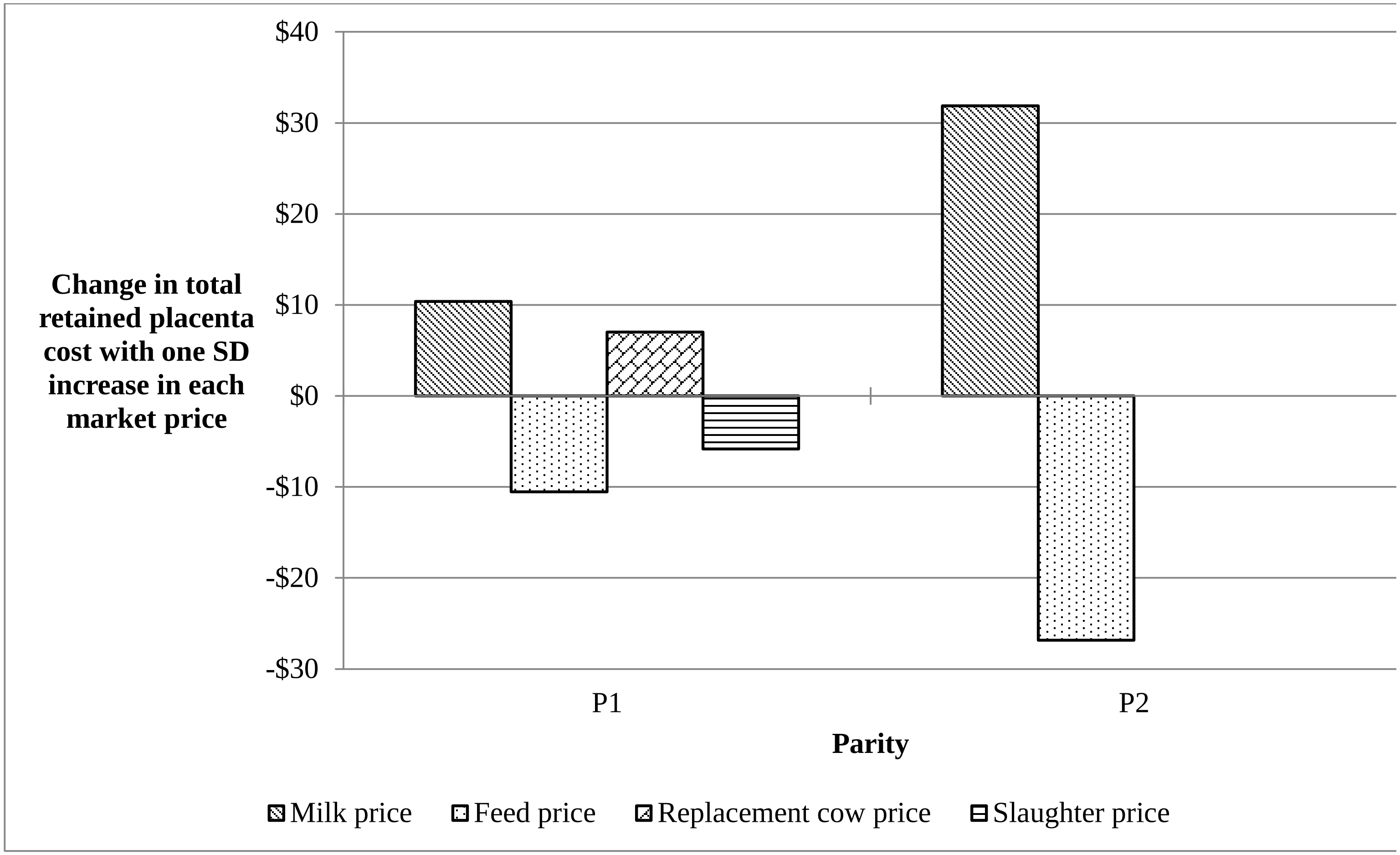
[1]P1: the primiparous cows
[2]P2: the multiparous cows

Figure 4.3 The relationship between market prices and the total metritis cost in the primiparous and multiparous cows[1, 2]



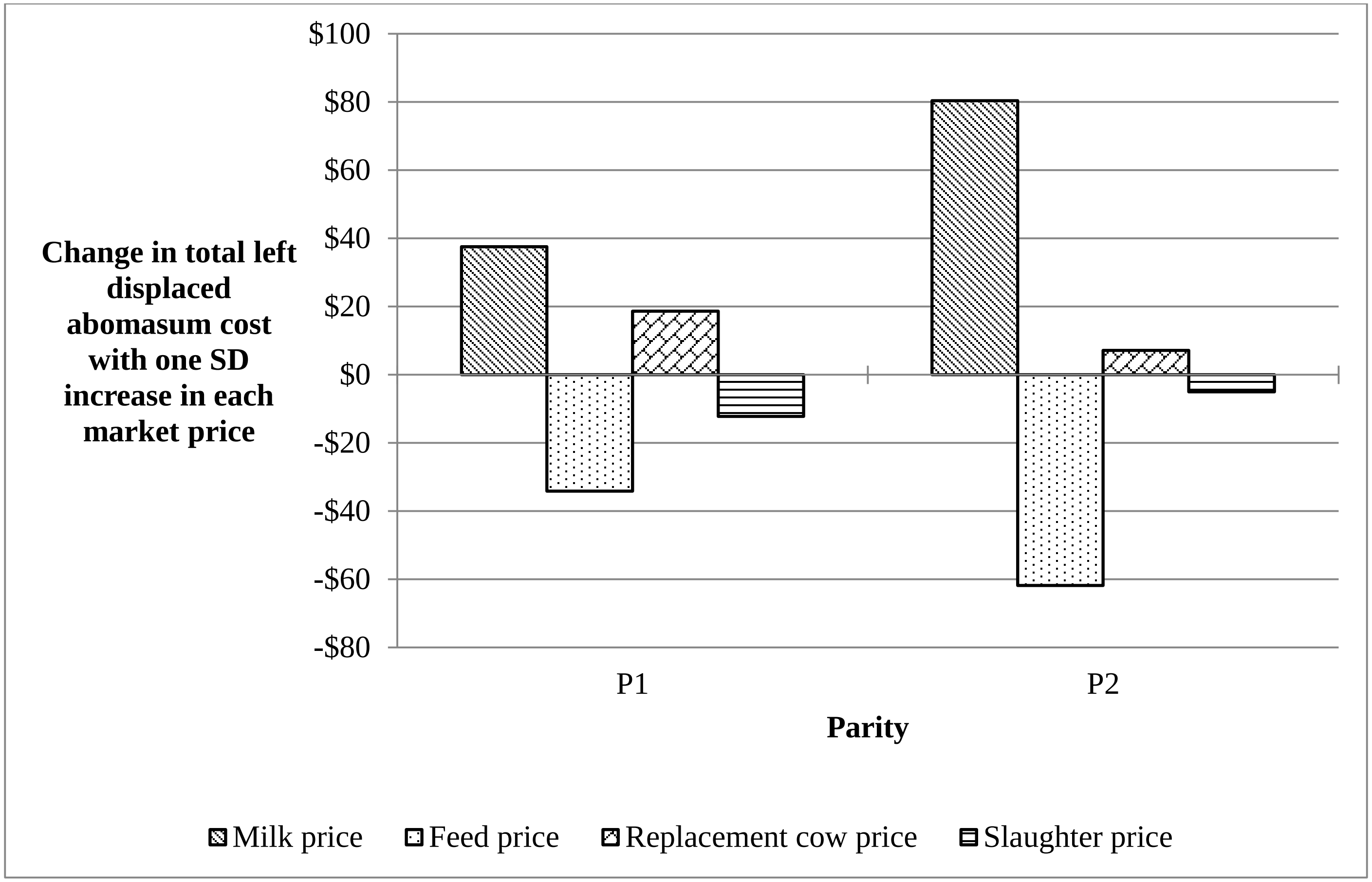
[1]P1: the primiparous cows
[2]P2: the multiparous cows

Figure 4.4. The relationship between market prices and the total retained placenta cost in the primiparous and multiparous cows[1, 2]



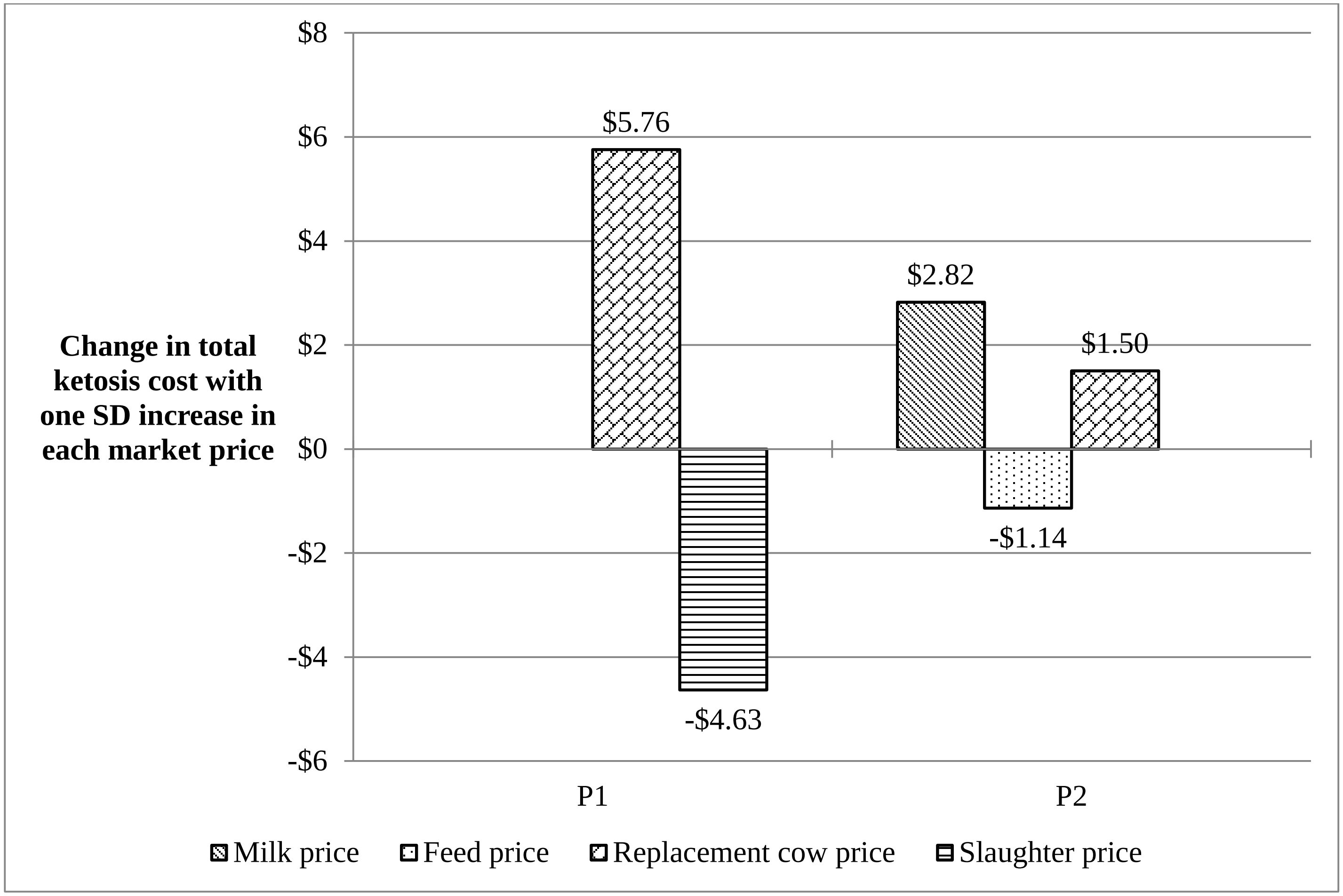
[1]P1: the primiparous cows
[2]P2: the multiparous cows

Figure 4.5. The relationship between market prices and the total left displaced abomasum cost in the primiparous and multiparous cows[1, 2]



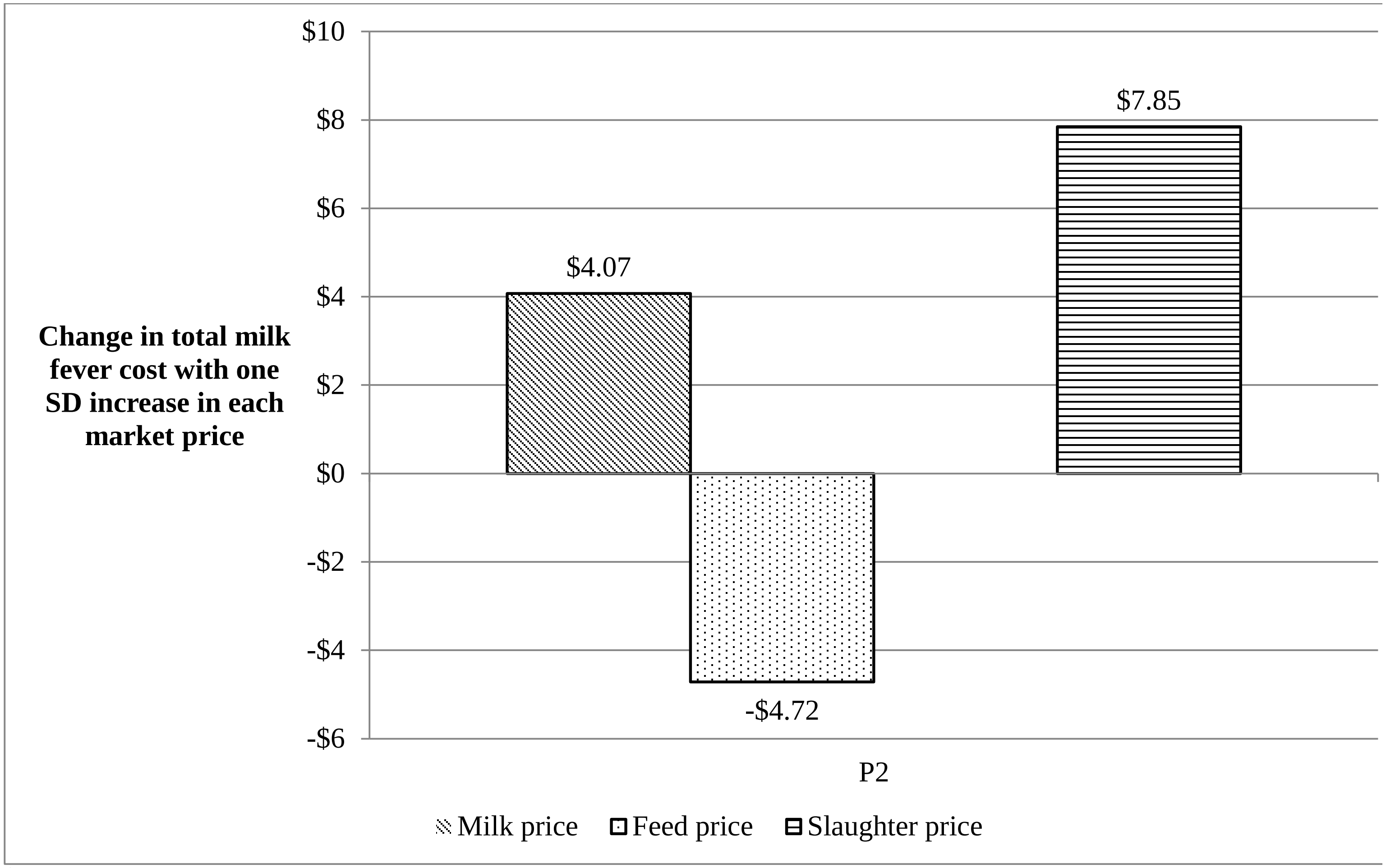
[1]P1: the primiparous cows
[2]P2: the multiparous cows

Figure 4.6. The relationship between market prices and the total ketosis cost in the primiparous and multiparous cows[1, 2]



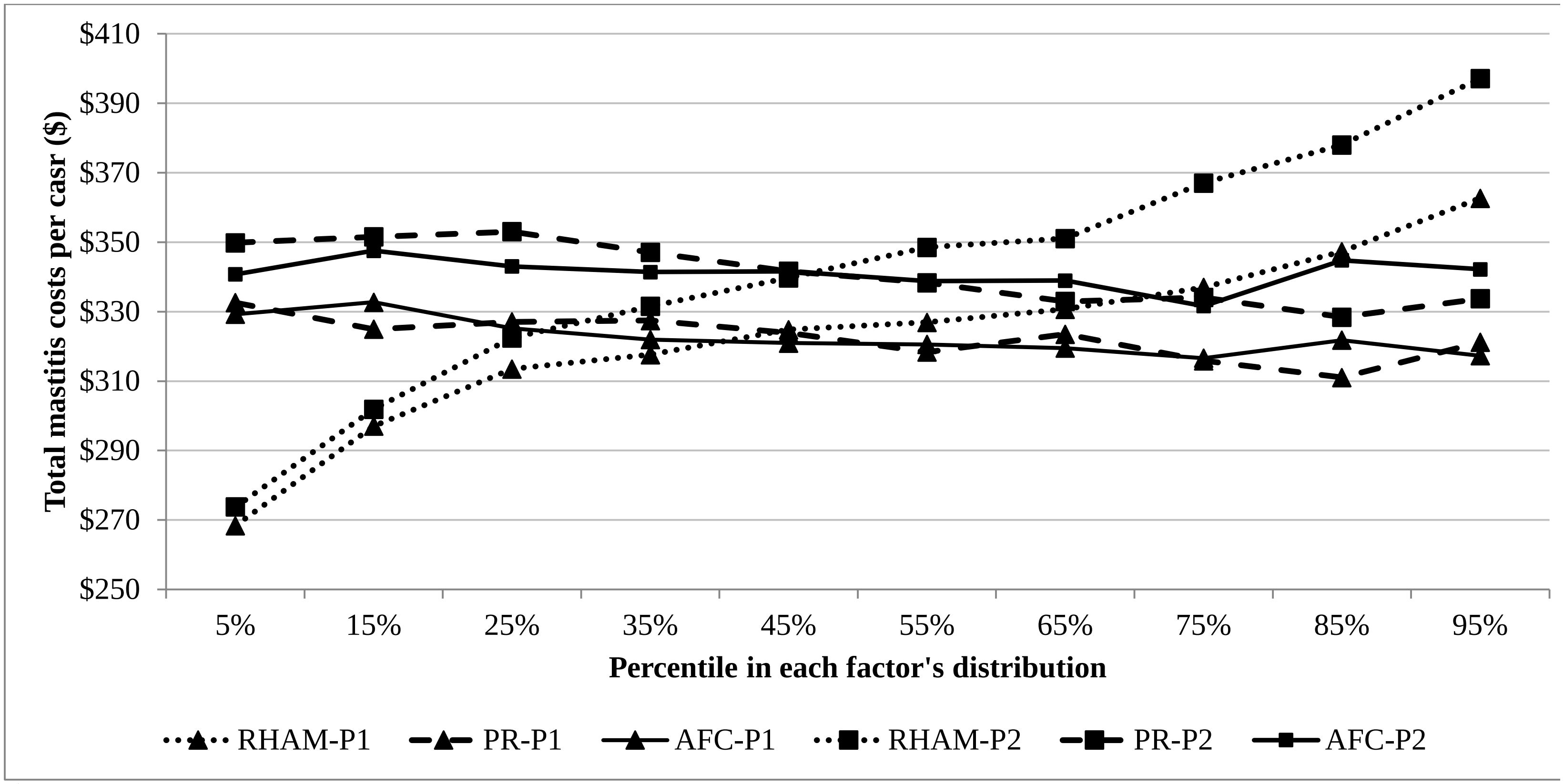
[1]P1: the primiparous cows
[2]P2: the multiparous cows

Figure 4.7. The relationship between market prices and the total milk fever cost in the multiparous cows[1,2]



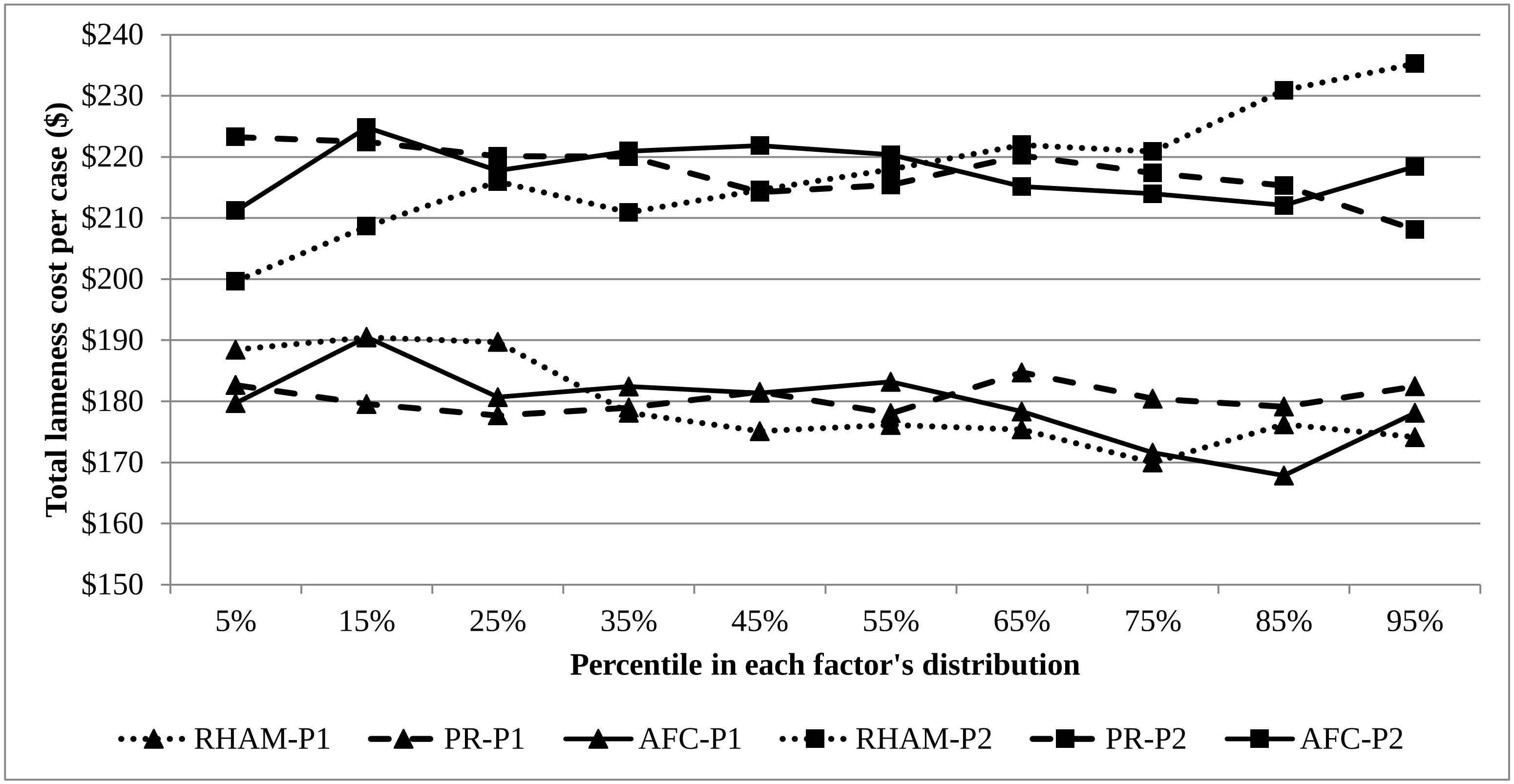
[1]P2: the multiparous cows
[2]The replacement cow price was not related to the mikl fever costs in the multiparous cows.

Figure 4.8. The relationship between herd performance and the total mastitis cost in the primiparous and multiparous cows[1,2,3,4,5,6]



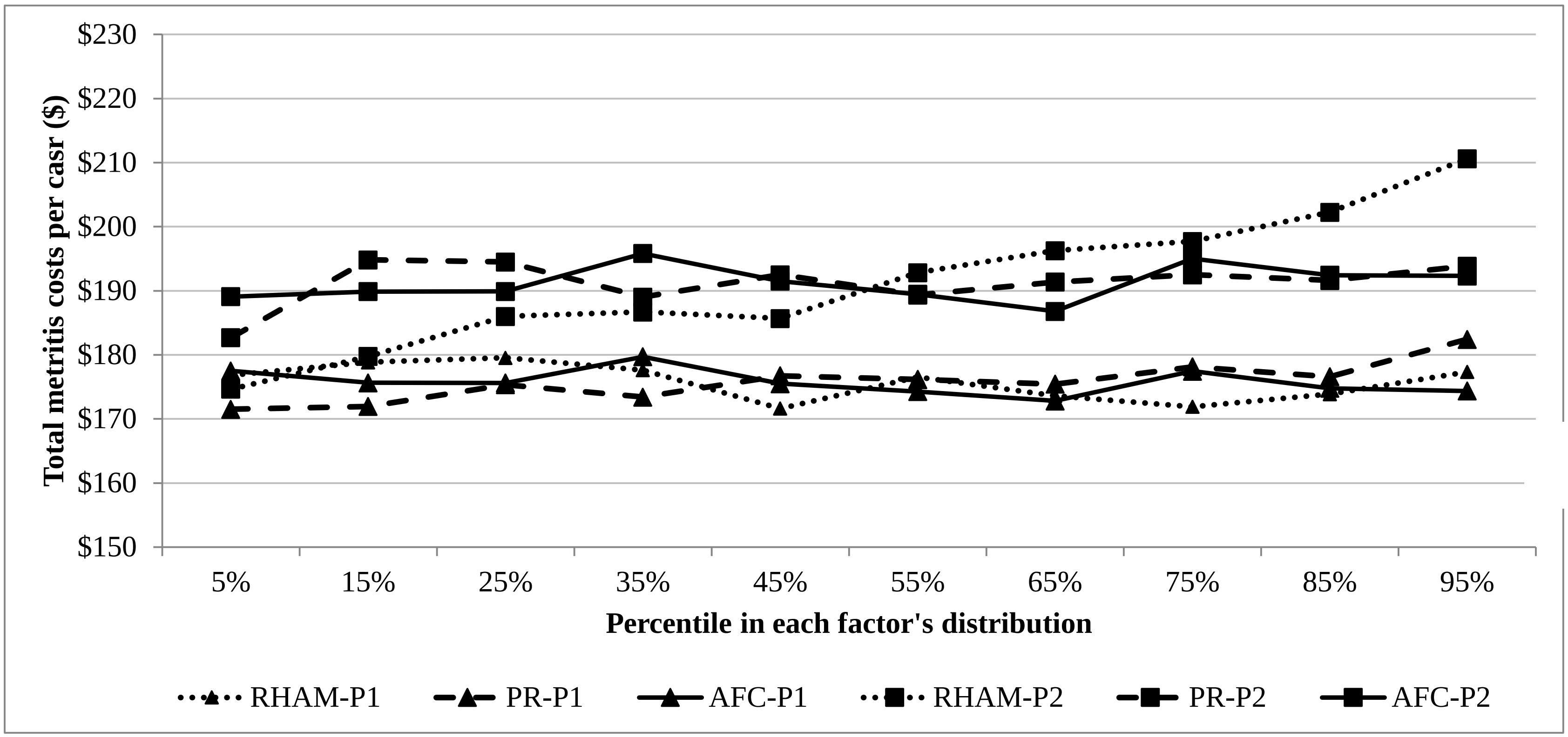
[1]RHAM: Rolling herd average milk production,
[2]AF: Age at the first calving,
[3]PR: Pregnancy rate,
[4]P1: Primiparous cows,
[5]P2: Multiparous cows,
[6]RHAM-P1: The effect of the rolling herd average milk prodctuion in the multiparous cows.

Figure 4.9. The relationship between herd performance and the total lameness cost in the primiparous and multiparous cows[1,2,3,4,5,6]



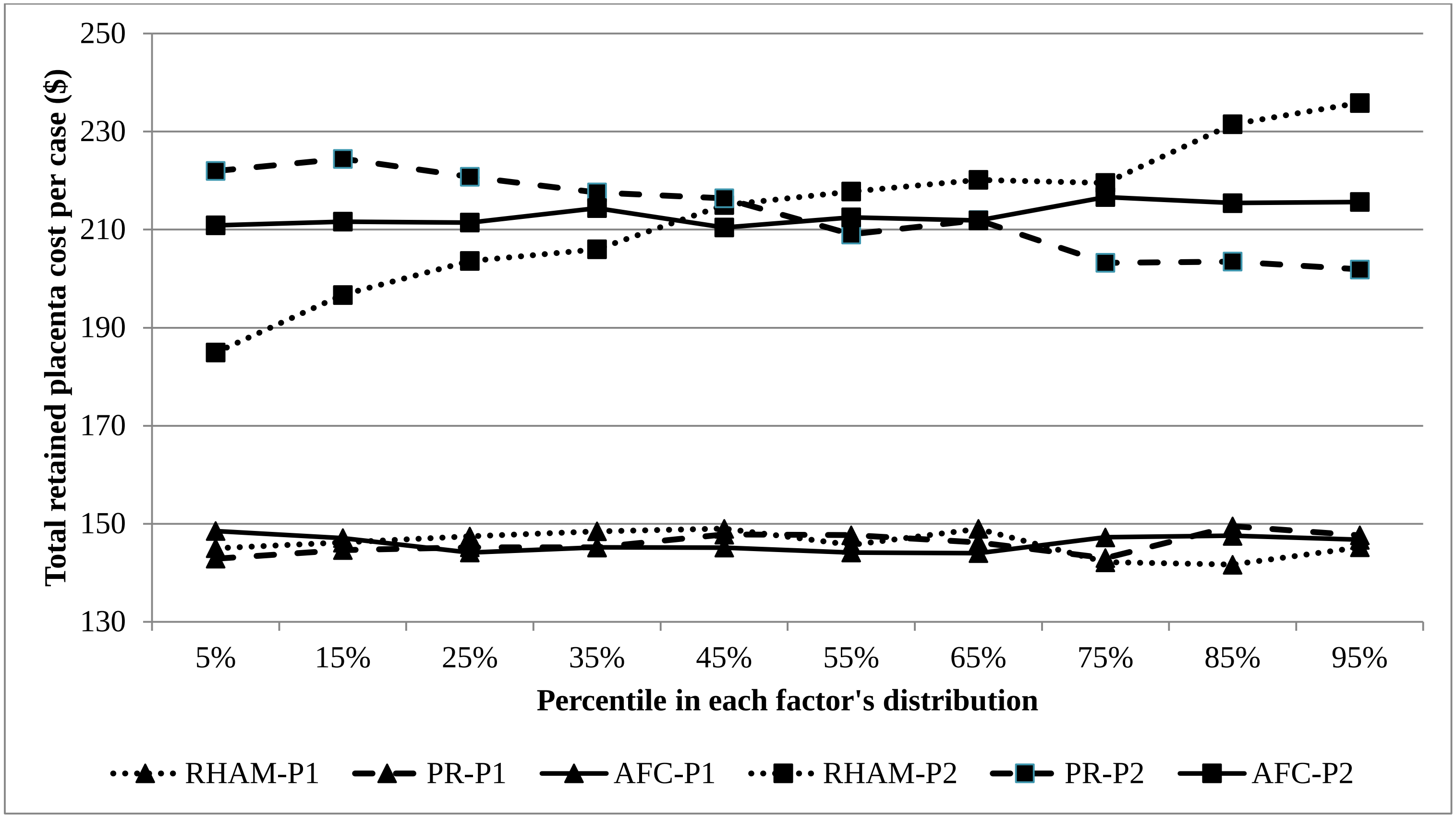
[1]RHAM: Rolling herd average milk production,
[2]AF: Age at the first calving,
[3]PR: Pregnancy rate,
[4]P1: Primiparous cows,
[5]P2: Multiparous cows,
[6]RHAM-P1: The effect of the rolling herd average milk prodctuion in the multiparous cows.

Figure 4.10. The relationship between herd performance and the total metritis cost in the primiparous and multiparous cows[1,2,3,4,5,6]



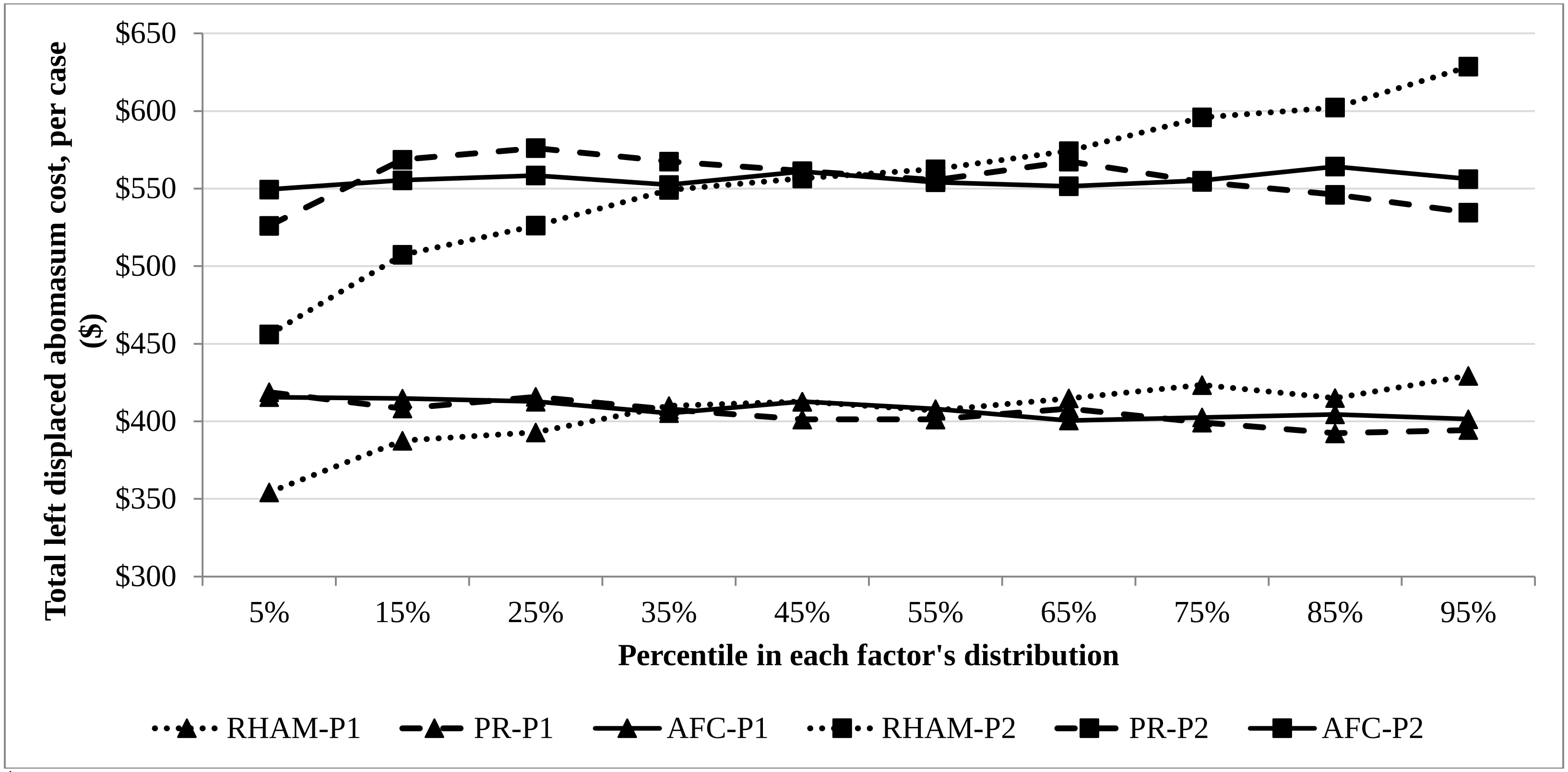
[1]RHAM: Rolling herd average milk production,
[2]AF: Age at the first calving,
[3]PR: Pregnancy rate,
[4]P1: Primiparous cows,
[5]P2: Multiparous cows,
[6]RHAM-P1: The effect of the rolling herd average milk prodctuion in the multiparous cows.

Figure 4.11. The relationship herd performance and the total retained placenta cost in the primiparous and multiparous cows[1,2,3,4,5,6]



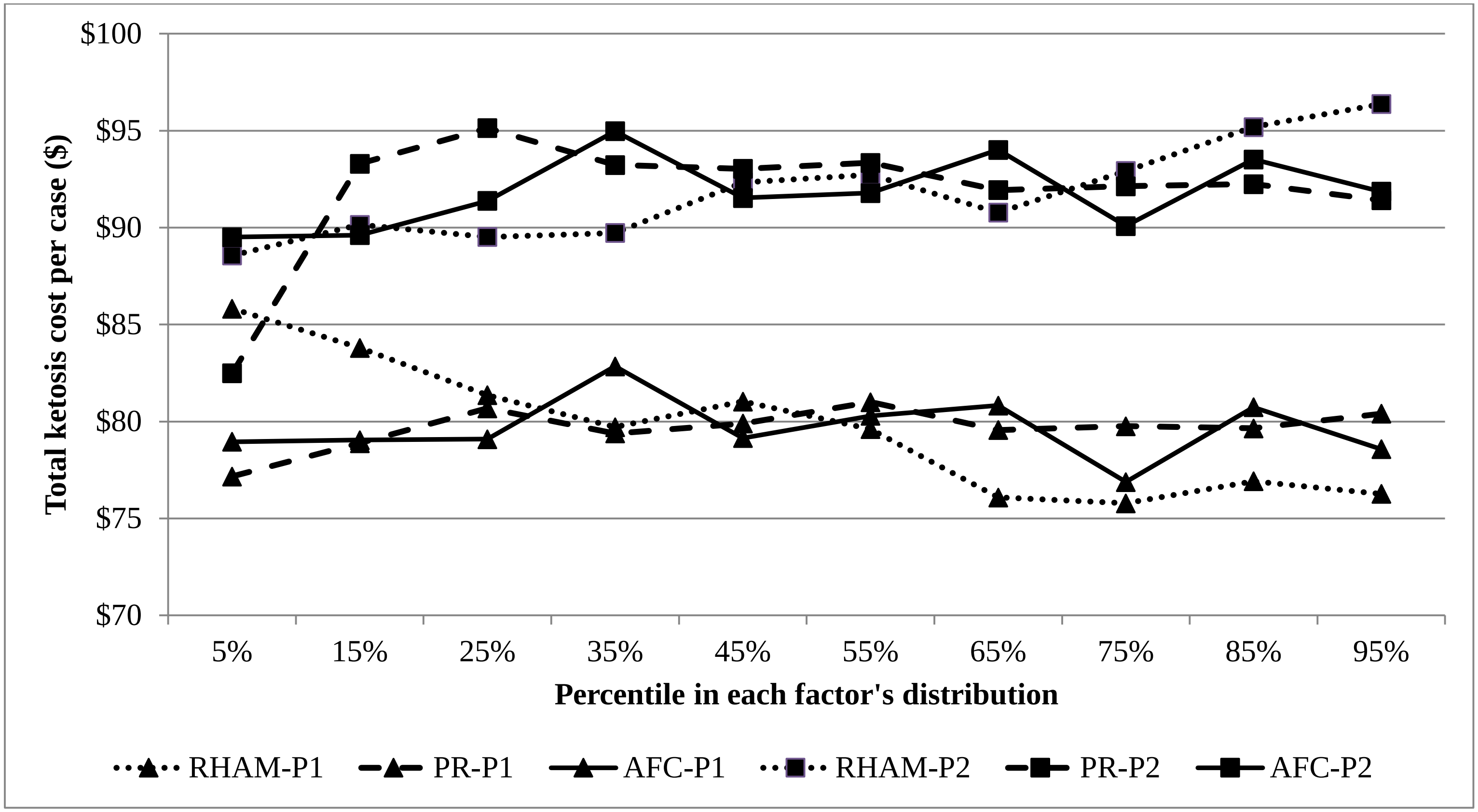
[1]RHAM: Rolling herd average milk production,
[2]AF: Age at the first calving,
[3]PR: Pregnancy rate,
[4]P1: Primiparous cows,
[5]P2: Multiparous cows,
[6]RHAM-P1: The effect of the rolling herd average milk prodctuion in the multiparous cows.

Figure 4.12. The relationship between herd performance and the total left displaced abomasum cost in the primiparous and multiparous cows[1,2,3,4,5,6]



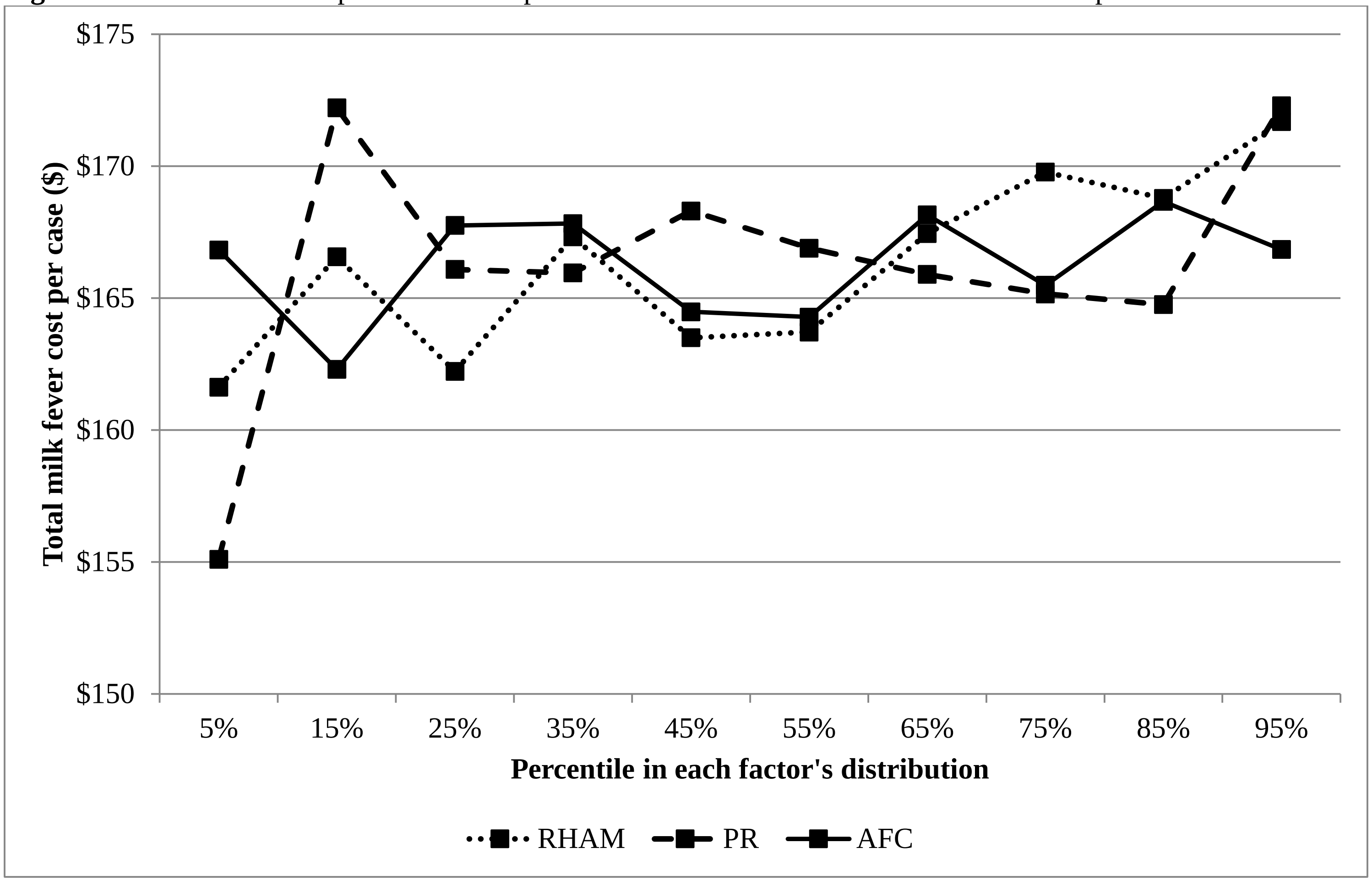
[1]RHAM: Rolling herd average milk production,
[2]AF: Age at the first calving,
[3]PR: Pregnancy rate,
[4]P1: Primiparous cows,
[5]P2: Multiparous cows,
[6]RHAM-P1: The effect of the rolling herd average milk prodctuion in the multiparous cows.

Figure 4.13. The relationship between herd performance and the total ketosis cost in the primiparous and multiparous cows[1,2,3,4,5,6]



[1]RHAM: Rolling herd average milk production,
[2]AF: Age at the first calving,
[3]PR: Pregnancy rate,
[4]P1: Primiparous cows,
[5]P2: Multiparous cows,
[6]RHAM-P1: The effect of the rolling herd average milk prodctuion in the multiparous cows.

Figure 4.14. The relationship between herd performance and the total milk fever in the multiparous cows [1, 2, 3]



[1]RHAM: Rolling herd average milk production,
[2]AF: Age at the first calving,
[3]PR: Pregnancy rate,

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VITA

Di Liang was born on May 21st, 1990 in Jiujiang, Jiangxi Province, China. Di attended China Agricultural University in 2007 after graduation from Jiujiang First High School. She obtained a Bachelor's degree in Animal Science and continued education in University of Kentucky. Under the direction of Dr. Jeffrey Bewley, Di studied dairy health economics for her Master's of Science.

Di presented her projects at the 2012 Joint Annual ADSA-AMPA-ASAS-CSAS-WSASAS Meeting in Phoenix, AZ and 2013 Joint Annual ADSA-AMPA-ASAS-CSAS-WSASAS Meeting in Indianapolis, IN. She was awarded the National Mastitis Council Annual Meeting Scholar in 2013 and got chance to present in the 52nd National Mastitis Council Annual Meeting in San Diego, CA. Di finished an additional research project about the influence of breed, milk production, season, and ambient temperature on dairy cow reticulorumen temperature; and the results were published in Journal of Dairy Science (Volume 96, issue 8). In addition to research, Di worked as a teaching assistant in Dairy Science and Dairy Decision-making courses.

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