Investment analysis of in-line automated mastitis detection systems for pasture-based dairy farms in New Zealand

Minor thesis (24 ects)
BEC-80424

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Abstract

Comprehensive investment analyses combining science on mastitis with effectiveness of in-line automated mastitis detection systems have not previously been performed. In this study the financial consequences on farm level of installing an automated mastitis detection system using electrical conductivity sensors at quarter level instead of visual detection of clinical mastitis (by teat-stripping the entire herd every 30 milkings at a detection rate of 70%) was simulated for an average, pasture-based New Zealand dairy farm with 402 cows, producing 346 kg of milksolids per cow per year, a lactation length of 42 weeks, four milk recordings per season and a simulated incidence of clinical mastitis episodes of 14.8% of the entire herd per year. Clinical mastitis episodes were only treated after the second observation of clots. Subclinical mastitis was not treated, but all intramammary infections were assumed to cure during dry cow therapy at the end of lactation. The investment analysis model simulated the pathways intramammary infections follow, labour requirements to detect and treat clinical mastitis episodes, the number of undetected intramammary infections turning into subclinical mastitis, milk production losses related to subclinical mastitis, early treatment effects of clinical mastitis on antibiotic use, and simulated the transmission of pathogens. The calculated optimal overall detection rate per time-window of 10 milkings of quarter level electrical conductivity sensors was 88%. This resulted in detection and treatment of 90.2% of all clinical mastitis episodes at an average delay of 2.3 milkings from the start of the clinical mastitis episode until treatment, compared to detection and treatment of 46.1% at a delay of 8.8 milkings using visual detection. Installation of quarter level electrical conductivity sensors on every second bail of the milking parlor decreased detection and treatment of the total clinical mastitis episodes to 55.1% at an average delay of 3.2 milkings. Investing in automated mastitis detection is most appealing for farmers aiming to decrease labour requirements of detecting clinical mastitis episodes while maintaining or improving the percentage of detected and treated clinical mastitis episodes. A Monte Carlo simulation with milk price ($4.35:$8.70 per kilogram of milksolids) and clinical mastitis incidence (0.148, standard deviation 0.03) as risky variables resulted in a mean marginal financial effect of $1,736 ($313:$3,617) per year and a mean net present value of $-8,923 ($-20,748:$4,853) per year. The profitability of investing in automated mastitis detection greatly depends on the total investment costs. The model allows analysis of different automated mastitis detection systems, adjustment of model inputs to farm specific values, and analysing farm practises alternative to teat-stripping all cows on a regular basis.

Keywords: Automated mastitis detection, sensors, investment analysis, dairy, pasture-based dairying, New Zealand
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# List of abbreviations and definitions

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<td>Automated Mastitis Detection.</td>
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<td>BMSCC</td>
<td>Bulk Milk Somatic Cell Count.</td>
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<td>CM</td>
<td>Clinical Mastitis: a clinical mastitis episode is the observation of clots (&gt;2mm in average diameter) at a minimum of 2 out of 3, or all 3, consecutive milkings.</td>
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<td>EC</td>
<td>Electrical Conductivity.</td>
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<td>EC&lt;sub&gt;quarter&lt;/sub&gt;</td>
<td>Sensors measuring the Electrical Conductivity of milk at a quarter level.</td>
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<tr>
<td>EC&lt;sub&gt;udder&lt;/sub&gt;</td>
<td>Sensors measuring the Electrical Conductivity of milk at whole udder level.</td>
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<td>ED</td>
<td>Early Detection: to alert for CM within a time window of 5 milkings centred around the first clot observation of a CM episode.</td>
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<td>EDR</td>
<td>Early Detection Rate: the percentage of CM episodes found within the ED time window.</td>
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<td>SCM</td>
<td>Subclinical Mastitis: quarter SCC exceeds 200,000 cells/ml and bacteria are isolated in the absence of clinical changes.</td>
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<td>IMI</td>
<td>Intramammary Infection.</td>
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<td>IRR</td>
<td>Internal Rate of Return.</td>
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<td>LD</td>
<td>Late Detection: the difference in detection time windows between Overall Detection and Early Detection.</td>
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<td>LDR</td>
<td>Late Detection Rate: the percentage of CM episodes found within the LD time window.</td>
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<td>NPV</td>
<td>Net Present Value.</td>
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<td>OD</td>
<td>Overall Detection: to alert for CM within a time window of 10 milkings from 2 milkings before the first clot observation until 7 milkings after the first clot observation.</td>
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<tr>
<td>ODR</td>
<td>Overall Detection Rate: the percentage of CM episodes found within the OD time window.</td>
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<tr>
<td>SCC</td>
<td>Somatic Cell Count.</td>
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<td>Visual detection</td>
<td>The reference situation prior to investing in AMD systems, in which the entire herd is teat-stripped once every 30 milking to detect CM.</td>
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Introduction

Mastitis is an intramammary infection (IMI) caused by an acute or chronic bacterial infection affecting milk quality, milk quantity and animal welfare (De Vliegher et al., 2012). An increase in somatic cell count (SCC) is often used as indicator for an IMI. These milk somatic cells are primarily leukocytes derived from the blood as a reaction of the immune system of the cow (Thompson-Crispi et al., 2014). An IMI can result in clinical mastitis (CM) or subclinical mastitis (SCM). CM is defined as visually abnormal milk, including the presence of flakes, clots or other gross alterations in appearance. This mostly coincides with quarter SCC exceeding 200,000 cells/ml. Where quarter SCC exceeds 200,000 cells/ml and bacteria are isolated in the absence of clinical changes, the quarter is defined as having SCM (Smith et al., 2001).

Generally under housed conditions, *Staphylococcus aureus* and *Coagulase-Negative Staphylococci* are the major cause of IMI, followed by *Streptococci* and *E. coli* (Contreras and Rodríguez, 2011, De Vliegher et al., 2012). In the pasture-based context of New Zealand, *Streptococcus uberis* is responsible for the largest proportion of IMIs, especially during early lactation and the dry period (Denis et al., 2009). Seasonally calving herds were found to have a CM incidence significantly lower compared to herds calving throughout the year, presumably due to the absence of transmission of infections from cows in mid-late lactation to freshly calved cows (Cagienard, 1983). However, a study on 14 dairy farms from the Northland region of New Zealand showed that CM occurred in still 14.8% of lactating cows (Petrovski et al., 2009). As a comparison; the study of Van den Borne et al. (2010b) reported a mean CM incidence of 33.8% of lactating cows in The Netherlands, where cows are housed indoors during certain parts of the year. The CM incidence rates differ largely between farms (Hogeveen et al., 2011), which indicates that scope for improvement exists to minimize the CM incidence.

CM has negative effects on animal welfare, since cows can have swollen painful udders and high fever. These cows eat and drink less. Furthermore, unlike typical sickness behaviour, they spend less time lying. During the time they rest, they avoid lying on the side of the inflamed udder quarter (Siivonen et al., 2011). Besides the negative impact on animal welfare, mastitis is considered to be the most costly health issue in dairy cattle (Green et al., 2012, Halasa et al., 2007, Wells et al., 1998). Economic damage caused by mastitis can be split into categories such as milk production losses, veterinary costs, treatment costs, discarded milk, increased labour costs, costs of involuntary culling, replacement costs and loss of milk quality (Hogeveen and Østerås, 2005). Examination of the economic costs of both CM and SCM in New Zealand has suggested that over NZ$300 million are lost.
to the dairy industry annually (Malcolm, 2007). Considering the negative impact of mastitis on animal welfare and farm economics, early detection or even prevention of mastitis is important.

In New Zealand, visual detection of CM by teat-stripping all cows is labour demanding and staff only detected 80% of the CM events (Claycomb et al., 2009). Milk recordings providing information on milk production and SCC of individual cows (to detect CM or SCM) have limitations as well, since most dairy farms in New Zealand perform milk recordings only three or four times per season (Anonymous, 2014b). Installing in-line automated mastitis detection (AMD) systems offers the opportunity to monitor milk properties of individual cows every milking session. The most commonly used AMD systems use changes in electrical conductivity (EC) of whole udder milk (EC_udder) or quarter milk (ECQuarter) as indicator for mastitis. Fewer systems estimate SCC based on either reaction with a test reagent or by using light spectroscopy (Anonymous, 2013a, Rutten et al., 2013, Steeneveld and Hogeveen, 2015).

Even though in-line AMD systems offer the opportunity to monitor milk properties of individual cows every milking session, in-line AMD systems are not yet common practice in New Zealand: only 6% of New Zealand dairies have these systems installed (Edwards et al., 2014) as compared to 37% of the farms with a conventional milking system in the Netherlands (Steeneveld and Hogeveen, 2015). The cause for this low adoption rate might be that data on the costs and benefits of investing in in-line AMD systems are lacking, making it difficult for farmers to make a sound and well-informed investment decision (Jago et al., 2013). Multiple studies have reported on costs of mastitis (e.g.: Bar et al., 2008, Heikkilä et al., 2012, Huijps et al., 2009, Huijps et al., 2008) or on the sensitivity and specificity of in-line AMD systems (e.g.: Hogeveen et al., 2010, Huybrechts et al., 2014, Mottram et al., 2007, Song and Van Der Tol, 2010). However, studies combining the costs of mastitis with performance characteristics of in-line AMD systems to develop an investment analysis model are lacking.

Kamphuis et al. (2013) identified three performance requirements of AMD systems: (1) detection of CM, (2) management of bulk milk SCC (BMSCC) levels and (3) support selective dry cow therapy management decisions at the end of lactation. This study developed an investment analysis model for AMD systems to detect CM within pasture-based dairy farm systems in New Zealand. Financial profitability of investing in AMD systems to detect CM instead of using visual detection of CM were estimated using a partial budget approach.
Materials and methods

Detection of CM using AMD systems was compared with visual detection of CM (by teat-stripping all cows once every 30 milkings) for a modelled pasture-based farm in New Zealand (farm data and standard practices based on New Zealand averages or expert opinions). Two types of AMD systems were evaluated: those using ECudder and those using ECquarter. The investment analysis model was developed in Microsoft Excel software (Microsoft Windows, 2010) and was based on a partial budget. Modelled parameters to compare a system using AMD and visual detection included: the percentage of detected and treated CM episodes, the delay from the start of the CM episode until treatment, the effect of delay on the use of antibiotics per treatment, the total use of antibiotics, the dynamics of mastitis states (CM, SCM, self-cure), the effect of mastitis states on milk production losses, the dynamics of mastitis transmission, labour demand, and the amount of discarded milk. The financial consequences of detecting CM using an AMD system instead of visual detection were estimated. The profitability of investing in an AMD system was evaluated by calculating the net present value (NPV) and the internal rate of return (IRR). Furthermore, a sensitivity analysis was performed to assess which model inputs are the main drivers. Finally, a Monte Carlo simulation was performed to assess the effects of variations in milk price and CM incidence on the profitability of investing in AMD systems. The sensitivity analysis and Monte Carlo simulation were performed using the add-in software @Risk for Microsoft Excel (Palisade Corporation, 2014).

An overview of default model input values is provided in Appendix I. Screenshots of the investment analysis model are given in Appendix II.

Definition of clinical mastitis

Episodes of CM were defined according to protocols for field evaluation of in-line AMD systems (Kamphuis et al., 2013): a CM episode is the observation of clots (>2mm in average diameter) at a minimum of 2 out of 3, or all 3, consecutive milkings. Figure 1 illustrates how clot observations are used to identify CM. Clot observations are present in 7 out of 14 consecutive cow milkings. The CM episode starts at the fifth milking. The clot observation at the second milking is a stand-alone observation and is, therefore, not considered to be part of the CM episode.

To link CM episodes with alerts generated by an AMD system, time-windows for AMD alerts were also defined according to the same protocols for field evaluation of in-line AMD systems (Kamphuis et al., 2013). The time window for an AMD system to detect CM early (Early Detection, ED) is to alert for CM within a time window of 5 milkings centred around the first clot observation of a CM episode.
The time window for an AMD system to detect CM (Overall Detection, OD) extends this ED time window to the last clot observation in the CM episode or to a maximum of 10 consecutive milkings. An example of the ED and OD time windows for the illustrated CM episode are presented in Figure 1. In addition to the ED and OD time windows defined by Kamphuis et al. (2013), this study also defined a Late Detection (LD) time window as the difference in detection time windows between OD and ED. The Overall Detection Rate (ODR), Early Detection Rate (EDR) and Late Detection Rate (LDR) are the percentages of CM episodes found within the OD, ED or LD time window.

Pathways of clinical mastitis infections

Figure 2 shows the modelled pathways, based on expert-knowledge, that a cow with an IMI can follow. Of all IMIs, 50% is assumed to become CM, 30% to become SCM and 20% to self-cure. Of the non-detected proportion of CM cases 20% is assumed to remain CM, 48% to become SCM after the first time window for Overall Detection (OD) and 32% to self-cure after the first time window for OD (Lacy-Hulbert, 2014, DairyNZ, Hamilton, New Zealand, personal communication; McDougall, 2014, Anexa Animal Health, Morrinsville, New Zealand, personal communication). This assumption had the consequence that the ODR of a detection system (whether AMD or visual detection) determined the number of CM episodes being treated, the delay from the start of the CM episode until treatment, the number of CM cases becoming SCM and the number of CM cases to self-cure. In other words: a poor ODR (whether AMD or visual detection) will result in fewer CM cases being treated and in more cows having SCM. If cows get another CM episode within the same lactation, they enter the model as a new CM episode to follow the same pathways in Figure 2. Cows with SCM were not treated during lactation, but dry cow therapy was applied after each lactation and was assumed to cure all IMI’s (both CM and SCM).
Distribution of mastitis incidence

The total CM incidence per year was set at 14.8% (Petrovski et al., 2009). The distribution of the CM incidence over the year (as a proportion of the total CM incidence) of pasture-based dairying systems has been reported by McDougall (2005). The reported incidences were plotted and a power trend line was added to calculate the CM incidence per day after the start of lactation (Equation 1). In this way the exact moment during lactation when cows get CM was determined.

Equation 1: Formula to predict clinical mastitis (CM) incidence per day after the start of lactation.

\[
CM\ incidence = 0.264 \times day^{-0.426}
\]
Required teat-strip checks to assess moment of treatment

Due to the applied definition of CM, the possible clot pattern variations during the OD time window were limited to 40 different clot patterns. For every possible moment of alert (during a total of 10 milkings, ranging from 2 milkings before until 7 milkings after the first clot observation of a CM episode, Figure 1) and clot pattern variation, two parameters were calculated:

1) the number of teat-strip checks required from the first AMD alert until treatment,

2) the delay (milking) between the start of the CM episode and treatment.

These parameters were determined for both the ED and the LD time window. The clot patterns were assumed to be random (but had to be valid according to the used definition of CM), although the model allows modification to add weights to specific clot patterns if these appear not to be random during future research. An example of a clot pattern, the required number of teat-strip checks from the first AMD alert until treatment, and the delay between the start of the CM episode until treatment for an ED time window is demonstrated in Figure 3.

Figure 3: Example of a clot (C) pattern for a cow having a clinical mastitis (CM) episode (red dashed boxes). Yellow dotted boxes show the milkings to teat-strip the cow from alerts (A) during the early detection time window until the first possibility for treatment (T) after observing the second clot. The dotted vertical line represents the end of the early detection time window.
Since the specificity of AMD systems is not 100%, a proportion of AMD system alerts will be false positive. The model assumption was that farmers marked and teat-stripped an alerted cow and that this alerted cow was not treated until clots were observed for two out of three consecutive milkings. If no clots were observed at all, the cow was only teat-stripped for three consecutive milkings. The next assumption was that if a farmer got an alert from the AMD system, close and diligent attention was paid to the milk of the teat-stripped cows and that clots were found if present. That means that the visual detection rate after getting an alert from the AMD system was assumed to be 100%.

**Automated mastitis detection performance**

To achieve a higher ODR of CM episodes, the sensitivity of the AMD system can be altered. Lowering the threshold of an AMD system to generate an alert, results in a higher ODR and, therefore, more CM episodes being detected and treated. However, this lower threshold comes with the trade-off of a lower specificity, hence having more false positive alerts. A farmer cannot know whether an alert is false positive or true positive, so every alert has to be checked by teat-stripping the cow and inspecting the milk for clots. Kamphuis et al. (2013) expressed the specificity of AMD systems as the number of false alerts per 1000 milkings (FAR1000).

Equation 2 and Equation 3 summarize the relation between ODR and EDR (for AMD systems using ECudder and those using ECquarter, respectively) to determine the EDR based on the user input for ODR. Equation 4 and Equation 5 show the relation between ODR and FAR1000 (for AMD systems using ECudder and those using ECquarter, respectively) to determine the FAR1000 based on the user input for ODR. The polynomial coefficients for Equation 2 and Equation 4 (AMD systems using ECudder) were derived by means of plotting a trend line on the same data used for developing protocols for field evaluation of in-line AMD systems (Kamphuis et al., 2013). These data were collected at three moments during lactation, each moment lasting three weeks, on six pasture-based dairy farms with rotary milking parlors and with AMD systems measuring ECudder installed on every bail. The polynomial coefficients for Equation 3 and Equation 5 (for AMD systems using ECquarter) were derived from Claycomb et al. (2009). Since Claycomb et al. (2009) did not make the distinction between ED and LD, half of the OD was assumed to be ED and half to be LD. The AMD system using ECudder and the one using ECquarter were used as illustrative examples of AMD systems. The investment analysis model, however, does allow for parameter input of other AMD technologies (e.g., AMD systems based on SCC measurements).

**Equation 2: Relation between Overall Detection Rate (ODR) and Early Detection Rate (EDR) for automated mastitis detection systems using electrical conductivity on whole udder level.**

\[
EDR = -1.74 \times ODR^2 + 2.44 \times ODR - 0.368
\]
Equation 3: Relation between Overall Detection Rate (ODR) and Early Detection Rate (EDR) for automated mastitis detection systems using electrical conductivity on quarter level.

$$EDR = 0.5 \times ODR$$

Equation 4: Relation between Overall Detection Rate (ODR) and false alert rate per 1000 milkings (FAR1000) for automated mastitis detection systems using electrical conductivity on whole udder level.

$$FAR1000 = 258 \times ODR^2 + 105 \times ODR - 39.7$$

Equation 5: Relation between Overall Detection Rate (ODR) and false alert rate per 1000 milkings (FAR1000) for automated mastitis detection systems using electrical conductivity on quarter level.

$$FAR1000 = 9.00 \times 10^8 \times e^{(20.5 \times ODR)}$$

Assessment of detection probability using automated mastitis detection

A farmer can decide to install an AMD system on every second or third bail instead of on every bail to save investment costs, at the trade-off that the ODR of the AMD decreases (the model uses installation of an AMD system on every bail as default). The model’s assumption was that stepping onto a bail with an AMD system was random. The proportion of milkings within the OD time window that a cow with CM is missed because she didn’t step onto a bail with an AMD system (Probability Missed bail \([PM_{bail}]\)) equals \((1-(1/n^*))\). If a cow did step onto a bail with an AMD system, there was the additional probability that the cow was not alerted by the AMD system (Probability Missed AMD \([PM_{AMD}]\)), depending on the ODR of the AMD system. Equation 6 summarizes the cumulative probability for an AMD system to miss a cow with a CM episode \((PM_{cum})\) within an OD time window.

Equation 6: Cumulative probability of missing a cow with a clinical mastitis episode \((PM_{cum})\) as a result of the cow not stepping onto a bail with an Automated Mastitis Detection (AMD) system installed \((PM_{bail})\) or not being detected by the AMD system \((PM_{AMD})\).

$$PM_{cum} = (PM_{bail} + PM_{AMD}) - (PM_{bail} \times PM_{AMD})$$

If a CM cow was not detected within the first 10 milkings (maximum OD time-window), the cow could remain clinical, change into SCM or self-cure (Figure 2). The cows that remained clinical could be detected in the next time window of 10 milkings. A proportion of CM cows might still not be detected and could be detected in the next time window of 10 milkings, and so on until the next milk recording event where undetected CM cows were assumed to be found. The model calculated the proportion of cows detected in each time window and calculated both the required number of teat-strip checks and the associated delay from the start of the CM episode until treatment. The delay in treatment for those cows being alerted during the first time window of 10 milkings was calculated by assigning the delay for ED and LD proportionally to the EDR and LDR. For cows that were not

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* AMD systems are installed on every nth bail: n=1 means an AMD system is installed on every bail; n=2 means an AMD system is installed on every second bail; n=3 means an AMD system is installed on every third bail.
detected in the first time window of 10 milkings but in successive time windows of ten milkings, the ODR was used.

Assessment of detection probability using visual detection

A similar approach was used to determine the average delay from the start of a CM episode until treatment when only visual detection was used. In this study, visual detection of CM episodes is done by teat-stripping all cows on a regular basis. The frequency of this visual detection can be modified, but the model used a default value of teat-stripping cows once every 30 milkings, which falls within the range of common practice in New Zealand (Neal, 2014, DairyNZ, New Zealand, personal communication). The visual detection rate of detecting clots has been estimated at 80.0% (Claycomb et al., 2009, Hillerton, 2000). However, having to teat-strip all cows during a milking, farmers were assumed to pay less attention to the milk compared to a situation where farmers are alerted by an AMD system for a limited number of cows. Therefore, the visual detection rate of CM was assumed to be lower than 80.0% (McDougall, 2014, Anexa Animal Health, Morrinsville, New Zealand, personal communication) and the default value was set at 70%. Similar to the AMD system situation, it was assumed that farmers (with a system using visual detection) marked and teat-stripped cows with CM until clots were observed for two out of three consecutive milkings, and that treatment only started after clots were observed for two out of three consecutive milkings.

If a CM cow was not detected at the first teat-strip check after the start of the CM episode, the cow could remain clinical, change into SCM or self-cure (Figure 2). The cows that remained clinical could be detected at the next teat-strip check. A proportion of CM cows might still not be detected and could be detected at the next teat-strip check, and so on. The model calculated the proportion of cows detected at each teat-strip check and calculated both the required number of teat-strip checks until the second clots were observed and the associated delay from the start of the CM episode until treatment.

The model allows users to opt for CM cows to be found at the next milk recording (for both AMD or visual detection) or for CM cows to move on to the next time window of ten milkings (for AMD) or the next teat-strip check (for visual detection) until they were detected. The default value was set at finding and treating undetected cows after a milk recording. If cows get recurrent CM, they enter the model as a new CM episode to follow the same pathways in Figure 2.

Labour requirements

Labour requirements for both the use of an AMD system and visual detection were calculated based on (1) the required number of teat-strip checks from an AMD system alert or from conducting a
regular visual check (by teat-stripping all cows) until treatment, (2) the labour required per treated cow during the treatment period, and (3) the milk discarding period.

Based on the possible clot patterns (Figure 3), the calculated number of checks for ED was 3.2 milking and for LD was 2.6 milking. These were both used proportionally to EDR and LDR for the first time window of 10 milking for OD, when using an AMD system. Cows not being detected during that first time window for OD and that were detected during successive time windows, required treat-strip checks during 2.5 milking. This is because possible clot patterns were ‘clot-clot’, ‘clot-blank-clot’, ‘blank-clot-clot’ or ‘blank-clot-blank-clot’ \((2+3+2+3)/4=2.5\)^. In addition to checking of true alerts, false alerts are also checked. The FAR1000 was multiplied with the total number of milkings per year. The model assumed false alerts to be marked and checked for three consecutive milkings, since the farmer doesn’t know beforehand whether an alert is an early alert or a false alert. However, the parameter FAR1000 doesn’t provide any information on which cows are alerted falsely. If a cow was alerted and marked, whether a cow gets alerted again within the next two milkings doesn’t influence the required number of checks, since the cow was checked anyway. Therefore, a correction factor was built into the model to correct for double false alerts. Of all false alerts, 25\% was assumed to occur within the three consecutive milkings after the first alert (DelaRue, 2014, DairyNZ, Hamilton, New Zealand, personal communication). Thus, the default value of the correction factor was set at 0.75 (1-0.25). The default time required to teat-strip an alerted cow was set at twenty seconds per cow.

CM cows detected by visual detection were assumed to be marked and checked for 1.5 additional milkings (possible clot patterns after the first clot were another clot or blank-clot \((1+2)/2=1.5\)^). The default time required to teat-strip a cow (when teat-stripping all cows on a regular basis) was set at twenty seconds per cow. If the moment of visual detection coincided with a milk recording event, the model assumption was that no teat-strip check took place on that moment.

Total labour requirements for treated cows were calculated by multiplying the number of treated cows for both AMD and visual detection with the labour requirements during the treatment phase (default 5 minutes per dosage of antibiotics; National Mastitis Advisory Committee, 2006) and during the discarding phase (default 13,5 milkings times 2 minutes per milking; National Mastitis Advisory Committee, 2006).

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\* These clot pattern were assumed to be equally likely, so a simple average was used, not a weighted average
Default costs of labour for both teat-stripping and treatment of CM cows was set at $18.66\textsuperscript{‡} per hour (Anonymous, 2014a).

**Early treatment and its effects on antibiotic use**

During an experimental set-up, early treatment of CM significantly reduced the use of antibiotics and the degree of milk production losses (Milner *et al.*, 1997). In the current study, early treatment effects on milk production losses were ignored and only early treatment effects on antibiotic use were included. Label recommendation of lactating cow antibiotics in New Zealand is typically to use three dosages of antibiotics per treatment (Anonymous, 2015). The higher required dosages of antibiotics to resolve signs of CM reported by Milner *et al.* (1997) were rescaled with a factor of 0.38 to get to this New Zealand standard level. To create consistency with Milner *et al.* (1997), the current model assumed that the first visually detectable clots appeared two milkings before the severe clots that were visible at 3.5 milkings after the EC warning reported by Milner *et al.* (1997).

To determine the effect of the moment of treatment on the use of antibiotics, a Michaelis Menten curve was fitted (Equation 7, Figure 4) to the theoretical minimum level (2.3 dosages), maximum level (3.8 dosages) and the level of dosages at the second milking with clots (3.0 dosages) which were calculated by the rescaling of the antibiotic use reported by Milner *et al.* (1997). The number of milkings where half of the maximum use of antibiotics was reached, was 5.4 milkings. The theoretical minimum level of antibiotic use was 2.3 dosages, but due to the model restriction that cows were not treated until the second milking at which clots were observed, the effective use of antibiotics could not be lower than 3 dosages per treated CM cow.

\[
\text{Use of antibiotics (dosages)} = 2.3 \text{ dosages} + \frac{\text{delay} \times (3.8 \text{ dosages} - 2.3 \text{ dosages})}{(\text{delay} + 5.4 \text{ milkings})}
\]

\textsuperscript{‡} Calculated salary as per “Assistant Herd Manager”, assuming 50 hours/week and 48 weeks/year at work
Figure 4: Graph showing the required dosages of antibiotics as an effect of delay from start clinical mastitis (CM) episode until treatment (milkings) until signs of clinical mastitis have disappeared. Minimum use of antibiotics per treatment was 2.3 dosages, maximum was 3.8 dosages. The origin represents the start of the CM episode. The red line shows the effective minimum use of three dosages of antibiotics.

The expected delays (in milkings) from the start of the CM episode until treatment of all CM cases were inserted by the model in Equation 7, resulting in a range of estimates for the use of antibiotics. The individual estimates for the use of antibiotics were weighted by an equal probability to determine the average use of antibiotics per treated CM episode for both detection through an AMD system and through visual detection.

The annual use of antibiotics at herd level when using an AMD system or by visual detection was calculated by multiplying the number of treated animals (depending on the detection rates) with the use of antibiotics per treated cow. Default costs per dosage were set at $7.08 per dosage (Anonymous, 2006).

**Milksolids production curve**

The production curve of milksolids was modelled using the functional form of Wood (1967). The input parameters of this model were calibrated by fitting the curve to available data of a model summary report on milksolids production of cross-bred herds (Anonymous, 2012). The Wood-model parameter inputs were a lactation length of 294 days (42 weeks) (Lacy-Hulbert, 2014, DairyNZ, Hamilton, New Zealand, personal communication) and day of peak milk production at day 55 after
start of lactation (Anonymous, 2012). The production level was dependent on user input, but the default value was set on 346 kg of milksolids per cow per year (Anonymous, 2013b). Cows were milked twice a day. During the colostrum period the production level was set to zero kg of milksolids, since this milk wouldn’t be sold for human consumption.

With this production curve for milksolids, the amount of discarded milk for each treated CM episode was calculated, taking the production level at the moment of treatment into account. The default value for the withholding period was 13.5 milkings\(^6\) (Anonymous, 2006). The model’s input options included to either feed discarded milk to the calves during the first 70 days of lactation (resulting in no costs of discarded milk for the first 70 days of lactation, before calves are weaned) or discard milk during the complete withholding period for all treated cows in the entire lactation. In the current study, the default was set at discarding milk during the complete withholding period. Costs per kg of discarded milksolids were set at $2.37/kg of milksolids, calculated by subtracting average production costs ($4.13/kg of milksolids, (Anonymous, 2013b)) from the average milk price ($6.50 per kg of milksolids, (Neal, 2014, DairyNZ, New Zealand, personal communication)).

For every cow with SCM as a result of a non-detected CM episode, the milk production losses due to elevated SCC levels were calculated as a percentage of the normal production predicted by the production curve for milksolids, taking the moment of obtaining SCM into account. Normal SCC equalled the default BMSCC of 204,000 cells/ml (Anonymous, 2013b) and average cow SCC when having SCM was estimated at 800,000 cells/ml (Lacy-Hulbert, 2014, DairyNZ, Hamilton, New Zealand, personal communication). For every doubling of cow SCC, the kg of milksolids was reduced with 2.1% (Anonymous, 2014d) until the end of lactation. Costs of these milksolids production losses were set at $2.37/kg of milksolids, calculated by subtracting average production costs ($4.13/kg of milksolids, (Anonymous, 2013b)) from average milk price (default $6.50 per kg of milksolids, (Neal, 2014, DairyNZ, New Zealand, personal communication)).

**Transmission of pathogens**

In addition to the milksolids production losses due to elevated SCC (Anonymous, 2014d), SCM cows can transmit pathogens to other cows with the risk of causing IMIs (McDougall, 2014, Anexa Animal Health, Morrinsville, New Zealand, personal communication). Therefore, a transmission model similar to the Susceptible-Infected-Removed (SIR) model of Kermack and McKendrick (1927) was developed (Equation 8).

\[^6\] Includes discarding of the milk during the milking before treatment
Of the total number of cows (N), cows are either susceptible to IMI (S), infected (I) or removed (R) by treatment or self-cure. The average transmission rate per 10 milkings (β) was calculated by combining the transmission rates of pathogens and their share of the total number of pathogens during each part of the season. Van den Borne et al. (2010a) reported transmission rates for S. uberis (0.21/14 days), S. aureus (0.25/14 days) and S. dysgalactiae (0.21/14 days). Even though S. uberis is classified as an environmental pathogen, it can act as a contagious pathogen too (Phuektes et al., 2001, Zadoks et al., 2001). No data were found on transmission rates for other pathogens. Therefore, only these three types of pathogens were included as transmittable pathogens in the model.

Petrovski et al. (2011) reported the pathogen patterns present at New Zealand dairy farms and demonstrated that S. uberis, S. aureus and S. dysgalactiae form an average share of 53.3% of the pathogens. Their share of the total number of pathogens per part of the season was expressed per time window of 10 milkings by means of adding a trend line. Also the transmission rates were expressed per time window of 10 milkings. In that way, the time windows for transmission rates were made consistent with the time windows for detection.

\[
\frac{dl}{dt} = \frac{\beta * S * I}{N} - R
\]

Cows with SCM cows transmit mastitis and cause new IMI’s, as per the pathway described by Figure 2. In other words: poor sensitivity of detecting CM episodes resulted in more SCM cows, and therefore an increased risk of transmitting mastitis and causing new IMI’s. This in turn resulted in more new CM cases. The current study had the same default value for mastitis incidence as a starting value for both a system using AMD and a system using visual detection, which enabled taking only costs into account where a difference was found between a system using AMD and a system using visual detection (all other costs would be the same for both systems). However, these new CM cases caused by transmission also involved other costs (e.g. culling). Therefore, the default total costs per new CM case was set at $305,90 (Anonymous, 2006). The costs per new SCM case were milk solids production losses due to elevated SCC, as described in “Milk solids production curve”.
Investment analysis

Firstly, the optimal\textsuperscript{**} ODR was determined, to act as a model input for the subsequent calculations. Then the investment analysis was performed based on the difference in annual cash flow between AMD and visual detection. This comprised the total use of antibiotics, discarded milk, production losses due to SCM, new cases of CM due to transmission of pathogens, labour requirements, AMD system maintenance (default was 2.0\% of the total investment per year (DelaRue, 2014, DairyNZ, Hamilton, New Zealand, personal communication)) and additional costs of the AMD system per milking (e.g., the use of reagents where applicable). Since our study evaluated EC sensors that require no additional use of reagent, the default value for additional costs were set at $0.00 per milking).

The investment costs for the AMD system are dependent on the number of sensors installed, the variable costs per installed sensor and the fixed costs for the AMD system. Default fixed costs for AMD systems (both EC\textsubscript{udder} and EC\textsubscript{quarter}) were set at $3,000 (Doohan, 2014, Dairy Automation Limited, Hamilton, New Zealand, personal communication). Default costs per installed sensor were set at $500 for AMD systems using EC\textsubscript{udder} (DelaRue, 2014, DairyNZ, Hamilton, New Zealand, personal communication) and $1,000 for AMD systems using EC\textsubscript{quarter}. (Doohan, 2014, Dairy Automation Limited, Hamilton, New Zealand, personal communication). The average number of cows on New Zealand farms is 402 cows (Anonymous, 2013b). Default value for the number of installed sensors (with a sensor on every bail) was set at 25 sensors (e.g., a swing-over herringbone with 25 sets of cups). These assumptions resulted in a total investment of $15,500 for AMD systems using EC\textsubscript{udder} and $28,000 for those using EC\textsubscript{quarter} (Table 1).

Table 1: Costs involved for investing in automated mastitis detection by electrical conductivity (EC) sensors on whole udder level and EC sensors on quarter level.

<table>
<thead>
<tr>
<th></th>
<th>EC\textsubscript{udder}</th>
<th>EC\textsubscript{quarter}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed sensors</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Costs per installed sensor</td>
<td>$ 500</td>
<td>$ 1,000</td>
</tr>
<tr>
<td>Fixed costs</td>
<td>$ 3,000</td>
<td>$ 3,000</td>
</tr>
<tr>
<td>Total investment</td>
<td>$ 15,500</td>
<td>$ 28,000</td>
</tr>
</tbody>
</table>

After the last year of the system’s life span (default value was 15 years) the residual value of the system after depreciation was added. A declining balance depreciation was used with a diminishing

\textsuperscript{**} Based on the difference in annual cash flow between the system using AMD and the system using visual detection.
value of 30% (Anonymous, 2011). Then the saved tax (default marginal tax rate was set at 17.5% (Anonymous, 2014c)) over the depreciation was added and the tax paid over the residual value was subtracted. Next the net present value (NPV) at a discount rate of 5% and the internal rate of return (IRR) were calculated. The discounted payback period was calculated over the discounted values after tax.

In the investment analysis the scenarios of installing AMD sensors on every bail, every second bail, or every third bail of the milking parlor were evaluated on the percentages of detected CM episodes, the delay from the start of the CM episode until treatment, differences in annual cash flow and net present value. The total difference in annual cash flow comprised four categories: “treatment CM” (difference in antibiotics and discarded milk), “untreated CM” (difference in new cases of CM and production losses due to SCM), “labour” (difference in labour costs of detection and of treatment) and “additional costs AMD” (maintenance costs and other costs of the AMD system, such as reagents). These categories were calculated as the annual cash flow for a system using AMD minus the annual cash flow for a system using visual detection. A positive value meant that the revenues or saved expenses of the system using AMD were larger than the revenues or saved expenses of the system using visual detection.

**Sensitivity analysis and Monte Carlo simulation**

In this study, the add-in software @Risk 6 for Excel (Palisade Corporation, 2014) was used to perform the sensitivity analysis and Monte Carlo simulation to assess the sensitivity of the investment analysis model to variations in model inputs.

The visual detection rate of a system using visual detection was evaluated by scenarios ranging from 40% to 100%. The frequency of performing teat-strip checks in a system using visual detection was evaluated by simulating teat-strip checks every ten, twenty, thirty, forty or every fifty milkings. All other input settings were set at default values as described in the previous sections. An overview of these default input values is given in Error! Reference source not found. Appendix I.

The Monte Carlo simulation was performed with the CM incidence and milk price as risky variables, since these parameters are harder to control for farmers. Again, all other model inputs were set at the default values. For the incidence of CM a normal distribution was used with mean=0.148 (Petrovski et al., 2009) and standard deviation=0.03 (Neal, 2014, DairyNZ, New Zealand, personal communication). For the milk price a uniform distribution was used (Neal, 2014, DairyNZ, New Zealand, personal communication) at the interval $4.35:$8.70 per kilogram of milksolids (Anonymous, 2013b). Note that the input value for milk price at each iteration was maintained
during the entire system life span, so no year to year variations were modelled. All calculations were performed for both AMD systems using ECudder and those using ECquarter, simulating at 1,000 iterations.
Results

Optimisation of overall detection rate

Figure 5 graphically demonstrates the effect of the ODR of AMD systems on the differences in annual cash flows between an AMD system using EC at udder level and a system using visual detection. The theoretical optimal ODR of the AMD system using EC_{udder} would be 0% (Figure 5). However, since animal welfare and penalties of the milk processor were not included in the model, an ODR of 23% was considered to be the optimum level for AMD systems using EC_{udder}. Figure 5 clearly shows a turning point here, since the AMD system using EC_{udder} started generating many false positive alerts. As a result, a large labour input was required for teat-stripping cows that were falsely alerted, decreasing the profitability of investing in this AMD system rapidly. Therefore, the ODR was set at a default value of 23% in the calculations that follow.

Figure 6 graphically demonstrates the effect of the ODR of AMD systems on the difference in annual cash flows between an AMD system using EC_{quarter} and a system using visual detection. At an ODR above 75% the AMD system using EC_{quarter} started generating many false positive alerts. As a result, a larger labour input was required for teat-stripping cows that were falsely alerted. The optimal ODR was found at 88% and was set as the default ODR for AMD systems using EC_{quarter}.

Figure 5 and Figure 6 show that both the AMD systems using EC_{udder} and those using EC_{quarter} have very similar responses in annual cash flows per category to changes in ODR. As ODR increased, more CM episodes were detected and treated, resulting in higher costs of antibiotics and discarded milk for the system using AMD (category “Treatment CM”). Since more CM episodes were treated, less CM episodes became SCM, resulting in lower costs of production losses due to SCM and fewer new cases of CM due to a lower transmission of pathogens (category “Untreated CM”). The slightly higher value for “total difference in annual cash flow” at low ODR can be explained by the different pathways CM cases could follow in the model (Figure 2): at a very low ODR, few of the new CM episodes caused by transmission of pathogens were treated and more of these new CM episodes became SCM or self-cured. CM episodes that self-cured involved no costs and the costs of cows with SCM were lower than the costs of new CM cases, thus resulting in a positive difference in annual cash flow for the category “Untreated CM”. The value of the category “additional costs AMD” consisted of maintenance costs of the AMD system and was independent of the ODR.

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†† Based on the difference in annual cash flow between a system using AMD and a system using visual detection.
Figure 5: Effect of overall detection rate on the total difference in annual cash flow (---) between Automated Mastitis Detection (AMD) using EC at whole udder level and visual detection per category. This total difference in annual cash flow is formed by different categories, and the effect of the overall detection rate is also demonstrated per category, being: “Treatment CM” (—••) including differences in antibiotic use and discarded milk, “Untreated CM” (- • -) including differences in new cases of CM and production losses of SCM, “Labour” (- - -) including differences in labour costs of detection and of treatment of CM, and “Additional costs AMD” (***)) including costs of maintenance of the AMD system.
Figure 6: Effect of overall detection rate on the total difference in annual cash flow (—) between Automated Mastitis Detection (AMD) using EC at quarter level and visual detection per category. This total difference in annual cash flow is formed by different categories, and the effect of the overall detection rate is also demonstrated per category, being: “Treatment CM” (—••) including differences in antibiotic use and discarded milk, “Untreated CM” (- • -) including differences in new cases of CM and production losses of SCM, “Labour” (- - -) including differences in labour costs of detection and of treatment of CM, and “Additional costs AMD” (•••) including costs of maintenance of the AMD system.

Installation of automated mastitis detection systems on fewer bails

Percentage of detected clinical mastitis episodes

Figure 7 shows the percentages of detected and treated CM episodes for visual detection and for AMD systems using ECudder or ECquarter. Also the effect of installing AMD sensors on fewer bails of the milking parlor on the percentages of detected and treated CM episodes is presented.

The percentage of detected and treated CM episodes in a system using visual detection was 46.1%. The AMD system using ECudder did not achieve that level of detected and treated CM episodes: the percentages of detected and treated CM episodes were 38.4%, 29.2% and 26.1% when installed on every bail, every second bail or every third bail of the milking parlor, respectively. The AMD system using ECquarter performed best of all three systems when installed on every bail of the milking parlor (90.2% detected and treated CM episodes). The percentage of detected and treated CM episodes by
the AMD system using EC\textsubscript{quarter} drastically reduced when installing on every second bail of the milking parlor, but was still higher than both other systems (55.1%). However, installation of an AMD system using EC\textsubscript{quarter} on every third bail of the milking parlor resulted in a percentage of detected CM episodes lower than the system using visual detection (43.4%).

![Figure 7: Effect of installing an Automated Mastitis Detection (AMD) sensor every bail, every second bail or every third bail of a milking parlor on the percentage of clinical mastitis (CM) episodes being detected and treated. AMD systems using Electrical Conductivity (EC) on whole udder level (blue diagonally striped bars) and those using EC at quarter level (green solid bars) were compared with visual detection (yellow horizontally striped bars).](image)

**Delay from start clinical mastitis episode until treatment**

Figure 8 shows the average delay from the start of a CM episode until treatment for visual detection and for AMD systems using EC\textsubscript{udder} or EC\textsubscript{quarter}. Also the effect of installing AMD sensors on fewer bails of the milking parlor on this delay is presented.

The delay from the start of the CM episode until treatment was consistently the shortest for an AMD system using EC\textsubscript{quarter}. Installation on every bail, every second bail or every third bail of the milking parlor resulted in an average delay of 2.3, 3.2 and 4.4 milkings, respectively. The delay was the longest for a system using visual detection by teat-stripping the entire herd every 30 milkings (8.8 milkings). A system using EC\textsubscript{udder} had an average delay in between the values of the AMD system using EC\textsubscript{quarter} and a system using visual detection. Installation on every bail, every second bail or every third bail of the milking parlor resulted in an average delay of 5.1, 7.0 and 7.7 milkings, respectively. Nota bene, the delay from the start of the CM episode until treatment only addressed...
CM cows that were detected and treated. Non-detected CM episodes became SCM or self-cured (Figure 2).

![Figure 8: Effect of installing an Automated Mastitis Detection (AMD) sensor every bail, every second bail or every third bail of a milking parlor on the milkings delay from the start of a clinical mastitis (CM) episode until treatment for detected CM episodes. AMD systems using Electrical Conductivity (EC) on whole udder level (blue diagonally striped bars) and those using EC at quarter level (green solid bars) were compared with visual detection (yellow horizontally striped bars).](image)

Figure 7 and Figure 8 implied that the AMD system using $EC_{\text{quarter}}$ performs better than the AMD system using $EC_{\text{udder}}$. Therefore, the AMD system using $EC_{\text{quarter}}$ was used to illustrate the NPV under default settings, and was used to examine the sensitivity of the investment analysis model to the visual detection rate and the frequency of visual checks (in a system using visual detection). Additionally, the effects of variation in milk price and CM incidence were illustrated for the AMD system using $EC_{\text{quarter}}$ in a Monte Carlo simulation. All of these calculations were also performed for the AMD system using $EC_{\text{udder}}$. These latter results will not be discussed in the remainder of this document, but results of this analyses are summarized in Appendix III.

**Difference in annual cash flow and net present value**

Installation of an AMD system on fewer bails of the milking parlor drastically reduced the profitability of the AMD system, but the total investment costs are also a key determinant on the NPV of the AMD system (Figure 9).
Installation of an AMD system using $EC_{\text{quarter}}$ on every bail resulted in a difference in annual cash flow just over $1,700 and a NPV just under $-8,900. Installation of this system on fewer bails of the milking parlor reduced the total investment costs, but resulted in a much lower difference in annual cash flow (around $150). The NPV of installing an AMD system using $EC_{\text{quarter}}$ on every second bail was around $-12,000 and on every third bail was around $-8,200.

![Figure 9: Effect of installing an automated mastitis detection system using Electrical Conductivity (EC) at quarter level on every bail, every second bail or every third bail of a milking parlor on the total difference in annual cash flow (green solid bars) and on the net present value (blue diagonally striped bars).]

**Sensitivity analysis**

**Visual detection rate**

The visual detection rate of the person milking, using visual detection only, has little impact on the profitability of investing in AMD systems (Figure 10). Varying the visual detection rate (default was 70%) between 40% and 100% resulted in a difference in annual cash flow (between an AMD system using $EC_{\text{quarter}}$ and a system using visual detection) varying between just over $1,500 and just over $1,700.

As the visual detection rate increased, more CM episodes were detected and treated in the system using visual detection, resulting in higher costs of antibiotics and discarded milk (category “Treatment CM”). Since more CM episodes were treated, fewer became SCM, resulting in lower costs of milksolids production losses caused by SCM and fewer new CM episodes due to transmission of pathogens (category “Untreated CM”). As the visual detection rate increased, the
system using visual detection marked, teat-stripped and detected more CM episodes, resulting in a higher labour requirement for detection and treatment of CM episodes (category “Labour”).

The value of the category “additional costs AMD” consisted of maintenance costs of the AMD system using $\text{EC}_{\text{quarter}}$ and was not dependent on the visual detection rate.

![Figure 10: Sensitivity of the total difference in annual cash flow (-----) between a system using Automated Mastitis Detection (AMD) with Electrical Conductivity (EC) at quarter level and a system using visual detection only to the visual detection rate of a system using visual detection only. This total difference in annual cash flow is formed by different categories: “Treatment CM” (——) including differences in antibiotic use and discarded milk, “Untreated CM” (- - -) including differences in new cases of CM and production losses of SCM, “Labour” (- - -) including differences in labour costs of detection and of treatment of CM, and “Additional costs AMD” (••••) including costs of maintenance of the AMD system. The default visual detection rate was 70%.](image)

**Frequency of teat-stripping**

The frequency of teat-stripping the entire herd in the situation prior to investing in AMD systems (using visual detection) impacts the profitability of investing in AMD systems mainly through the labour requirement for detecting CM episodes (Figure 11). Varying the frequency of teat-stripping the entire herd from once every ten milkings to once every fifty milkings, resulted in a difference in annual cash flow (between an AMD system using $\text{EC}_{\text{quarter}}$ and a system using visual detection) varying between just over $2,400 and just under $1,400 (red line).
Figure 11: Sensitivity of the total difference in annual cash flow (red line) between a system using Automated Mastitis Detection (AMD) with Electrical Conductivity (EC) on quarter level and a system using visual detection only to the frequency of teat-stripping the entire herd in a system using visual detection. This total difference in annual cash flow is formed by different categories: “Treatment CM”, including differences in costs of antibiotics and discarded milk; “Untreated CM”, including differences in costs of milksolids production losses caused by SCM and new cases of CM due to transmission of pathogens; “Labour”, including differences in labour costs for detection and treatment of CM episodes.

That indicates that installing an AMD system would be most favourable for farmers who teat-strip the entire herd very regularly, who aim to decrease the labour requirement of detecting CM episodes (Figure 11) while maintaining or improving the percentage of detected and treated cows (Figure 7).

Monte Carlo simulation

Figure 12 shows a cumulative density function of the effect of variation in milk price and CM incidence on the difference in annual cash flow between an AMD system using EC_{quarter} and a system using visual detection. The mean difference in annual cash flow between an AMD system using EC_{quarter} and a system using visual detection was $1,736 (range $313-$3,617). This range was virtually equally caused by variation in milk price as by variation in CM incidence, as can be observed from the tornado chart in Figure 13. The variations in CM incidence had a larger effect on the difference in annual cash flow for an AMD system using EC_{quarter} than for AMD systems using EC_{udder} (Appendix III,
Figure 23). The reason for this is probably the difference in ODR (88% versus 23%, respectively). The IRR of the AMD system using EC<sub>quarter</sub> became positive in 38% of the iterations, but the mean IRR was -1.11%. The minimum IRR was -14.1% and the maximum was 7.68%, as is shown in the probability density function in Figure 14. The NPV varied between $-20,748 and $4,853 (mean: $-8,923) (Figure 15). In 3.1% of the iterations the IRR was 5% or higher, resulting in a positive NPV. Due to the negative NPV, the discounted payback period could not be calculated.

From the positive difference in annual cash flow ($1,736) and the negative IRR and NPV (-1.11% and $-8,923, respectively) was concluded that the profitability of investing in AMD systems using EC<sub>quarter</sub> is dependent on the investment costs, but is negative under the current default settings.

![Difference in annual cash flow](image)

Figure 12: Monte Carlo simulation, cumulative density function: effects of variation in milk price and the percentage of clinical mastitis on the difference in annual cash flow for electrical conductivity sensors on quarter level.
Figure 13: Monte Carlo simulation, tornado chart: effects of variation in milk price and the percentage of clinical mastitis on the difference in annual cash flow for an AMD system using electrical conductivity on quarter level.

Figure 14: Monte Carlo simulation, probability density function: effects of variation in milk price and the percentage of clinical mastitis on the Internal Rate of Return (IRR) for an AMD system using electrical conductivity on quarter level.
Figure 15: Monte Carlo simulation, probability density function: effects of variation in milk price and the percentage of clinical mastitis on the Net Present Value (NPV) for an AMD system using electrical conductivity on quarter level.
Discussion

The main purpose of the current study was to develop a framework for an investment analysis model for AMD systems when implemented in New Zealand dairy farming. Assumptions and estimations based on expert knowledge were required for a number of aspects for which data were limited. Additional research on these particular aspects would create more accurate relationships for the investment analysis model. The main assumptions and estimations are discussed in this section.

The modelled IMI pathways and their proportions were estimated by expert knowledge (Lacy-Hulbert, 2014, DairyNZ, Hamilton, New Zealand, personal communication; McDougall, 2014, Anexa Animal Health, Morrinsville, New Zealand, personal communication). According to their estimations 32% of undetected CM cows will self-cure (Figure 2). A study of Williamson and Lacy-Hulbert (2013) reported that 36% of CM cows that were treated with homeopathic treatment cured. This slightly higher cure rate of homeopathic treated cows seems to correspond relatively well with the estimated self-cure rate in the current study.

The CM incidence distribution was based on data of McDougall (2005). This curve was strongly skewed to the left, which meant that cows had a very high risk of obtaining CM at early lactation relatively to late lactation. According to the trend line, 87% of the CM incidence would occur in the first month after calving. This implied that hiring extra labour to securely and routinely check all milk for abnormal signs during that first month could be adequate to detect most of the CM cases. However, a spread in calving pattern which is common in the context of seasonal dairy farming in New Zealand (Burke, 2014, DairyNZ, Hamilton, New Zealand, personal communication), results in a CM distribution which is stretched over a longer period than one month. As an example: an illustrative calving pattern for the period from one week before the planned start of calving (PSC) until ten weeks after the PSC could be 8.0% per week (PSC-1wk); 12.5% per week (PSC until PSC+3wks); 9.0% per week (PSC+4wks until PSC+6wks); 4.0% per week (PSC+7wks until PSC+9) and 3.0% per week (PSC+10 wks) of the cows having calved. If this illustrative calving pattern was inserted in the current model, the 87% incidence of cows with CM would be spread over a period of three months instead of one month. The assumption made in the current model was that visual detection of CM (teat-stripping the entire herd on a regular basis) was performed on a regular interval during the entire period that cows were in lactation. Although the calving pattern stretched the herd level incidence over a longer period than the incidence on cow level, it may still be worthwhile performing the visual detection more frequently during early lactation than during late lactation. This was not accounted for in the current model.
Another strategy that was not included in the current model, was to combine AMD and visual detection with a California Milk Test to detect cows with high SSC (Middleton et al., 2004). Instead of teat-stripping alerted cows for multiple milkings, a California Milk Test could be performed to get an immediate result on the SCC of cows, requiring less milkings to teat-strip cows. Although not tested in this study, the current model allows adjustment of settings to examine that particular scenario with using the CMT test. Another scenario could be visual detection by teat-stripping one teat at a time for four consecutive milkings. This scenario was also not researched in more detail in the current study, but the model does allow such a scenario to be analysed.

Milner et al. (1997) reported effects of early treatment of CM on the required use of antibiotics and on the degree of milk production losses. Although they could be included in the current model, the effects of early treatment on milk production losses were excluded from the model, as no recent evidence was found to support these effects on milk production losses (Lacy-Hulbert, 2014, DairyNZ, Hamilton, New Zealand, personal communication; McDougall, 2014, Anexa Animal Health, Morrinsville, New Zealand, personal communication). The study that would relate closest to milk production losses would be the study of McDougall et al. (2009), which shows a decrease in milk production until treatment (after which milk production increases again within a relatively short time frame), but no effects of early treatment were reported in that study. Early treatment would only minimise the period of pathogen transmission and reduce the period in which a cow has CM symptoms (McDougall, 2014, Anexa Animal Health, Morrinsville, New Zealand, personal communication). Results supporting this theory were given by Pearson et al. (2013); IMIs caused by S. uberis resulted in similar milk production losses for CM episodes (which were treated with antibiotics) as for SCM. The study of Pearson et al. (2013) supports the decision not to include early treatment effects on milk production losses, but indicates that including only milk production losses for cows with SCM for the rest of lactation due to a rise in SCC is not sufficient; milk production losses after treatment of CM episodes should have been included in the model as well.

In contrast to early treatment effects on milk production losses, early treatment effects on the use of antibiotics were included in the current study. In the current study it was assumed that leaving a CM cow untreated for a prolonged period would result in an increased use of antibiotics. However, this was not supported by literature other than Milner et al. (1997). The results of Milner et al. (1997) were obtained in an experimental setup in England in which the IMI was induced, possibly resulting in a more intense infection as compared to a normal infection. Since the used number of dosages of antibiotics per treated cow in that study was considered to be extremely high (Lacy-Hulbert, 2014, DairyNZ, Hamilton, New Zealand, personal communication), that number of dosages
was rescaled in the current study to a level which was considered appropriate for New Zealand conditions. Therefore, the number of dosages to resolve CM was set at three in the current study, where treatment started after the second clot observation. This meant that the use of antibiotics of Milner et al. (1997) had to be multiplied by a factor of 0.38 to rescale it to this New Zealand standard level. To create consistency with Milner et al. (1997), the current model assumed that the first visually detectable clots appeared two milkings before the severe clots that were visible at 3.5 milkings after the EC warning reported by Milner et al. (1997). The mean number of dosages used in the conventional treatment group for *S. aureus* was 10 dosages (Milner et al., 1997). This study took this 10 dosages as the plateau level of antibiotic use. Multiplied with the factor of 0.38, the maximum level for New Zealand standards would be 3.8 dosages per treated CM episode. That means, for example, that most cows are treated with three dosages and some cows with more dosages. The theoretical minimum level for New Zealand standards would be (0.38 * 6.0 =) 2.3 dosages per treated CM episode. However, due to the model restriction that cows were not treated until the second milking at which clots were observed, the effective use of antibiotics could not be lower than 3 dosages per treated CM cow.

Additional research on early treatment effects on the use of antibiotics under New Zealand conditions would create a more solid foundation for this part of the current model. The current model assumes that high AMD performance leads to early detection, resulting in a lower use of antibiotics. However, farmers might be tempted to treat more cows if more cows are alerted, possibly resulting in an increased use of antibiotics. Although the effects on the use of antibiotics might be debatable, the model still provides valuable information on the delay from the start of the CM episode until the moment of treatment (particularly with user input options as installing an AMD sensor on fewer bails of the milking parlor instead of on every bail).

Very little data was available on transmission rates of pathogens. The assumed proportions of transmittable pathogens and the associated transmission rates per time window of ten milkings of the current model were approximations based on the studies of Petrovski et al. (2011) and Van den Borne et al. (2010a). The current model provided a framework to simulate the dynamics of pathogen transmission as an effect of differences in CM detection between AMD and visual detection. However, additional research in this field are desirable to consolidate the economic effects of transmission of pathogens, since the modelled new cases of CM and milk production losses due to SCM caused by this transmission have a substantial effect on the profitability of investing in AMD systems. New cases of CM as a result of pathogen spreading by undetected CM cows were not included in the labour calculations of this model, since the costs of labour were already included in
the overall costs per new case of CM (Anonymous, 2006). The same principle is applicable to costs of culling.

Only AMD systems using ECudder and those using ECquarter were included in this study. Insufficient data was available on other AMD technologies, but the model framework allows addition of different AMD technologies to examine their performance as compared to visual detection. The available data on AMD systems using EC was also limited. The relation between ODR and FAR1000 (Equation 5) for AMD systems using ECquarter was extrapolated from very few data, as Claycomb et al. (2009) only reported the AMD performance within a narrow ODR range of 83-86%.

Table 1 shows the default values for investment costs in AMD systems using ECudder and ECquarter. The model assumption was that cows were alerted while standing on the bail. This doesn’t necessarily require an electronic cow identification system, since the cow was assumed to be visually marked for later inspection if required. Installation of an electronic cow identification system would cost roughly $80,000 (Doohan, 2014, Dairy Automation Limited, Hamilton, New Zealand, personal communication). However, these systems probably would not be installed for the sole purpose of AMD, but also for other purposes (for example, automated drafting or individual feeding) (DelaRue, 2014, DairyNZ, Hamilton, New Zealand, personal communication). Some milk meter systems include EC sensor technology and would retail at a price of $1,300 per installed device (Doohan, 2014, Dairy Automation Limited, Hamilton, New Zealand, personal communication). Since it was not clear which proportion of that price could be attributed to the EC technology and which proportion to the other functions of the milk meter system, the current model used price estimations for separate EC sensors. (DelaRue, 2014, DairyNZ, Hamilton, New Zealand, personal communication; Doohan, 2014, Dairy Automation Limited, Hamilton, New Zealand, personal communication).

The second and third requirement identified by Kamphuis et al. (2013), to manage the BMSCC and to support individual cow dry-cow therapy decisions, were not included in the present study. The economic consequences of these requirements could be evaluated in future research.
Conclusions and recommendations

Comprehensive investment analyses combining science on mastitis with effectiveness of in-line AMD systems have not previously been performed. With this study a framework was created for an investment analysis model, to compare the financial consequences of investing in AMD systems. In this study, AMD systems using EC\textsubscript{udder} and those using EC\textsubscript{quarter} were compared with visual detection by teat-stripping all cows on a regular basis, providing the opportunity to analyse different AMD systems and to adjust model inputs to farm specific values. The model allows for adoptions to analyse different scenarios, for example to analyse farm practises alternative to teat-stripping all cows on a regular basis.

The investment analysis model gave insight in the main drivers of the profitability of investing in AMD systems, showing that investing in AMD systems would be most favourable for farmers who like to decrease the labour requirement of detecting CM episodes while maintaining or improving the percentage of detected and treated CM episodes. AMD systems using EC\textsubscript{quarter} perform better than those using EC\textsubscript{udder}. Installation of an AMD system using EC\textsubscript{quarter} on every bail of the milking parlor results in the highest difference in annual cash flow ($1,736), but the profitability depends greatly on the total investment costs. Under the default settings used in this study, investing in an AMD system using EC\textsubscript{quarter} was not profitable (IRR: -1.11% ; NPV: $-8,923). It would be most advantageous for farmers if the AMD system is complementary to other technologies they are already investing in (such as milk meters), since investment costs attributed to the AMD systems are low in that case.

The investment analysis model was reliant on expert opinions where reliable data was absent or insufficient. Suggestions for further research are to investigate the pathways IMIs follow (becoming CM, SCM or self-cure), the proportion of double false alerts to optimise the labour requirement assessed in the model, pathogen transmission rates, and early treatment effects on the use of antibiotics. The current model only included the requirement of AMD systems to detect CM episodes, therefore the requirements to manage the BMSCC and to support individual cow dry-cow therapy decisions by using AMD systems could be added to the current model in future research. Finally, questions were raised on the profitability of treating CM episodes (other than for animal welfare reasons) and the relations between CM episodes and SCC.
Acknowledgements

DairyNZ provided me the opportunity and means to perform this study, for which I am very thankful. All DairyNZ staff are gratefully acknowledged for creating the cordial atmosphere, but special gratitude goes to Mark Neal, Brian DelaRue and Callum Eastwood for their guidance during the project. Great appreciation goes to Claudia Kamphuis for her supervision on this project and her contributions to the writing of this script. I would like to thank Jane Lacy-Hulbert and Scott McDougall for their useful contributions through inspiring discussions. Niels Rutten is acknowledged for sharing parts of his own work to demonstrate how to construct an investment analysis model. Finally, Eric Hillerton and Henk Hogeveen are acknowledged for initializing this project and giving me the opportunity to work on it in New Zealand.


McDougall, S., M. A. Bryan, and R. M. Tiddy. 2009. Erratum to “Effect of treatment with the nonsteroidal antiinflammatory meloxicam on milk production, somatic cell count, probability of re-


### Appendix I

Summary of default values for investment model inputs for Electrical Conductivity (EC) sensors on whole udder level and EC sensors on quarter level.

<table>
<thead>
<tr>
<th>AMD system</th>
<th>EC&lt;sub&gt;quarter&lt;/sub&gt;</th>
<th>EC&lt;sub&gt;udder&lt;/sub&gt;</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed costs</td>
<td>3,000</td>
<td>3,000</td>
<td>$</td>
<td>Doohan, 2014, pers.com.</td>
</tr>
<tr>
<td>Number of installed sensors</td>
<td>25</td>
<td>25</td>
<td>sensors</td>
<td>Model input</td>
</tr>
<tr>
<td>Sensor at every N&lt;sup&gt;th&lt;/sup&gt; bail</td>
<td>1</td>
<td>1</td>
<td>N&lt;sup&gt;th&lt;/sup&gt; bail</td>
<td>Model input</td>
</tr>
<tr>
<td>Maintenance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional costs per milking</td>
<td>0</td>
<td>0</td>
<td>$/cow/milking</td>
<td>Model input</td>
</tr>
<tr>
<td>System life span</td>
<td>15</td>
<td>15</td>
<td>years</td>
<td>Model input</td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall detection rate</td>
<td>88</td>
<td>23</td>
<td>%</td>
<td>Claycomb &lt;i&gt;et al.&lt;/i&gt; (2009); Kamphuis &lt;i&gt;et al.&lt;/i&gt; (2013)</td>
</tr>
<tr>
<td>Early detection rate</td>
<td>44</td>
<td>10</td>
<td>%</td>
<td>Kamphuis &lt;i&gt;et al.&lt;/i&gt; (2013); Model input</td>
</tr>
<tr>
<td>Late detection rate</td>
<td>44</td>
<td>13</td>
<td>%</td>
<td>Kamphuis &lt;i&gt;et al.&lt;/i&gt; (2013); Model input</td>
</tr>
<tr>
<td>FAR1000</td>
<td>6</td>
<td>0</td>
<td>/1000 milkings</td>
<td>Claycomb &lt;i&gt;et al.&lt;/i&gt; (2009); Kamphuis &lt;i&gt;et al.&lt;/i&gt; (2013)</td>
</tr>
<tr>
<td>Accounting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discount rate</td>
<td>5.0</td>
<td>5.0</td>
<td>%</td>
<td>Model input</td>
</tr>
<tr>
<td>Marginal tax rate</td>
<td>17.5</td>
<td>17.5</td>
<td>%</td>
<td>Model input, based on IRD (2014)</td>
</tr>
<tr>
<td>Diminishing value assets</td>
<td>30</td>
<td>30</td>
<td>%</td>
<td>IRD (2011)</td>
</tr>
</tbody>
</table>

### Farm data

<table>
<thead>
<tr>
<th>Production</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cows</td>
<td>402</td>
<td>402</td>
<td>cows</td>
<td>Anonymous (2013c)</td>
</tr>
<tr>
<td>Production per cow per year</td>
<td>346</td>
<td>346</td>
<td>kg milksolids</td>
<td>Anonymous (2013c)</td>
</tr>
<tr>
<td>Milkings per day</td>
<td>2</td>
<td>2</td>
<td>milkings/day</td>
<td>Model input</td>
</tr>
<tr>
<td>Year average bulk milk somatic cell count</td>
<td>204</td>
<td>204</td>
<td>(*1000) cells/ml</td>
<td>Anonymous (2013c)</td>
</tr>
<tr>
<td>Colostrum period</td>
<td>8</td>
<td>8</td>
<td>milkings</td>
<td>Model input</td>
</tr>
</tbody>
</table>

### Clinical mastitis (CM)
### Minor thesis

#### Business Economics Group

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative percentage of CM cases per year</td>
<td>14.8</td>
<td>14.8</td>
<td>%</td>
<td>Petrovski et al. (2009)</td>
</tr>
<tr>
<td>Discarding period milk (incl treatment)</td>
<td>13.5</td>
<td>13.5</td>
<td>milking</td>
<td>National Mastitis Advisory Committee (2006)</td>
</tr>
<tr>
<td>Time farmer during treatment phase</td>
<td>5</td>
<td>5</td>
<td>min/cow/treatment</td>
<td>National Mastitis Advisory Committee (2006)</td>
</tr>
<tr>
<td>Time farmer during discarding phase</td>
<td>2</td>
<td>2</td>
<td>min/cow/milking</td>
<td>National Mastitis Advisory Committee (2006)</td>
</tr>
<tr>
<td><strong>Subclinical mastitis (SCM)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production losses</td>
<td>2.1</td>
<td>2.1</td>
<td>%</td>
<td>Anonymous (2014b)</td>
</tr>
<tr>
<td>SCM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Labour AMD system</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time needed to check alerts</td>
<td>0.33</td>
<td>0.33</td>
<td>min/alert</td>
<td>Model input</td>
</tr>
<tr>
<td>Period checking false alert</td>
<td>3</td>
<td>3</td>
<td>milking</td>
<td>Model input, based on Kamphuis et al. (2013)</td>
</tr>
<tr>
<td>FAR1000 adjustment factor</td>
<td>0.75</td>
<td>0.75</td>
<td>-</td>
<td>DelaRue, 2014, pers.com.</td>
</tr>
<tr>
<td><strong>Visual detection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milkings between visual check</td>
<td>30</td>
<td>30</td>
<td>milking</td>
<td>Model input</td>
</tr>
<tr>
<td>Visual detection rate</td>
<td>70</td>
<td>70</td>
<td>%</td>
<td>Model input, based on McDougall, 2014, pers.com.</td>
</tr>
<tr>
<td>Required time to check individual cow visually</td>
<td>0.33</td>
<td>0.33</td>
<td>min/cow</td>
<td>Model input</td>
</tr>
<tr>
<td>Average period checking cow detected with clots</td>
<td>2.5</td>
<td>2.5</td>
<td>milking</td>
<td>Model input, based on Kamphuis et al. (2013)</td>
</tr>
<tr>
<td><strong>Milk recording</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency milk recording at visual detection</td>
<td>4</td>
<td>4</td>
<td>milk recordings/year</td>
<td>Anonymous (2014a)</td>
</tr>
<tr>
<td>Frequency milk recording at AMD system</td>
<td>4</td>
<td>4</td>
<td>milk recordings/year</td>
<td>Anonymous (2014a)</td>
</tr>
<tr>
<td><strong>Costs and prices</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production costs</td>
<td>4.13</td>
<td>4.13</td>
<td>$/kg milksolids</td>
<td>Anonymous (2013c)</td>
</tr>
<tr>
<td>Drugs</td>
<td>7.08</td>
<td>7.08</td>
<td>$/dosage</td>
<td>National Mastitis Advisory Committee (2006)</td>
</tr>
<tr>
<td>Labour</td>
<td>18.66</td>
<td>18.66</td>
<td>$/hour</td>
<td>Federated Farmers of New Zealand (2014)</td>
</tr>
<tr>
<td>Average costs of new CM case due to infection by SCM</td>
<td>305.90</td>
<td>305.90</td>
<td>$/extra CM case</td>
<td>National Mastitis Advisory Committee (2006)</td>
</tr>
</tbody>
</table>

### Additional settings
<table>
<thead>
<tr>
<th>Question</th>
<th>Minor thesis</th>
<th>Business Economics Group</th>
<th>Jeroen de Veer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Include early treatment effects on milk production losses CM?</td>
<td>No</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>Feed discarded milk containing antibiotics to calves?</td>
<td>No</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>Find remaining CM cases at herd testing?</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>Model input</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix II

Welcome to the investment analysis model for n-line Automated Mastitis Detection (AMD) systems. This model compares AMD systems with visual detection (teat-stripping all cows on a structural basis) on the following aspects:

- Delay from start clinical mastitis episode until treatment;
- Effect of delay on use of antibiotics per treatment;
- Dynamics of mastitis states (clinical mastitis, subclinical mastitis, self-cure);
- Effect of mastitis states on milk production losses, number of treatments, discarded milk and total use of antibiotics;
- Dynamics of mastitis transmission;
- Labour demand.

The model is highly adjustable to user preferences. Click on "Adjust settings" to customise the settings to farm specific values. Click on "Simulate" to start the scenario simulation. After completing the simulation, the results can be plotted in a graph by clicking on "Graph".

Figure 16: Screen shot of the welcome screen of the investment analysis model.
**Figure 17:** Screen shot of the settings tab of the investment analysis model.
<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Difference (AMD vs visual)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treated CM</td>
<td>Antibiotics</td>
<td>102.50</td>
</tr>
<tr>
<td></td>
<td>Production losses</td>
<td>Not included</td>
</tr>
<tr>
<td></td>
<td>Discarded milk</td>
<td>30.45</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>132.95</td>
</tr>
<tr>
<td>Untreated CM</td>
<td>New CM cases</td>
<td>1,105.14</td>
</tr>
<tr>
<td></td>
<td>Production losses, SCM</td>
<td>291.65</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>1,396.79</td>
</tr>
<tr>
<td>Labour</td>
<td>Treatments CM</td>
<td>83.28</td>
</tr>
<tr>
<td></td>
<td>Check cows visually</td>
<td>1,863.32</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>1,946.60</td>
</tr>
<tr>
<td>Additional costs</td>
<td>Maintenance</td>
<td>560.00</td>
</tr>
<tr>
<td></td>
<td>Additional sensor costs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>560.00</td>
</tr>
</tbody>
</table>

**Total difference in annual cash flow:** \$ 2,413.67

**CM detection performance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AMD</th>
<th>Visual</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay from start CM episode until treatment (milking)</td>
<td>2.3</td>
<td>5.0</td>
<td>-2.7</td>
</tr>
<tr>
<td>Use of antibiotics per treated CM cow (doses)</td>
<td>3.1</td>
<td>3.4</td>
<td>-0.3</td>
</tr>
<tr>
<td>Detected CM cows and treated (cow/year)</td>
<td>53.6</td>
<td>45.2</td>
<td>8.4</td>
</tr>
<tr>
<td>Undetected CM cows becoming SCM (cow/year)</td>
<td>3.5</td>
<td>6.6</td>
<td>-3.1</td>
</tr>
<tr>
<td>Undetected CM cows self-cured (cow/year)</td>
<td>2.3</td>
<td>5.7</td>
<td>-3.4</td>
</tr>
</tbody>
</table>

**Transmission**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AMD</th>
<th>Visual</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>New CM cases due to transmission (cow/year)</td>
<td>3.2</td>
<td>6.8</td>
<td>-3.6</td>
</tr>
<tr>
<td>New SCM cases due to transmission (cow/year)</td>
<td>2.3</td>
<td>6.6</td>
<td>-4.3</td>
</tr>
<tr>
<td>New self-cured IMI's due to transmission (cow/year)</td>
<td>1.5</td>
<td>4.4</td>
<td>-2.9</td>
</tr>
</tbody>
</table>

**Production losses**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AMD</th>
<th>Visual</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production losses, SCM (kg milk solids/cow/year)</td>
<td>142.2</td>
<td>133.2</td>
<td>9.0</td>
</tr>
<tr>
<td>Discarded milk (kg milk solids/cow/year)</td>
<td>242.3</td>
<td>204.7</td>
<td>37.6</td>
</tr>
</tbody>
</table>

**Labour**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AMD</th>
<th>Visual</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test-strip checks (check/cow/year)</td>
<td>3,311</td>
<td>21,556</td>
<td>-18,245</td>
</tr>
</tbody>
</table>

Figure 18: Screen shot of the simple results tab of the investment analysis model.
Appendix III

The results of the sensitivity analysis and the Monte Carlo simulation for AMD systems using EC_{udder} are described in this section.

The visual detection rate of the person milking, using a system with visual detection, has little impact on the profitability of investing in AMD systems (Figure 19). Varying the visual detection rate (default was 70%) between 40% and 100% resulted in a difference in annual cash flow (between an AMD system using EC_{udder} and a system using visual detection) varying between just under $300 and just under $500.

As the visual detection rate increased, the system using visual detection detected and treated more CM episodes, resulting in higher costs of antibiotics and discarded milk (category “Treatment CM”). Since more CM episodes were treated, fewer became SCM, resulting in lower costs of milksolids production losses caused by SCM and fewer new CM episodes due to transmission of pathogens (category “Untreated CM”). As the visual detection rate increased, the system using visual detection marked, teat-stripped and detected more CM episodes, resulting in a higher labour requirement for detection and treatment of CM episodes (category “Labour”). The value of the category “additional costs AMD” consisted of maintenance costs of the AMD system using EC_{udder} and was not dependent on the visual detection rate.
Figure 19: Sensitivity of the total difference in annual cash flow (——) between a system using Automated Mastitis Detection (AMD) with Electrical Conductivity (EC) on whole udder level and a system using visual detection only to the visual detection rate of a system using visual detection only. This total difference in annual cash flow is formed by different categories: “Treatment CM” (—••) including differences in antibiotic use and discarded milk, “Untreated CM” (- - -) including differences in new cases of CM and production losses of SCM, "Labour" ( - - ) including differences in labour costs of detection and of treatment of CM, and “Additional costs AMD” (••••) including costs of maintenance of the AMD system. The default visual detection rate was 70%.

The frequency of teat-stripping the entire herd (using a system with visual detection) impacts the profitability of investing in AMD systems mainly through the labour requirement for detecting CM episodes (Figure 20). Varying the frequency of teat-stripping the entire herd from once every ten milkings to once every fifty milkings, resulted in a difference in annual cash flow (between an AMD system using EC_{udder} and a system using visual detection) varying between just over $1,100 and $100 (red line).
Figure 20: Sensitivity of the total difference in annual cash flow (red line) between a system using Automated Mastitis Detection (AMD) with Electrical Conductivity (EC) on whole udder level and a system using visual detection only to the frequency of teat-stripping the entire herd in a system using visual detection. This total difference in annual cash flow is formed by different categories: “Treatment CM”, including differences in costs of antibiotics and discarded milk; “Untreated CM”, including differences in costs of milksolids production losses caused by SCM and new cases of CM due to transmission of pathogens; “Labour”, including differences in labour costs for detection and treatment of CM episodes.

The AMD system using EC\textsubscript{udder} operates at a low ODR (23%, as compared to 88% of the AMD system using EC\textsubscript{quarter}). Installing that AMD system on fewer bails of the milking parlor effectively decreases the percentage of detected and treated CM episodes even further. Thus, few of the new CM episodes caused by transmission of pathogens were treated and more of these new CM episodes became SCM or self-cured. CM episodes that self-cured involved no costs and the costs of cows with SCM were lower than the costs of new CM cases, thus resulting in a positive value in the category “Untreated CM”. Since animal welfare and penalties of the milk processor were not included, the increasing difference in annual cash flow and NPV were considered not to be representative (Figure 21).
Figure 21: Effect of installing an automated mastitis detection system using Electrical Conductivity (EC) at whole udder level on every bail, every second bail or every third bail of a milking parlor on the total difference in annual cash flow (green solid bars) and on the net present value (blue diagonally striped bars).

Figure 22 shows a cumulative density function of the effect of variation in milk price and CM incidence on the difference in annual cash flow for an AMD system using EC$_{udder}$. The mean difference in annual cash flow between a system using AMD and a system using visual detection was $472 (minimum was $295, maximum was $472). This range was most predominantly caused by variation in milk price, as can be observed from the tornado chart in Figure 23. The IRR of the AMD systems using EC$_{udder}$ did not become positive (mean was -7.79%, minimum was -11.4%, maximum was -3.45%), as is shown in the probability density function in Figure 24. The NPV varied between $-10,634 and $-6,768 (mean was $-9,113) (Figure 25).

From the positive difference in annual cash flow ($472) and the negative IRR and NPV (-7.79% and $-9,113, respectively) was concluded that the profitability of investing in AMD systems using EC$_{udder}$ is dependent on the investment costs, but is negative under the current default settings.
Figure 22: Monte Carlo simulation, cumulative density function: effects of variation in milk price and the percentage of clinical mastitis on the difference in annual cash flow for electrical conductivity sensors on whole udder level.

Figure 23: Monte Carlo simulation, tornado chart: effects of variation in milk price and the percentage of clinical mastitis on the difference in annual cash flow for electrical conductivity sensors on whole udder level.
Figure 24: Monte Carlo simulation, probability density function: effects of variation in milk price and the percentage of clinical mastitis on the Internal Rate of Return (IRR) for electrical conductivity sensors on whole udder level.

Figure 25: Monte Carlo simulation, probability density function: effects of variation in milk price and the percentage of clinical mastitis on the Net Present Value (NPV) for electrical conductivity sensors on whole udder level.