Economical Consequences of Johne’s Disease Control Programs

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1 Summary

A stochastic simulation model, developed by the Wageningen Farm Management Group, has been modified to reflect dairy production parameters in Pennsylvania. Also additional control programs, specific for Pennsylvania where built into the simulation model. The simulation model is based on five integrated parts, (1) herd dynamics, (2) Johne’s disease dynamics, (3) control of Johne’s disease, (4) economics and (5) assimilation of different farm types. Input data were collected from literature or obtained from expert meetings. The original model was validated under Dutch circumstances. Because of the stochastic nature of the model, there is variation in the epidemiological and economic results, representing the good- and worst case scenarios. In general, results were in agreement with former studies. The results showed that ‘test and cull’ strategies are not effective in reducing the Johne’s disease prevalence. Better management and hygiene are much more effective control tools and necessary critically. ‘Heifer contract raising’ appeared to be an effective, cheap and therefore very attractive way of reducing Johne’s disease under Pennsylvanian conditions. An important factor is the age of the calves at the start of the contract, which should be as young as possible. A second important factor is that the management and hygiene during the first days on the dairy farm are adequate. Sensitivity analyses of some parameters and assumptions in the model was performed. It is concluded that the model provides a simple and fast method to determine the epidemiological and economical effects of different control strategies. Because of the models’ flexibility, it can be used to examine a variety of strategies for specific herds.
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3 Introduction

Due to an increased concern associated with Johne’s disease, interest has increased for efficient Johne’s disease control programs. The “National Johne’s Working Group” (Stabel, 1998) has three main research priorities which are (1) diagnostic test development, (2) immunology of infection and (3) vaccine development. In many cases, ‘test and cull’ strategies were not effective to control Johne’s disease (NJWG, 1999). To design an effective control program against Johne’s, more research should be done on the epidemiological and economical consequences of different control programs. An important question is how to control Johne’s disease both in an epidemiological effective and economical efficient way.

Walker et al. (1988) were the first to attempt to development of a model of paratuberculosis infection in dairy herd. Collins and Morgan (1991) made an effort to develop a simpler model of paratuberculosis and to define factors that are most critical to the spread of the disease in a dairy herd. After developing this model, they refined the model to allow simulations of intervention strategies to control the spread of Johne’s disease (Collins and Morgan, 1992). However, their model did not include specific control tools but assumed only one infection route, which can be changed during simulation of a control program. The current simulation study, developed in this project can be used to evaluate the epidemiological and economical consequences of different control strategies against Johne’s disease on dairy farms. Cows are simulated individually, so ‘test and cull’ strategies can be simulated in an accurate way. Furthermore, several infection routes will be modeled separately to allow simulations of different calf-management techniques that minimize the exposure of calves to Mycobacterium paratuberculosis. Special attention will be paid on the epidemiological and economical effects of ‘heifer contract raising’, which can be used as a control tool against Johne’s disease, especially under U.S. conditions.

4 Goals of the study

- Evaluate the “U.S. Voluntary Johne’s Disease Herd Status Program” on it’s epidemiological and economical consequences and give comments on the program and (if necessary and possible) give recommendations about a more efficient or economical more attractive control program;

- Evaluate heifer contract rearing as a potential control tool for Johne’s disease as well. By starting the contract when the calves are young, during the most susceptible time of their lives, the spread of Johne’s can be greatly curtailed;

- Rank or evaluate different control measurements (for instance milk replacer, calving lots etc.) against Johne’s on their epidemiological and economical consequences;

- Explore the revenues of perfect information (test with 100% sensitivity and specificity).
5 Material and Methods

5.1 General herd characteristics

The simulation model is a so-called ‘Monte Carlo’ model in which stochastic events find place randomly by using different probability distributions. Those stochastic events are of major influence on the outcomes for individual animals (e.g. become infected or not, culled of not). In this way, variation and uncertainty around the results of the process are taken into the model so that not only average results can be determined, but also good- and worst case scenarios. For this reason, a large number of runs of the model (iterations) are needed to estimate the variation in outcomes.

The simulation model works with time steps of half a year and the basic entity of the model is an animal. In other words, animals are followed in time and for each animal it e.g. age, production level or infection status will be determined. Therefore, the model can be called a dynamic model; it contains time as a variable and can simulate the behavior of a system over time (Dijkhuizen and Morris, 1997).

By categorizing farms by their management, herd-size and Johne’s disease status (infected vs. free), all possible situations can be modeled. In the model many different control strategies can be simulated during a certain number of years, by default a 20 years period. In general, control tools can be divided into two categories, (1) tests and cull strategies and (2) different management strategies. By aggregating the results on farm level of many different dairy farms, we can get insight in the results on e.g. farm type level, disease status level, State level or National level.

5.2 Cows’ life cycle

The basic unit of the simulation model is one dairy herd. The model works with a standard herd of e.g. 50, 100 or 200 cows plus additional youngstock. Heifers do calf at an age of two years, and the calving interval is one year. Respectively, 65% and 98% of the US dairy farms have a calving interval (CI) less than 13 and 15 months (NAHMS, 1996). The National Dairy Heifer Evaluation Project (USDA: APHIS: VS, 1993) found an average calving interval of 12.8 months. All female calves (50% of the calves) are raised on the farm and 93.4% of the calves are born alive (NAHMS, Dairy 1996). In this model surplus of the heifers are sold randomly at an age of 1½ to 2 years.

5.3 Disease spread

5.3.1 Infection statuses

The spread of Johne’s disease is one of the main processes of the simulation model. Each cow has an infection status, which can change in time due to e.g. an infection. The six infection statuses, defined in the simulation model are:

A. Susceptible calves (calves until an age of 1 year);
B. Resistant animals (none infected animals older than 1 year);
L. Latent infected animals (infection, not spreading M. paratuberculosis);
C. Low infectious (infected and spreading M. paratuberculosis two months after calving);
D. Highly infectious (infected and spreading);
K. Clinical (infected, clinical and spreading M. paratuberculosis constantly)

All animals are in one of these six infection statuses, depending on (1) their age, (2) the fact if they are infected or not and (3) on the age when they will become infectious and start shedding M. paratuberculosis.

5.3.2 Infection status dynamics

At the moment of infection of an animal (only possible for calves younger than one year, infection status A), the model already determines randomly at which age this animal will become low infectious (C) and highly infectious (D) and clinical (K). When the animal reaches these ages, it will become low infectious, highly infections and clinical, but only if the animal is still alive. This process is shown in figure 1.
The age, at which an infected animal becomes highly infectious, depends on the age that the animal is infected. Both the age when the animals becomes ‘low’ and ‘highly infectious’ and the age when it becomes ‘clinical infected’ are related to the age that the animal becomes highly infectious. The minimal, most likely and maximal age that an animal becomes highly infectious after an infection at different ages, is shown in Table 1 (Expert opinion, 1999).

Table 1. Minimal, most likely and maximum age that an animal becomes highly infectious

<table>
<thead>
<tr>
<th>Age of infection</th>
<th>Min</th>
<th>Most likely</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congenital infection</td>
<td>1.5</td>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>Around birth or due to colostrum</td>
<td>2</td>
<td>3.5</td>
<td>20</td>
</tr>
<tr>
<td>Milk or surrounding 1– 6 months</td>
<td>2</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Surrounding 7-12 months</td>
<td>4.5</td>
<td>6</td>
<td>20</td>
</tr>
</tbody>
</table>

Before an animal becomes highly infectious, it is low infectious. This period starts two lactations before the animal becomes highly infectious. The minimal age that an animal becomes low infectious is two years. Between the age of infection and the age of becoming low infectious, the infected animal is latently infected (L), so it is not shedding M. Paratuberculosis (Figure 1).

After the highly infectious period, an animal can become clinically infected. The length of the highly infectious period is modeled with a triangular distribution. The minimal, most likely and maximal lengths of the highly infectious period and of the clinical period are shown in Table 2.

Table 2. Minimal, most likely and maximum length of the highly infectious and clinical period

<table>
<thead>
<tr>
<th>Length of highly infectious period (triangular distribution)</th>
<th>Min</th>
<th>Most likely</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval (years)</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Length of clinical period (triangular distribution)</th>
<th>Min</th>
<th>Most likely</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval (months)</td>
<td>0</td>
<td>0.5</td>
<td>3</td>
</tr>
</tbody>
</table>

Also the length of the clinical period (in months) is modeled with a triangular distribution (Table 2). It is estimated that animals are a maximal of three months clinical before they will be culled and leave the herd.
5.3.3 Infection routes

The spread of Johne’s disease on a farm can take place by many different infection routes. The model is dynamic; all infection probabilities change as infected animals join the herd or are culled, and they are all recalculated at the start of each time-step. The infection routes, which are included in the model, are:

1. Fetal infections;
2. Infections during birth;
3. Infections due to drinking colostrum;
4. Infections due to drinking milk;
5. Infections due to fecal contamination of environment, 0-6 months of age;
6. Infections due to fecal contamination of environment, 7-12 months of age;

All infection routes, except for the fetal infections are depending on the actual hygiene and management on the farm, which is also called the ‘farm type’ or the ‘risk profile of the farm’. Improving the hygiene and management of the farm can eliminate or reduce certain infection routes in the simulation model, so the spread of Johne’s on the farms changes (see for further explanation “5.4. Control of Johne’s disease”).

1. Fetal infections
Fetal infections are always considered in the simulation model and are not related to the hygiene and management on the farm. There is no possible way to reduce this infection route, other than culling infected cows. The fetal infection probabilities for different infection statuses of the dam are shown in Table 3.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Highly infectious animal, period before becoming clinical</th>
<th>Clinical animal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt; 1 year</td>
<td>6-12 mo.</td>
</tr>
<tr>
<td>Infection probability</td>
<td>0.035</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Seitz et al. (1989) estimated the risk of uteri transmission of *M. paratuberculosis* at 26.4% for fecal culture-positive animals (the 95% confidence interval was between 11.3% and 40.7%). Sweeney et al. (1992b) found 5 of 58 (9%) fecal culture-positive for *M. paratuberculosis* with positive a fetus. All 5 culture-positive fetuses were from cows that were classified as heavy fecal shedders (5 out of 28, 18%), which is in agreement with the fetal infection probabilities, shown in Table 3. In clinical infected cows, the fetal infections develop with a higher frequency; Doyle (1958) found a frequency of 37% of the calves being culture-positive.

2. Infections during birth
The infection probability during birth depends both on (1) the infection status of the dam and (2) the infection status of the other cows in the herd. The infection status of the other cows in the herd is important because of possible contamination of the calving pen when it is not cleaned properly. Table 4 shows the infection probabilities for different infection statuses of the dam and other cows in the herd (Expert opinion, 1999).

<table>
<thead>
<tr>
<th>Status of the rest of the herd</th>
</tr>
</thead>
<tbody>
<tr>
<td># C-animals = 0</td>
</tr>
<tr>
<td>--------------------------------</td>
</tr>
<tr>
<td>Not infectious dam</td>
</tr>
<tr>
<td>Low infectious (C)</td>
</tr>
<tr>
<td>Two calving before highly inf. (D)</td>
</tr>
<tr>
<td>One calving before highly inf. (D)</td>
</tr>
<tr>
<td>D or K dam</td>
</tr>
</tbody>
</table>

So e.g., if the infection status of the dam is not infected (B) or latent infected (L), so the dam is not shedding, but there are one or more other infectious cows in the herd, the infection probability during birth is still higher than 0. With a none shedding dam, but with other low infectious cows in the herd the probability will be 2.5%. With other highly infectious or clinical cows in the herd it will be 10%.
3. Infections via drinking colostrum

Streeter et al. (1995) isolated *M. paratuberculosis* from colostrum of 8 (22.2%) out of 36 fecal culture-positive animals and from milk of 3 (8.3%) of them. Cows that were heavy shedders were more likely to shed the organism in the colostrum, than light shedders were. Also Sweeney et al. (1992a) found that the prevalence of milk infection was highest with heavy fecal shedding of *M. paratuberculosis* and lowest with light shedding.

An infection via colostrum in the simulation model can occur via two different routes:

- Via colostrum from the own dam;
- Via colostrum from other cows (when the farmer is feeding mixed or pooled colostrum).

The first route (colostrum from own dam) can only occur when the dam is infected and the farmer is not feeding colostrum replacer. Based on literature and expert knowledge, the next infection probabilities (Table 5) are estimated and used in the simulation model.

<table>
<thead>
<tr>
<th>Infection status of the dam</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low infectious dam (infection status C)</td>
<td>0.30</td>
</tr>
<tr>
<td>Highly infectious or clinical infected dam (infection status D or K)</td>
<td>1.00</td>
</tr>
</tbody>
</table>

If an infected dam has infectious colostrum, it is assumed that she also has infectious milk. This is in agreement with Sweeney et al. (1991) who stated that presumably the organism is also shed in colostrum if it is shed in the milk.

The second infection route via drinking infectious colostrum from other cows depends on several parameters. First, the number of cows in the herd with infectious colostrum is important, the more there are the higher the infection probability. Each infected dam in the herd, with a calf, has a chance (see Table 5) to give infectious colostrum. Secondly, the number of calves that get colostrum from one cow is used as an input parameter in the model, which does not change during time. Lastly, the total number of calves from 0-6 months is used to calculate the infection probability. The infection probability due to drinking mixed or pooled colostrum is calculated with the next formula.

\[
P \text{ (colostrum other cows)} = (1 - (1 - \frac{a}{b})^n)
\]

where
- \(a\) = Number of calves that get colostrum from one cow
- \(b\) = Number of calves 0-6 months
- \(n\) = Number of cows with infectious colostrum

The infection route via mixed colostrum is only taken into account if the farmer really feeds mixed or pooled colostrum to his calves. If the farmer stops feeding colostrum from other cows, this infection probability will become zero.

4. Infections via drinking milk

Calves can also become infected due to drinking infectious milk. There are three types of milk that calves can get in the simulation model:

1. Bulk or pooled milk;
2. Rest milk (waste or treated milk);
3. Milk replacer.

When a farmer feeds infectious bulk- or pooled milk (1) potentially all calves, which are drinking milk at that time, will become infected. This can only occur when there are one or more highly infectious or clinical cows in the herd which are shedding such large amounts of *M. paratuberculosis* in their milk that it will make all the bulk milk infectious. It is estimated that only 20% of the highly infectious or clinical cows are shedding large amounts of *M. paratuberculosis* in their milk.
When a farmer feeds rest milk (2) calves can become infected too. Rest (waste- or treated) milk comes from cows if e.g. their milk is withhold for human consumption because of a treatment with an antibiotic. The probability of infection via drinking pooled milk depends on (1) the number of cows with rest milk, (2) the total number of calves and (3) the number of calves, which get rest milk of one cow with rest milk. The next formula is used to calculate the infection probability via rest milk:

\[ P \text{ (infection via rest milk)} = 1 - (1 - \frac{a}{b})^n \]

where
- \( a \) = number of calves that get rest milk from one cow;
- \( b \) = total number of calves in the herd;
- \( n \) = number of cows with rest milk.

Both infection routes via bulk milk or rest milk are only taken into account if the farmer really feeds them. While the feeding of milk replacer to calves will eliminate the risk of infection via milk, many farms still continue to feed whole milk rather than milk replacer (Sweeney et al., 1992b).

5. Infections due to fecal contamination of environment, 0-6 and 7-12 months of age

The Reed Frost method is used to simulate the infection probability via fecal contamination via the environment. This probability depends on the number of infectious cows (low- or highly infectious or clinical), which is in agreement with findings from Rosenberger et al. (1991). Another input parameter in the Reed Frost formula is the number of effective contacts. Effective contact rate describes the infectivity of the causative agent and the intimacy of contact between infectious and susceptible individuals (Maia, 1952). For paratuberculosis on a dairy farm, this could also be considered a measure of how long calves are in intimate contact with their dams or other adult cows after birth and the level of hygiene in the calving pens and calf rearing facilities (Collins and Morgan, 1991).

In the simulation model, the infections due to fecal contamination of the environment is only one of the six infection routes. The Reed-Frost formula, which is used to calculate the infection probability, is:

\[ P \text{ (environmental infection) } = 1 - (1 - \frac{k \times S}{N})^I \]

where
- \( k \) = number of effective contacts (between calves and cows > 2 years);
- \( S \) = susceptibility (100% or 32% for respectively 0-6 and 7-12 months);
- \( N \) = number of cows older than two years;
- \( I \) = number of infectious cows.

An important input parameter in the simulation model is ‘the number of effective contacts’ (\( k \)). This parameter is estimated for PA conditions (Table 6).

Collins and Morgan (1991 and 1992) also used the Reed-Frost method to calculate the probability of new \( M. \) paratuberculosis infections. In contrast to the current simulation model, this was their only infectious route in their model, where in the current model there are several (see 5.3.3. Infection routes). Collins and Morgan defined \( k \) as “the number of effective cow-calf contacts per year” and used time-steps of one year. They used the next assumptions in their simulation model:

1. \( M. \) paratuberculosis infection is spread from all infected adults (> 2 year) to calves;
2. all infected animals become infectious at two years of age;
3. recovery from paratuberculosis does not occur;
4. non-infected animals older than one year are resistant;
5. the herd size is constant.

An assumption (2) that all infected animals are infectious after two year of age, has a large influence on the transmission rate of Johne’s disease in their model. In practice most of the infected animals are not infectious but latently infected and not spreading \( M. \) paratuberculosis (McCaughan, 1992; Whitlock, 1997). So, the number of effective cow-calf contacts, which Collins and Morgan estimated \( k = 2.1 \) was probably an under-estimation because of the higher number of infectious cows in their model than there are on a dairy farms.
Depending on the management practices of the dairy farm, $k$ can vary between 0 (totally no contacts) and the number of adult cows (each calf has an effective contact with each adult cow). Reaching a zero level is probably not possible. It is estimated that $k$, without any control measurement on an average Pennsylvanian dairy farm is equal to the numbers, which are shown in table 6.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Average farm</th>
<th>Better hygiene farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young calves (0-6 mo.)</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>Older calves (7-12 mo.)</td>
<td>5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

There is no difference assumed between the contact rate of young and older calves with adult cows because of lack of good data quantitative data. The only difference between the two age groups of susceptible calves (0-6 and 7-12 months) is that the older 7-12 months old calves are less susceptible. Their lower susceptibility is also shown in Figure 2. Furthermore, calves from 7-12 months can only become infected via fecal contamination of the environment, and not via the other infection routes, because e.g. they are not fed any whole milk anymore.

6. Infections due introduction of an infected animal on the farm

An ‘open dairy farm’ is defined as a farm where animals are introduced sometimes. Because of the introduction of new animals, Johne’s disease can be (re-) introduced on the farm. The probability of introducing a Johne’s infected cow on a farm depends both on (1) the number of bought animals and (2) the prevalence of Johne’s disease in the population from which the farmers introduces his animals. This prevalence is related to the prevalence in the specific county, state or country. In this simulation model it is assumed that without a control program on dairy farms, the prevalence of Johne’s disease of the bought animals will increase, and with a control program it will decrease.

Experts have estimated that most of the dairy farms that are infected with Johne’s disease do frequently buy cattle. Therefore, in the simulation model it is assumed that in year 0, all farms are open. It is estimated that there is a 20% probability per year of buying an infected heifer or cow. This estimate is based on the assumption that farms buy a few animals per year and the true prevalence in Pennsylvania, which change during time depending on the control program. Without any control strategies, an increase of the probability of infection of one percent per year is assumed because the true prevalence will increase (based on the results of the simulation model of an average farm). If a control program is simulated, a decrease of one percent of the probability per year is assumed, also based on the results of the model of a closed farm with control.

5.3.4 Prevalence of Johne’s disease

The distribution of the test prevalence of Johne’s disease on Pennsylvanian dairy herds is an input variable in the simulation model. In the NAHMS seroprevalence study (Ott et al., 1999), a total of 31,745 cows were tested from 967 herds that did not vaccinate against Johne’s disease. Vaccinating herds were not included in seroprevalence estimates since test status may be confused by vaccination. The results of this study are shown in the next paragraphs and are used as input in the simulation model.

5.3.4.1 Vaccination

In 1995 (Ott et al., 1999) 5.4% of the dairy herds did normally vaccinate against Johne’s disease. On dairy herds, smaller than 100 cows, 100-199 cows and herds larger than 200 this was respectively 4.7%, 7.9% and 10.0%. So, larger herds do vaccinate more often than smaller herds.

5.3.4.2 Animal-level

The overall percentage of test positive cows (the test prevalence) was 2.6%. If the sensitivity is estimated at 45% or 20%, the adjusted (true) prevalence of $M. paratuberculosis$ infection at cow level is respectively 3.4% or 7.9%. This means that the estimated sensitivity has a large influence on the adjusted (true)
prevalence. With an estimated sensitivity between 5% and 10%, the adjusted (true) prevalence will probably higher than 20%-25%.

There was a (non-significant) trend that larger herds have a higher prevalence (Ott et al., 1999). The same trend was found in the Netherlands (Muskens and Jongeneel, 1999). In the NAHMS study (Ott et al., 1999) factors, which were significantly associated with the prevalence, were cow type, fecal score, body condition score and lactation number. The test prevalence was highest for cows in the 2nd, 3rd and 4th lactation. The prevalence in higher lactation numbers was probably lower, because part of the Johne’s infected cows are already culled before reaching this age. There was also a strong association between percent of cull cows with clinical signs consistent with Johne’s disease (as reported by the dairy producers) and the test prevalence of M. paratuberculosis (Ott et al., 1999)

5.3.4.3 Herd-level

In the NAHMS study (Ott et al., 1999) only 25 to maximal 40 cows in each herd were tested. Therefore a proportion of the infected herds were likely to have been missed by this sampling scheme (Ott et al., 1999). Assuming a specificity of 99%, 1% of the tests of non-infected cows will be false positive. This problem was particularly important in this study, because 55 percent of herd testing positive (224/408) had only a single positive test result.

Estimation of the true herd prevalence of M. paratuberculosis infection should incorporate factors, such as sensitivity, specificity, sample size and within-herd prevalence, that lead to uncertainty in the observed herd prevalence of 40.6 percent in this study (Martin et al., 1992). If only herds are diagnosed positive if they have two or more positive animals, the adjusted percentages of infected herds is 16.8%. If also herds with at least 5 percent of the cull cows with clinical signs are included, 21.4% of the herds are infected. These estimates however are likely to be underestimates of the real percentage of infected herds because e.g. 17.2% of the test negative herds had historical evidence of Johne’s disease (Ott et al., 1999).

Different factors (including the overall-sensitivity of the Elisa, which is lower than 20%) provide supportive evidence that the percentage of infected herds might be much higher than 21.4%. In the Netherlands, where the percentage of positive farms was about 40% (comparable with 41% in the U.S.), a group of Johne’s disease experts estimated that the percentage of infected farms (both test positive or test negative) is around 80%. This estimate is supported by a study in the Netherlands were around 80% of 100 unsuspected farms with no historical evidence of Johne’s disease, had one or more Johne’s disease infected animals within a few years of fecal testing every animal every year.

First of all, the distribution of the test prevalence on infected farms is needed for the simulation model. In table 7 the prevalence data, which are input for the model, are shown.

| Distribution of the test prevalence (Elisa, cows older than 2 years) in US dairy herds. |
|-------------------------------------------|-----------------|-----------------|
| Min. test prevalence | Max. test prevalence |
| Negative infected | 0 | 0 |
| Low prevalence | > 0 | < 3.3 % |
| High prevalence: | | |
| Subclass 1 | >= 3.3 % | < 6.7 % |
| Subclass 2 | >= 6.7 % | <= 100 % |

*Total percentage of test positive herds is 42.2% (NAHMS, 1996)*

For the dairy farms in the high prevalence category, two sub-categories were made, so the start test situation in the simulation model would better reflect the real test prevalence, which has been found on US dairy farms.
5.4 Control of Johne’s disease

5.4.1 Introduction

Some recommended control tools, stated in the Johne’s disease programs (“US Voluntary Johne’s disease Herd Status Program”) are:
1. Removal of calves from dams immediately after birth;
2. Ensuring colostrum for each calf is from it’s own dam;
3. Using milk replacer instead of waste milk;
4. Eliminating contact between young and mature cows;
5. Restricting calf raising duties;
6. Identification of positive animals and removal.

In the simulation model, many different control tools can be simulated and combined. The control tools can be separated into two different categories, (1) testing and culling test positive animals, eventually including the offspring of test positive animals and (2) hygiene and management tools. Both control categories will be described in the next two paragraphs.

5.4.2 Testing and culling of animals

In the simulation model, variation in the test strategies can be made by the next options:
- Tests can have different sensitivity, specificity, costs etc.
- Test can be serial, e.g. only culling a test positive cow after a positive confirmation test;
- Test can be parallel, e.g. Elisa and feces together;
- Frequency can be different, e.g. every half year, every year, every two years;
- Removal of a test positive animal and her last 1, 2, …x calf/calves;
- Not all animals are tested but only x of the herd;
- Different order of different tests in years;
- More testing and culling options are available or can be added.

All diagnostic tests have two important attributes, (1) the sensitivity and (2) the specificity. Precise determination of these values is essential to interpretation of test results, estimation of disease prevalence in herds and economic analysis of disease control programs by simulation models (Collins et al., 1993). However, because of the slow, chronic and progressive nature of Johne’s disease, the incubation period from infection to clinical disease is long and most M paratuberculosis-infected cattle in a herd are in pre-clinical stages. Estimating the sensitivity and specificity of diagnostic tests for sub-clinical paratuberculosis, without bias for or against any specific type of diagnostic test, has been difficult for investigators and Johne’s disease experts. Incorporation bias (selection of study subjects by use of the diagnostic test under evaluation or by use of a related test) and disease spectrum are two major problems that have affected studies of paratuberculosis test accuracy. Variation in definition of infected and non-infected cattle also are sources of disagreement between studies in which test sensitivity and specificity has been determined (Ransohoff and Feinstein, 1978).

The overall test sensitivity is a direct function of the distribution of the infection stages in the tested population. Infection stage is not directly related to the age of the cattle because the infection can run a slow or rapid course. In the model the factors that influence the course of infection are the age of infection and random variation. Ridge et al. (1991) and Sweeney et al. (1995) estimated the sensitivity and specificity for different infection statuses of Johne’s disease infected cows, which is shown in table 8.
Table 8. Sensitivity and specificity, which is used in the simulation model.

<table>
<thead>
<tr>
<th></th>
<th>ELISA (Ridge et al., 1991)</th>
<th>ELISA (Sweeney et al., 1995)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-clinical and not shedding</td>
<td>26.4% (+/- 10.2%)</td>
<td>N.A.</td>
</tr>
<tr>
<td>Pre-clinical and shedding (fecal pos.)</td>
<td>56.5% (+/- 9.3%)</td>
<td>15 % (+/- 6.6%)</td>
</tr>
<tr>
<td>Clinical infected</td>
<td>88.22% (+/- 5.5%)</td>
<td>87 % (+/- 8.4%)</td>
</tr>
<tr>
<td><strong>Specificity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>99.7 % (+/- 0.3%)</td>
<td>99 % (+/- 1.0%)</td>
</tr>
</tbody>
</table>

The agreement of ELISA results with those of tests that detect M. Paratuberculosis in fecal samples is lower than that with other serological tests. The low CV statistic (0.36) suggested that the ELISA identified a different population of infected cattle than did fecal culture (Collins et al., 1991). They calculated the sensitivity of ELISA and culture used in parallel was 69% for cattle in stage 1 and 2 of paratuberculosis. Sweeney et al. (1995) concluded that the ELISA sensitivity was significantly correlated with the number of colonies of M. paratuberculosis detected by fecal culturing. To calculate the overall sensitivity they used the fecal test as the “golden rule”. However, because the sensitivity of this test is not 100%, the overall test sensitivity of the ELISA test, which they calculated is an over-estimation of the true sensitivity. Infected and not shedding cows were not included in the infected test population and yet on the farm they are the largest group of infected animals.

Whitlock et al. (1997) concluded that the estimated ELISA sensitivity for, what they called stage I animals (pre-patent and pre-clinical, not yet shedding adequate organisms to be detectable by culture), is unknown. However, the authors believe the absorbed ELISA sensitivity for those animals will be very low (< 10%). For the animals that will be found positive by the current fecal culture, the absorbed ELISA detects approximately 24.6% of the animals (Whitlock et al., 1997). In the simulation model around 25% of the shedding animals are heavy shedders. So, in the model the sensitivity of the ELISA for culture positive (infectious) animals is around 0.75 * 10% + 0.25 * 60% = 23% (Table 9).

Table 9. Estimated sensitivity and specificity, which is used in the simulation model.

<table>
<thead>
<tr>
<th></th>
<th>Fecal</th>
<th>Pooled fecal</th>
<th>ELISA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity:</strong></td>
<td>0%</td>
<td>0%</td>
<td>1%</td>
</tr>
<tr>
<td>Latent period (L)</td>
<td>40%</td>
<td>36%</td>
<td>10%</td>
</tr>
<tr>
<td>Low infectious (C)</td>
<td>95%</td>
<td>95%</td>
<td>60%</td>
</tr>
<tr>
<td>Highly infectious (D)</td>
<td>90%</td>
<td>90%</td>
<td>80%</td>
</tr>
<tr>
<td><strong>Specificity:</strong></td>
<td>100%</td>
<td>100%</td>
<td>99%</td>
</tr>
</tbody>
</table>

The overall sensitivity of the ELISA test, taking into account the percentages of animals in each infection status, lies between 5% and 10% (because in the model around 70-80% of the infected animals are latent infected).

The overall sensitivity has a large influence on the adjusted (true) prevalence. This can be seen at the start of each simulation. Basis of the start of a control program is the current test prevalence. In other words, the simulation of a certain control program starts half a year after the test prevalence of a certain farm is between a certain minimum and maximum, which is reflecting the actual test prevalence, found on US dairy herds (Table 7).
5.4.3 The ‘U.S. Voluntary Johne’s Disease Herd Status Program’

5.4.3.1 Introduction and background

In 1993 a task force of the Johne’s disease committee of USAHA drafted a model Johne’s disease “Herd Certification Program” (see 1993 USAHA Proceeding). In 1998 a committee, appointed by the USAHA National Johne’s Working Group (NJWG) designed a more affordable and yet scientifically sound “Herd Certification Program”. This program was intended as a model and the guidelines of the program are considered minimal requirements for dairy operations. In summary, four Johne’s disease herd-levels are considered for an operation, which are related to the confidence of the freedom of the farm from Johne’s disease.

An evaluation of the ‘U.S. Voluntary Johne’s Disease Herd Status Program’ has never been performed. One of the goals of this study was to evaluate the effectiveness of this (minimal) Johne’s disease control program on the effectiveness to decrease the prevalence of Johne’s disease and to evaluate the economic consequences of this control program.

5.4.3.2 Overview of the ‘U.S. Voluntary Johne’s Disease Herd Status Program’

The basis of the ‘U.S. Voluntary Johne’s Disease Herd Status Program’ consists of four herd-levels (1 to 4). A farm can reach a next (higher) level when all tested animals (part of the herd or all animals) are tested negative. If one or more animals are tested positive (and eventually confirmed by another second test) the farm will go back to level 1.

There are two different tracks, designed to enter the program. The ‘Standard Track’ allows a minimal investment of funds and gradually increases the producer’s investment in the program, where the ‘Fast Track’ allows producers to proceed to a higher level of confidence more quickly than the Standard Track (NJWG, 1998).

A summary of the ‘US Voluntary Johne’s Disease Herd Status Program’ is shown in Table 10.

<table>
<thead>
<tr>
<th>Action</th>
<th>Standard Track</th>
<th>Fast Track</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level reached</td>
<td></td>
</tr>
<tr>
<td>Testing 30 animals (2nd lactation or older)</td>
<td>Level 0</td>
<td>Elisa testing all animals*</td>
</tr>
<tr>
<td>Fecal testing all animals*</td>
<td>Level 1</td>
<td></td>
</tr>
<tr>
<td>Elisa testing all animals*</td>
<td>Level 2</td>
<td>Fecal testing 30 animals*</td>
</tr>
<tr>
<td>Fecal testing all animals*</td>
<td>Level 3</td>
<td>Elisa testing all animals*</td>
</tr>
<tr>
<td>Every year fecal or Elisa testing all animals*</td>
<td>Level 4</td>
<td>Elisa testing 30 animals*</td>
</tr>
<tr>
<td>Stay in level 4</td>
<td>Stay in level 4</td>
<td></td>
</tr>
</tbody>
</table>

* If herd > 400 animals, a subset sampling will be taken

In the simulation model, the ‘US Voluntary Johne’s Disease Herd Status Program’ has been modeled as shown in Table 10, but can easily be modified to explore the influences of e.g. different tests and the numbers of animals tested.

5.4.4 Management control tools

There is no treatment of Johne’s disease. The key to preventing, controlling and eliminating Johne’s disease in a herd is improvement of the calf-management (McCaughan, 1992). Testing is a valuable tool to
evaluate the extent of the infection in the herd and to monitor progress of control efforts but does not have a large influence on the prevalence within the herd (McCaughan, 1992; Groenendaal et al., 1999). The general strategy for controlling *M. paratuberculosis* infections is adopting appropriate management and sanitation procedures for the individual farm.

Many specific methods can be used to accomplish the appropriate management and sanitation procedures. Important management factors to reduce the spread of Johne’s disease in a herd are (NJWG, 1999):

- Calves should be born in an area that is dry, clean of manure and well bedded. It’s essential that newborn calves are removed immediately after birth;
- Give only colostrum of the calves own dam or give artificial or pasteurized colostrum;
- Give only milk replacer instead of whole or pooled milk;
- House the calves separately from adults without direct contact with manure from adult cattle.

Because complete elimination of infected cattle is likely to take many years after Johne’s disease becomes invisible in the herd, preventive management should remain in place; otherwise, Johne’s disease is likely to recur (McCaughan, 1992). In the simulation model it is assumed that once the management has been changed, it will remain in place.

The management tools to control Johne’s disease that are possible in the simulation model:

I. Take hygienic measurements during birth (reduce the infection probability 'during birth' 90%);
II. Give calves only colostrum of their own mother (instead of pooled colostrum);
III. Give calves colostrum replacer;
IV. Give calves only milk replacer (totally no infections via milk);
V. Separate calves from 0-6 months of age (reduces the number of effective contacts with 90%);
VI. Separate calves from 7-12 months of age (reduces the number of effective contacts with 90%).
VII. Vaccination (postpone the age of becoming infectious and clinical)
VIII. Grouping of animals (used as a control tool)*:
   - Test negative and test positive group;
   - Young and old group (e.g. four years and older);
IX. Heifer contract rearing, starting and finishing at different ages;
X. More management tools are possible or can be added in the model.

* If animals are grouped (by using a test or an age as a grouping criteria), the calves of the cows which are in the ‘suspected group’ will not been kept for breeding but will be sold before an age of 2 years.

Not all above control tools will be simulated for this report. However, simulations of combinations of strategies, shown above, are possible and can be performed in the future.

5.4.5 **Heifer contract rearing as a control tool**

Heifer contract rearing has been added as a potential control tool against Johne’s disease as well. The way, in which heifer contract rearing influences the spread of Johne’s disease is described in detail in the next paragraphs.

5.4.5.1 **Background of ‘heifer contract rearing’ in the US**

In 1993 around 1.7% of all herds used ‘heifer contract rearing’ and in 1995, 4.1% of all operations did raise their calves on a ‘contract raising farm’. Also in the last years, the percentage of dairy farms, using ‘heifer contract rearing’ is still increasing. Table 11 shows the percentages for different herd sizes.

<table>
<thead>
<tr>
<th>Herd size</th>
<th>Percentage of operations which raised their calves on ‘contract rearing farms’</th>
<th>Percentage herds</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 99 cows</td>
<td></td>
<td>2.7 %</td>
</tr>
<tr>
<td>100 – 199 cows</td>
<td></td>
<td>6.5 %</td>
</tr>
<tr>
<td>&gt;= 200 cows</td>
<td></td>
<td>18.2 %</td>
</tr>
<tr>
<td>All herds</td>
<td></td>
<td>4.1 %</td>
</tr>
</tbody>
</table>
From table 6 it’s clear that larger herd use more often ‘contract heifer rearing’ then smaller farms do.

Currently, dairy farmers are facing the challenge of rising production costs, falling milk prices, and managing large and often highly leveraged capital investments (Willett, 1985). A growing number are contracting to have someone else raise their heifers off the farm, most of the time based on economical reasons. Willet (1985) calculated an increase in income from custom raising of $686.45 - $574.97 = $111.48 per heifer over 16 months raised on a contract heifer operation. However, resource situations and objectives vary so much between dairy farms that it is inappropriate to generalize about whether raising or contracting heifers is best, an economic analysis should be done on a case-by-case basis. Another advantage of ‘heifer contract raising’ is the possibility to add more cows due to the availability of underemployed resources. Thereby, the heifer contract grower may be more efficient than the dairy farmer due to specialization.

When alternative uses for freed-up resources are either absent or provide low returns, custom raising is less attractive. If the grower is not a good calf raiser, the heifers may be undersized and/or diseased or the farmer might not have an adequate supply of heifers bred on time. So, the quality of custom heifer raising is very important to make custom raising attractive (Willet, 1985).

In addition to the advantages and disadvantages of custom raising shown above, ‘heifer contract rearing’ could be a potential control tool against Johne’s disease. Years of research have failed to produce diagnostic tests of sufficient sensitivity to be used in test and cull control strategies. Consequently, ‘test and cull’ strategies alone are not enough to control or eradicate Johne’s disease. Prevention of the transmission from Johne’s disease infected to non-infected susceptibly animals due to a good hygiene and management is much more effective in controlling the disease (McCaughan, 1992). As a result of transferring the heifer raising activities to a contract heifer grower, the calves are effectively separated from older adult cows. So, contract rearing of calves can be seen as a control measure of Johne’s disease. However, the effects of ‘heifer contract rearing’ on the spread of Johne’s disease have not been studied before. A goal of this study is to evaluate the epidemiological and economical consequences of ‘heifer contract rearing’ vs. home rearing, which are related to Johne’s disease.

5.4.5.2 The consequences of “contract rearing” on the spread of Johne’s disease

The transmission (and control) of Johne’s disease, which could be limited by ‘heifer contract rearing’ in the model is related to the number of effective contacts (k). This number is used in the Reed Frost formula to calculate the infection probability via the environment:

\[
\text{Infection probability (RF)} = 1 - (1 - (k \times S) / N) ^ I
\]

where

- \( k \) = number of effective contacts (calf-adult cow contacts)
- \( N \) = number of adult cows in the herd
- \( I \) = number of infectious cows in the herd
- \( S \) = susceptibility (fraction relatively to the susceptibility on day 0)

The number of effective contacts between calves and adult cattle \( k \) will decrease after separating the calves effectively from the adult animals (e.g. due to separating them from older cows or due to ‘heifer contract rearing’). By calculating the number of effective contacts per day, we can calculate the reduction of \( k \) for each contract-rearing period (depending on when we start and stop the contract). So, e.g. if the calves are going to the ‘heifer contract rearing operation’ at an age of 30 days, the calves only have effective contacts with the older cows \( k \) from day 0 to 30.

An additional effect that has to be considered is that the susceptibility of calves decreases in time. By estimating the rate of decrease of the susceptibility (which is not known in literature) we can calculate the number of effective contacts between calves and adult cattle \( k \). Because the susceptibility decreases from 100% at day 0 to approximately 0% after about 360 days (1 year) not all contacts that an older calf has with infectious cows will be effective anymore. This can also be seen from the RF-formula above where S (the susceptibility between 0 and 1) reduces \( k \).
Hagan (1936) already concluded that young calves are most susceptible to Johne’s disease and that natural infections usually occur very early in life. Also Payne and Rankin (1961) concluded that adult cattle were more resistant to Johne’s disease by better elimination of infection. The exact nature of this resistance is not known. Possibly, adults become lightly infected and recover before disease develops, or adult cattle may destroy ingested bacilli. Larsen et al. (1975) also found that older cattle were more resistant to the \textit{M. paratuberculosis} bacillus, the lesions were less pronounced, and the numbers of colonies were fewer. In general, resistance against natural infections is estimated to occur between 6 and 12 month of age.

The susceptibility in the model is simulated, using two different approaches, a linear decline and an exponential decline. Both approaches are used in the model and are shown in figure 2.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{susceptibility.png}
\caption{The estimated susceptibility of calves until one year of age (relative to day 0)}
\end{figure}

An explanation of both the linear and exponential approach is given below.

1. \textit{Linear decline:}  
Because of the lack of data on the susceptibility of calves, related to their age, we could assume a simple linear decrease in susceptibility. The following formula has been used:

\[ S = 1 - \left( \frac{1}{360} \right) \times \text{Age} \]

where  
\begin{align*}
\text{Age} & = \text{Age of a calf (in days)} \\
\end{align*}

The number of effective contacts in a period from day x to y (in the first half year of a calf) is subsequently calculate by:

\[ k (\text{day } x \text{ to } y) = \frac{\text{Area under curve } x \text{ to } y}{\text{Area under curve } 0 \text{ to } 180} \times k (\text{tot}) \]

where  
\begin{align*}
k (\text{tot}) & = \text{the total number of effective contacts in the first half year} \\
\end{align*}

This simple linear approach can be compared to the more complicated and probably more biologically sound approach of an exponential decline of the susceptibility.

2. \textit{Exponential decline (default):}  
This approach assumes that the susceptibility decrease faster at a young age than at an older age. Biologically, this approach appears more accurate than a linear approach. The following formula to calculate the susceptibility at different ages (in days), has been used:

\[ S = e^{\text{intercept} \times t} \]

where  
\begin{align*}
\text{intercept} & = -0.01 \\
\text{Age} & = \text{age (in days)} \\
\end{align*}
The number of effective contacts in a period from day x to y (in the first half year of a calf) is subsequently calculate by:

$$k \ (\text{day x to y}) = \frac{\text{Area under curve x to y}}{\text{Area under curve 0 to 180}} \times (k \ (\text{tot}))$$

$$k \ (\text{day x to y}) = \frac{e^{\text{intercept \ y}} - e^{\text{intercept \ x}}}{(e^{\text{intercept \ 180}} - e^{\text{intercept \ 0}})} \times (k \ (\text{tot}))$$

where

$$k \ (\text{tot}) = \text{the total number of effective contacts in the first half year}$$

5.4.5.3 Economical consequences of contract rearing

The economical consequence of “contract raising” can be divided in two different categories:

1. Consequences of heifer contract rearing, which are not related to Johne’s disease
2. Consequences of heifer contract rearing, which are related to Johne’s disease

In the following text, both consequences will be explained.

1. Consequences of heifer contract rearing, which are not related to Johne’s disease

The economical consequences of heifer contract rearing, which are not related to Johne’s disease, are not included in the economical cost-benefit analysis because they are not the main interest of this study. However, in the simulation model there is an option to include them in the cost-benefit analyses in an easy manner. Under this option, the costs of home heifer rearing are seen as a benefit and the costs of “heifer contract rearing” are seen as a cost of control. In this way we can calculate the total economic effects of ‘heifer contract rearing’ or only the effects of ‘heifer contract rearing’ due to the reduction of the losses of Johne’s disease.

Gabler et al. (1999) obtained data from a convenience sample of operations from several geographic locations throughout Pennsylvania to collect cost information on the raising of replacement dairy heifers. Cost information was collected on feed, labor, health, reproduction, bedding, facilities, equipment, mortality and interest. The costs were grouped by the next age periods:

- 3d to weaning,
- weaning to 6 months
- 6 months to breeding and
- breeding to prefresh.

Table 12 shows for each period the daily costs of raising replacement dairy heifers both on the own operation and on a heifer contract rearing farm.

<table>
<thead>
<tr>
<th>Day start</th>
<th>Day end</th>
<th>Costs own</th>
<th>Costs contract</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>30</td>
<td>1.53</td>
<td>1.45</td>
</tr>
<tr>
<td>30</td>
<td>59</td>
<td>2.65</td>
<td>1.98</td>
</tr>
<tr>
<td>60</td>
<td>180</td>
<td>1.37</td>
<td>1.45</td>
</tr>
<tr>
<td>181</td>
<td>360</td>
<td>1.16</td>
<td>1.27</td>
</tr>
<tr>
<td>361</td>
<td>720</td>
<td>1.72</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Average (day 3-360) 1.37 1.39

Because the costs of ‘heifer contract rearing’, which they found for the youngest calves are lower than the costs on the own operations, heifer contract rearing which starts at a young age will be more attractive if the contract is started with a young age. However, as already stated above, situations and objectives vary so much that it is inappropriate to have one generalized economic analysis on ‘heifer contract rearing’.

Also Hoffman et al. (1999) calculated the costs of “own heifer rearing” on Wisconsin dairy herds (n = 62) as shown in Table 13.
Table 13. Costs of “own rearing” per calf ($ per day) in WI (Hoffman et al., 1999).

<table>
<thead>
<tr>
<th>Day start</th>
<th>Day end</th>
<th>Costs own raising</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Until group or heifer housing</td>
<td>2.78</td>
</tr>
<tr>
<td>90</td>
<td>132</td>
<td>1.22</td>
</tr>
<tr>
<td>133</td>
<td>183</td>
<td>1.30</td>
</tr>
<tr>
<td>184</td>
<td>255</td>
<td>1.33</td>
</tr>
<tr>
<td>256</td>
<td>300</td>
<td>1.38</td>
</tr>
<tr>
<td>301</td>
<td>360</td>
<td>1.35</td>
</tr>
<tr>
<td>361</td>
<td>426</td>
<td>1.52</td>
</tr>
<tr>
<td>427</td>
<td>489</td>
<td>1.80</td>
</tr>
<tr>
<td>490</td>
<td>574</td>
<td>1.90</td>
</tr>
<tr>
<td>575</td>
<td>621</td>
<td>1.75</td>
</tr>
<tr>
<td>622</td>
<td>654</td>
<td>1.81</td>
</tr>
<tr>
<td>655</td>
<td>720</td>
<td>2.06</td>
</tr>
</tbody>
</table>

Average (day 3 to 360) $ 1.65 / day

Because Gabler et al. (1999) calculated the costs for Pennsylvanian dairy herds, in the simulation model they will be used.

2. Economic consequences of heifer contract rearing, which are related to Johne’s disease

The economic consequences of “heifer contract rearing”, which are related to Johne’s disease are the main interest of this study. However, these consequences will be calculated with the simulation model. With the model, the losses of Johne’s disease with “home heifer rearing” will be compared with the losses of Johne’s disease with ‘heifer contract rearing’. The difference between those losses are equal to the benefits of “heifer contract rearing”, which are related to Johne’s disease. In other words, the reduction of the losses of Johne’s disease due to ‘heifer contract rearing’ are equal to the economic consequences of ‘heifer contract rearing, which are related to Johne’s disease.

5.5 Current management on and herd size of Pennsylvanian dairy herds

To estimate losses from Johne’s disease as well as the impact of control programs, several basic attributes of management practices must be known. The NAHM’s study (1997) will serve as a tool to determine the current management. The following population estimates refer to the current management practices. The reference population is U.S. dairy operations with at least 30 milk cows from all 20 participating States (Dairy ’96 Study States), representing 79 % of all U.S. dairy cows (NAHMS, 1997).

5.5.1 Management of the new-born calf

Table 14. Percent of operations by when newborn calves were usually separated from the dams

<table>
<thead>
<tr>
<th>Hours</th>
<th>Percentage operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 hours</td>
<td>13.1 %</td>
</tr>
<tr>
<td>1 – 6 hours</td>
<td>38.3 %</td>
</tr>
<tr>
<td>7 – 12 hours</td>
<td>23.0 %</td>
</tr>
<tr>
<td>13 – 24 hours</td>
<td>12.1 %</td>
</tr>
<tr>
<td>More than 24 hours</td>
<td>13.5 %</td>
</tr>
</tbody>
</table>

Only on 13.1% of the operations, calves stayed less than 1 hours with their dams, on the rest of the farms (86.9%) the contact between calf and dam was long, which increases the infection probability (McCaughan, 1992). It is concluded that on most of the dairy farms (where calves stay > 1 hour with their dam; 86.9% of the farms), the infection probability, which is shown in table 4 can be used. On the farms were calves are separated immediately from their dam, there is assumed to be a reduction of the infection probabilities around birth.
5.5.2 Colostrum management

Around 34% of the calves get their first colostrum during the first nursing, 64% of the calves get if from hand feeding from a bucket or bottle. In Table 15 the variation of the colostrum management is shown.

Table 15. Percentage of operations by colostrum management

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Percentage operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colostrum own dam</td>
<td>95 %</td>
</tr>
<tr>
<td>Colostrum pooled</td>
<td>3 %</td>
</tr>
<tr>
<td>Colostrum stored</td>
<td>2 %</td>
</tr>
</tbody>
</table>

The source of colostrum used in hand feeding on 95% of the operation is from the own dam and in only 3% from pooled colostrum of several cows. Less than 0.5% of the farms give commercial colostrum substitutes (NAHMS, 1993).

5.5.3 Bedding routines used for calving areas

In the calving areas, the next bedding routines are being used.

Table 16. Bedding routines

<table>
<thead>
<tr>
<th>Routines</th>
<th>Percentage operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between each bedding</td>
<td>70.4 %</td>
</tr>
<tr>
<td>Between every 2-5 calving</td>
<td>12.6 %</td>
</tr>
<tr>
<td>After 5 or more times calving</td>
<td>3.5 %</td>
</tr>
<tr>
<td>Bedding not used</td>
<td>13.5 %</td>
</tr>
</tbody>
</table>

Most of the operations (around 70%) add bedding material between every calving.

5.5.4 Milk replacement management

During a 1991-92 study by the National Animal Health Monitoring System (USDA: APHIS: VS), 9.2% of the dairy herds who use milkreplacer used in addition ‘whole milk’, 13.8% used ‘fresh/sour colostrum’ and 4.6% used ‘waste milk’. Other results show that calves are nearly always fed individually (> 96% of the operations). In the simulation study it is estimated that on less then 50% of the farms calves are fed (1) whole milk and on the rest (2) milk replacer (Table 20).

5.5.5 Usage of equipment

In Table 17, the percentage of operations is shown by how often they use equipment both for handling manure and feeding feed to heifers. This is important for the contact rate (in the model called $k$) between calves and adult cows.

Table 17. Percentage of operations by how often equipment used for manure handling was also used to handle feed fed to heifers less than 12 months of age

<table>
<thead>
<tr>
<th>Routines</th>
<th>Percentage operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regularly (at least weekly)</td>
<td>12.4 %</td>
</tr>
<tr>
<td>Occasionally (less than weekly)</td>
<td>10.5 %</td>
</tr>
<tr>
<td>Not a practice</td>
<td>77.1 %</td>
</tr>
</tbody>
</table>

Most of the operations (around 77%) almost never use dirty equipment for handling feed fed to heifers less than 12 months of age.
5.5.6  Direct contact between heifers and adult cows

In table 18, the percentage of operations is shown where calves of a certain age did have direct contact with adult cows in the herd in 1995. This is also important because of the possible infections due to contacts between both groups of animals.

<table>
<thead>
<tr>
<th>Age (months)</th>
<th>Percentage operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6 months</td>
<td>12 %</td>
</tr>
<tr>
<td>6 – 11 months</td>
<td>7 %</td>
</tr>
<tr>
<td>&gt; 12 months</td>
<td>81 %</td>
</tr>
</tbody>
</table>

In contrast to the situation on dairy farms in the Netherlands, in the US most operations (around 81%) have the calves separated from the older animals.

5.5.7  Introduction of cows

In the NAMHS study (1997) farmers where also asked if they bought any animals during the last year (1995). The results are shown in Table 19.

<table>
<thead>
<tr>
<th>Routines</th>
<th>Percentage operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not-weaned heifers</td>
<td>5.0 %</td>
</tr>
<tr>
<td>Dairy heifers weaned but not bred</td>
<td>7.3 %</td>
</tr>
<tr>
<td>Bred dairy heifers</td>
<td>18.5 %</td>
</tr>
<tr>
<td>Lactating dairy cows</td>
<td>19.9 %</td>
</tr>
<tr>
<td>Dry dairy cows</td>
<td>7.1 %</td>
</tr>
<tr>
<td>Other heifers and cows (incl. beef)</td>
<td>1.9 %</td>
</tr>
<tr>
<td>Bulls (weaned)</td>
<td>8.7 %</td>
</tr>
<tr>
<td>Steers (weaned)</td>
<td>2.0 %</td>
</tr>
<tr>
<td>Any beef or dairy cattle</td>
<td>43.9 %</td>
</tr>
</tbody>
</table>

Around 44% of the operations bought cattle during one year (open farm); most of them bought a bred or lactating dairy cow. This will be an under-estimation of the percentage of farms that sometimes buy animals.

5.5.8  Summary of the NAHMS study

In the NAHMS study (1997) it was concluded that opportunities for improving the herd management to control Johne’s disease are:

- At least 85% of the heifer calves remain with their dams more than 1 hour after birth;
- Many U.S. dairy operations used calving areas as hospital pens frequently (16%) or occasionally (39%);
- On 12% of the operations, equipment is not properly cleaned before using it to feed the heifers younger than 12 months;
- Heifers shared feed and water sources with adult cattle on 26% of operations;
- Around 44% of the operations introduced new cattle in 1995;
- Calving cows here housed with lactating cows on 55% of the operations;
- On 11.7% of the operations heifers younger than 6 months have direct contact with adult cows and on 7.0% with heifers from 7-11 months.

The results from the NAMHS study (1997) will be used to determine the current management on Pennsylvanian dairy herd.
5.5.9 Pennsylvanian dairy herds in the simulation model

Four main management characteristics of a dairy farm are distinguished in the simulation model, which are related to the spread of Johne’s disease:

1. **Calving area:**
   - No clean calving area and/or no quick separation of the calf from the dam: = 1-
   - Clean calving area and quick separation of the calf from the dam: = 1+

2. **Colostrum management:**
   - Mixed or pooled colostrum = 2-
   - Only colostrum from the own dam = 2+

3. **Milk management:**
   - Whole milk and/or pooled milk = 3-
   - Milk replacer = 3+

4. **Separation of calves from older cows:**
   - No proper separation = 4-
   - Proper separation = 4+

The categories for separation of different management types (‘risk profiles’), needed to reflect the variation between different dairy herds, and are shown in table 20. Table 20 is based on the results of the NAMHS study (1997).

<table>
<thead>
<tr>
<th>Management type</th>
<th>Calving area</th>
<th>Colostrum management</th>
<th>Milk management</th>
<th>Calf separation</th>
<th>Percentage of farms (estimated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Bad’</td>
<td>1 -</td>
<td>2 -</td>
<td>3 -</td>
<td>4 -</td>
<td>45%</td>
</tr>
<tr>
<td>‘Fair’</td>
<td>1 -</td>
<td>2 +</td>
<td>3 +</td>
<td>4 -</td>
<td>45%</td>
</tr>
<tr>
<td>‘Good’</td>
<td>1 -</td>
<td>2 +</td>
<td>3 +</td>
<td>4 +</td>
<td>10%</td>
</tr>
</tbody>
</table>

On most farms, calves are not separated accurately within one hour from the mother and on most farms colostrum is being pooled. Most of the farms do give their calves milk replacer but on some on the dairy farms whole milk is fed to the calves. Furthermore, the contact rate between calves and adults on Pennsylvanian dairy herds is estimated to be not very high after the calves are separated from their dams (Table 6). On the ‘Good’ farms the ‘number of effective contacts (k)’ is estimated to be only 50% compared to the ‘Bad’ and ‘Medium’ farms.

5.5.10 Herd size of dairy farms in Pennsylvania

Herd size may be an important factor, influencing the control of Johne’s disease. Three different herd sizes are distinguished, called small, medium and large herds. Information about herd-size etc is presented at [www.usaha.com](http://www.usaha.com). The National Agricultural Statistical Service (NASS, 1999) calculated the herd size of Pennsylvanian dairy herds, which is shown in Table 21.

<table>
<thead>
<tr>
<th>Herd size</th>
<th>Number of herds (*’98)</th>
<th>Estimated # of cows*</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-29</td>
<td>2,200</td>
<td>33,000</td>
<td>Small (50 cows)</td>
</tr>
<tr>
<td>30-49</td>
<td>3,700</td>
<td>148,000</td>
<td></td>
</tr>
<tr>
<td>50-99</td>
<td>3,700</td>
<td>277,500</td>
<td>Medium (100 cows)</td>
</tr>
<tr>
<td>100-199</td>
<td>1,050</td>
<td>157,500</td>
<td></td>
</tr>
<tr>
<td>200-499</td>
<td>235</td>
<td>58,750</td>
<td>Large (200 cows)</td>
</tr>
<tr>
<td>&gt;=500</td>
<td>15</td>
<td>10,500</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>10,900</td>
<td>685,250</td>
<td></td>
</tr>
</tbody>
</table>

* median herd size multiplied by the number of cows

In Pennsylvania there are totally around 10,900 dairy operations with one or more cows. Based on the results, shown in Table 24 there will be three different herd sizes simulated. ‘Small herds’ have 50 cows
(plus additional youngstock), ‘Medium herds’ have 100 cows and ‘Large herds’ 200 dairy cows. The Medium herds are used for all of the control programs, Small and Large herds for some programs.

5.6 Economic consequences of the control programs of Johne’s

In this paragraph, the different costs and benefits of a Johne’s control program are shown. The different components of the losses of Johne’s disease are shown in the next paragraphs. The benefits of a Johne’s control program are equal to the reduction of the losses due to Johne’s disease (benefit = losses without control – losses with control). The costs of a Johne’s control program can be categorized into costs of test and removal of positive animals and the costs of changing the management. The latter costs are not included in the simulation model because of the lack of proper data. However, the benefits of a certain management tool are equal to the money a farmer can spend on changing the management.

5.6.1 Losses of Johne’s disease

Losses due to Johne’s can be divided in three categories (Dijkhuizen and Morris, 1997):
1. Losses before culling
   • Milk production losses;
   • Vet and sample costs of clinical cows;
2. Losses at culling:
   • Decreased slaughter value;
3. Losses after culling:
   • Missed future income (also called Retention Pay Off-value);

In the next paragraph the costs shown above will be described.

5.6.1.1 Milk production losses

Milk production losses from cows infected with M. paratuberculosis has been estimated to range from 2.2% to 25% of non-infected herd mates (Norland et al., 1996; Buergelt and Duncan, 1978; Withlock et al., 1985; Wilson et al., 1993; Benedictus et al., 1987).

In the simulation model, the milk production losses are related to the infection status of the infected animal. Losses are higher if the cow is closer to the age when it will become clinical. The losses (as a percentage of the milk production without Johne’s disease) are shown in table 22.

<table>
<thead>
<tr>
<th>Infection status</th>
<th>Percentage decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latent infected or low infectious</td>
<td>0%</td>
</tr>
<tr>
<td>Low infectious</td>
<td>5%</td>
</tr>
<tr>
<td>Low infectious</td>
<td>10%</td>
</tr>
<tr>
<td>Highly infectious</td>
<td>15%</td>
</tr>
<tr>
<td>Clinical</td>
<td>20%</td>
</tr>
</tbody>
</table>

The default milk production of a cow in the simulation model is estimated to be 20,000 lbs., assuming a high producing herd (average in 1997 and 1998 were respectively 16,960 and 17,415 lbs. per cow (Pennsylvanian Agricultural Statistics Service Report, 1999). The average production costs and wholesome milk prices of 100 pounds of milk in 1997 – 1999 are shown in Table 23.

| Pennsylvania whole-sale milk prices and costs of producing milk |
|---------------------|---------------------|
| Routines | 1997 | 1998 |
| Milk prices (average) | $ 14.00 | $ 15.92 |
| Costs of Producing Milk | $ 14.62 | $ 13.53 |
The estimated average milk revenues are estimated on US$ 13.00 per 100 lbs. The costs of producing milk, as reported by the commercial dairy farmers, are shown in Table 24 (Linstedt, 1988).

<p>| Table 24. Costs of producing milk as reported by commercial dairy farmers, 1998 |</p>
<table>
<thead>
<tr>
<th>Cost category</th>
<th>Costs per 100 lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs of purchased feed:</td>
<td>$ 3.02</td>
</tr>
<tr>
<td>Costs of fertilizer &amp; lime:</td>
<td>$ 0.63</td>
</tr>
<tr>
<td>Costs of farm fuels &amp; lubricants:</td>
<td>$ 0.30</td>
</tr>
<tr>
<td>Costs of dairy animals purchased:</td>
<td>$ 0.25</td>
</tr>
<tr>
<td>Costs of hauling:</td>
<td>$ 0.55</td>
</tr>
<tr>
<td>Costs of paid on indebtness:</td>
<td>$ 0.42</td>
</tr>
<tr>
<td>Depreciation:</td>
<td>$ 0.69</td>
</tr>
<tr>
<td>Value of unpaid family labor:</td>
<td>$ 2.55</td>
</tr>
<tr>
<td>Costs of hired labor:</td>
<td>$ 0.67</td>
</tr>
<tr>
<td>Other costs:</td>
<td>$ 4.45</td>
</tr>
<tr>
<td><strong>Total costs:</strong></td>
<td><strong>$ 13.53</strong></td>
</tr>
<tr>
<td><strong>Losses per 100 lbs. of milk</strong></td>
<td><strong>$13 – $3 – $1 = $9</strong></td>
</tr>
</tbody>
</table>

In this study the losses of one kg of milk are calculated as the milk price minus the variable feed costs. The variable feed costs are calculated at $3.02/100 lbs., assuming that only the feed costs will decrease with a lower milk production. Because the total feed costs also include costs of ‘none purchased’ feed, which are estimated to be around $1 per 100 lbs., the total feed costs are $4 per 100 lbs. So, the losses due to 100 lbs. of milk loss are equal to the milk revenues minus the total feed costs, $13 – $3 – $1 = $9 per 100 lbs.

In the NAHMS study (Ott et al., 1999) the annual value of milk production was estimated as the reported annual rolling herd average milk production per cow multiplied by a milk price of $13/cwt (prices averaged $13.29/cwt for the January 1995-July 1996 time period of the study). They did not include any variable production costs in the calculations of these losses because of lacking data, so losses were equal to the value of the milk. This will gives an over-estimation of the losses due a lower milk production due to Johne’s disease.

5.6.1.2 Reduced slaughter value

One of the most obvious clinical signs of Johne’s is the weight loss, which can occur. The losses can be large on individual animals, but on average the reduction of the slaughter value are not very high. The estimated reduction shown in Table 25 is based on literature and expert knowledge and will be used in the model.

| Table 25. Estimated reduction of the slaughter value of infected animals |
| Status/Age | Latent infected | Low infectious | Highly infectious | Clinical |
| Reduction in slaughter value | 0% | 10% | 25% | 30% |

Ott et al. (1999) estimated the median slaughter value of a typical culled dairy cow in normal condition on US$ 400 per head and US$ 250 (38% reduction) per head for a poor-condition cull. Whitlock et al. (1985) found a mean price paid per 100 lbs. of body weight, which was $37.24 for the positive animals and $36.32 for the negative animals (this was not a significant difference). However, the mean total body weight of 1,095 lbs. for positive cows was 129 lbs. less than the mean weight of 1,224 lbs. for the negative cows (p < 0.05). Because the positive animals were fecal positive sub-clinical animals (shedding animals) the loss per cow (129 lbs. * $37.00) of $48.00 are within the range of losses used in the simulation study (Table 28).

Furthermore, in the NAHMS study (Ott et al., 1999) the calf price was $25 for day-old bull calves and $75 for day-old heifer calves. The average replacement costs were $1,100 per head based on average prices
received for replacement cows (January 1995 – July 1996). In the current simulation study, these costs are captured in the losses due to ‘missed future income’ (see next paragraph).

5.6.1.3 Missed future income

With the Marginal Net Revenue approach the optimum time for replacement is determined by comparison of the marginal net revenues anticipated from the present cow with the opportunity costs of postponed replacement. The latter value equals the maximum average net revenue anticipated from replacement cows. In this approach it must be assumed that all subsequent replacement cows are identical. This assumption makes it impossible to account for continuous genetic improvement and for seasonal variation in revenues and costs (Dijkhuizen and Morris, 1997).

Before determining the optimal life span of an animal, first the opportunity costs must be determined. The calculation is based on the average performance of animals present in the herd, assuming this to be the best estimate for expected future net revenue of young replacement animals. Future revenues and costs are weighted with the probability of animal survival. The formula is:

\[ \text{ANJ}_j = \frac{\sum_{i=1}^{j} p_i \cdot \text{MNR}_i}{\sum_{i=1}^{j} p_i \cdot 1_i} \]

where

- \( \text{ANJ}_j \) = expected average net revenue per year;
- \( r \) = decision moment of retention or replacement (1\( \leq i \leq j \)), which is at the end of period I;
- \( p_i \) = probability of survival until the end of period i, calculated from the moment at which the young animal starts its first production (end of period 0);
- \( l_i \) = length of period i (in years); and
- \( \text{MNR}_i \) = marginal net revenue in period i including a change in slaughter value and financial loss associated with disposal.

All replacement animals have the same optimal time of replacement because of the assumption that all subsequent replacement cows are identical. The optimal life span is the last period with a positive difference between expected marginal net revenue of the present animal and maximum average net revenue of its replacement.

The Retention Pay Off value is equal to the “total extra profit to be expected from trying to keep a cow until her optimal life-span, compared with immediate replacement, taking into account the risk of premature removal of retained animals”. The Retention Pay-off (RPO) is calculated as follows:

\[ \text{RPO}_{ij} = \sum_{j=1+1, \ldots, r} p_j \cdot (\text{MNR}_j - \text{ANR}_{\text{max}} \cdot 1_j) \]

where

- \( \text{RPO}_{i} \) = Retention Pay-Off at decision moment i;
- \( r \) = optimal moment for replacement
- \( p_j \) = probability of survival until the end of period j, calculated from decision moment i;
- \( l_j \) = length of period j (in years);
- \( \text{MNR}_j \) = marginal net revenue in period j; and
- \( \text{ANR}_{\text{max}} \) = expected maximum average net revenue per year.

A slightly different approach is used to calculate the Retention Pay Off (RPO) value for the months beyond the optimal life-span of the cow. The economic consequence of culling the cow during the next month at each age has to be compared with replacement the cow at the optimal time during the future period (Dijkhuizen, 1983). So in this case, the optimal life span could be the next period but also another time point in the future. To determine this time, the expected income from a cow culled in each future time point is calculated. The optimal time to cull the cow is when the RPO value is maximized, which is determined
using a DP approach. If the optimal time to cull the cow is determined, the Retention Pay Off value is equal to the RPO value when we cull the cow on this optimal month.

To calculate the RPO values for dairy cows under Pennsylvanian condition, a spreadsheet program has been developed. In the program the RPO value for each month and lactation, for cows having different milk production levels is calculated. The length of the calving interval, the survivability, milk production, lactation curves, feed costs, replacement costs and other input variables can all be changed and adapted easily to reflect other circumstances.

5.6.2 Costs of control of Johne’s disease

5.6.2.1 Costs of testing and culling of test positive animals.

Collins et al. (1993) estimated the costs of an ELISA test US$ 2.36 and of a traditional feces test $7.26. In a report to the Animal Health and Diagnostic Commission of the Pennsylvania Department of Agriculture (PADLS, 1997) the costs were stated as shown in Table 26. Finally, Sweeney and Whitlock (1999) estimated the average test costs on $5.00 per Elisa and $15.00 per fecal test.

<table>
<thead>
<tr>
<th>Test</th>
<th>Collins et al., 1992</th>
<th>PADLS</th>
<th>Sweeney and Whitlock, 1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELISA test</td>
<td>$ 2.36</td>
<td>$ 5.50 (single) or $ 3.50 (herd)</td>
<td>$ 5.00</td>
</tr>
<tr>
<td>Fecal test</td>
<td>$ 7.26</td>
<td>$ 13.00 (single) or $ 9.00 (herd)</td>
<td>$15.00</td>
</tr>
</tbody>
</table>

In the simulation model, the costs per test are respectively $5.00 per ELISA and $15.00 per fecal test (Sweeney and Whitlock, 1999). In addition to this, the average costs of one visit of the veterinarian are $25 for each cow tested another $2 (Whitlock and Sweeney, 1999). The veterinarian costs are added to the total costs of testing.

The costs of removing test positive animals are equal to the RPO of the culled animal. If the removed cow has a decreased milk production, the reduction of it’s RPO value due to this lower milk production will be added to the losses due to Johne’s disease.

5.6.2.2 Costs of changing the management (for instance calving lots or milk replacer).

Some of the changes in the management will have extra costs. Because the costs of changing the management are difficult to estimate and very variable between individual farm, these costs will be included in the cost benefit analyses. The Net Present Value (NPV) of a control strategy is in this case, equal to the amount of money that can be spent on this specific control strategy. This approach is used for control strategies where changes of the management are considered. For control strategies where tests are being used, the costs of the strategy are included in the model and the Benefit-Costs ratio can be calculated (see 5.6.3 Cost Benefit Analyses).

One of the costs, which is possible to estimate are the costs of milk replacer instead of whole milk. Today’s high quality milk replacer, represent a significant cost-saving opportunity for the dairy producer and calf raiser. When fed properly, high quality milk replacer will allow calf growth and performance equal of that attainable with whole milk. Significant price differences in milk replacer occur for a variety of reasons including types of ingredients, manufacturing technology and, ultimately, nutritional quality.

To calculate the costs and benefits of feeding calf milk replacer, the following worksheet can be used (it is generally accepted based on research that one 50-pound bag of calf milk replacer is equivalent to approximately 400 pounds of whole milk).
Example

Price received for whole milk: $13 /cwt.

Value of 400 lbs. of whole milk (50 lbs. solids)

Equals $52

Costs of 50 lbs. of milk replacer Minus $40

Therefore Savings Equals $12

* 50 lbs. of milk replacer is the average amount required, to raise a calf from birth to weaning

From the calculation shown above it becomes clear that not all changes in management, which reduce the spread of Johne’s disease, do cost money. Some of them will be economical attractive anyway, irrespective of the reduction of the losses due to Johne’s disease.

5.6.3 Cost Benefit analysis

For each ‘test and cull’ control program a Benefit-Costs ratio (BC-ratio), also called ‘returns to each dollar invested’, and a Net Present Value (NPV) for each control strategy can be calculated. Because there are no costs of a better hygiene and management included, only a NPV of those strategies can be calculated.

To calculate the BC-ratio and the NPV all costs and benefits need to be discounted; in other words, the costs and benefits made in the future need to be recalculated to their current value. So, the costs and benefits are corrected with an interest percentage per year, which is equal to the market interest minus the inflation, using the following formula:

\[
\text{Current value} = \frac{\text{Future value}}{(1 + \text{real interst}/100)^n}
\]

with

- real interest percentage = 5%
- \( n \) = number of years

With the discounted revenues and costs both the BC-ratio and the Net Present Value can be calculated over a certain period:

\[
\text{BC-ratio} = \frac{\text{Total discounted revenues}}{\text{Total discounted costs}}
\]

\[
\text{Net Present Value} = \text{Total discounted profits} - \text{Total discounted costs}
\]

In the simulation study, both the BC-ratio and the NPV will be calculated over a 20-year period. The Net Present Value (NPV) is a standard economic measure used to value investments that have an extended time component. It is the most reliable measure of economic efficiency and used in the calculation of benefit-cost ratios (Dijkhuizen and Morris, 1997).
5.7 Simulated control strategies against Johne’s disease

In the current simulation study only a limited number of control programs of Johne’s disease will be simulated. Special attention is paid to (1) the “U.S. Voluntary Johne’s Disease Herd Status Program” and (2) ‘heifer contract rearing’ as a control tool against Johne’s disease. Furthermore, the effect of several management tools will be determined to rank and evaluate them on their epidemiological and economical consequences. Also the revenues of perfect information (e.g. test with 100% sensitivity and specificity) will be explored. The next strategies are simulated to determine their epidemiological and economical effects:

“Basic situation”:
0. No control, keep the current management;

“U.S. Voluntary Johne’s Disease Herd Status Program”:
1. Standard track;
2. Fast track.

“Heifer Contract Rearing”
3. From 1-360 days of age;
4. From 1-360 days of age, including better hygiene and management;
5. From 30-360 days of age;
6. From 30-360 days of age, including better hygiene and management;
7. From 180-360 days of age;
8. From 180-360 days of age, including better hygiene and management.

“Rank and Evaluate Management Tools”
9. Hygienic calving lots;
10. Only colostrum from own dam;
11. Only milk replacer;
12. Hygienic heifer raising;
13. All management tools together;
14. All management tools together & Standard Track;
15. All management tools together & Fast Track;

“Perfect Information”:
16. Standard track with perfect tests;
17. Fast track with perfect tests.

The control strategies 9 to 15 are only simulated for farms, which have a ‘bad’ management because only on those farms all four management tools will have an effect on the current management without control.
6 Results

6.1 Epidemiology

6.1.1 No Control

In Figure 3, the average true prevalence on 100 cow dairy herds, under the current management (without any future changes in the management of the farms and no other control measurements) is shown. The four lines represent an typical Pennsylvanian dairy farm (All farms; weighted average) and the three different ‘farm types’ separately (Bad, Fair and Good, Table 20).

![Figure 3](image)

*Figure 3. True prevalence on an average infected Pennsylvanian dairy farm and on farms with different levels of hygiene management.*

From Figure 3, it becomes clear that, without any control strategies, the prevalence will increase on infected dairy operations with ‘bad’ or ‘fair’ management. Due to variation between farms, on individual dairy farms with a good management, prevalence can increase, decrease or stay the same. The line of “All farms” represents an average Pennsylvanian dairy farm and is a weighted average of the three levels of hygiene and management. This line also increases steadily.

The variation of the true prevalence on infected Pennsylvanian dairy farms is shown in Figure 4.
Figure 4. Variation of the true prevalence on infected Pennsylvanian dairy farms

Figure 4 shows there is a large variation in the true prevalence between infected dairy farms. Around 10% of the dairy farms have a true prevalence, which is higher than 50% and without any control strategy it will increase to more than 80% in 20 years. On the low prevalence farms, the true prevalence will increase slower as shown by the 10%-percentile line. Because some farms have a very high prevalence, the average prevalence is higher than the median.

6.1.2 U.S. Voluntary Johne’s Disease Herd Status Program; Standard and Fast Track

In Figure 5, the average true prevalence on a typical infected Pennsylvanian dairy farm, is shown without control (also Figure 4) and under the Standard and Fast Track of the U.S. Voluntary Johne’s Disease Herd Status Program.

Figure 5. Average true prevalence on an infected typical Pennsylvanian dairy herd without control (None) or under the Standard or Fast Track

Both Tracks of the Voluntary Johne’s Disease Herd Status Program do limit the spread of Johne’s disease, but are not capable of decreasing the average true prevalence. The Standard Track is more effective in
limiting the spread of Johne’s disease than the Fast Track, but neither will reduce the average true prevalence.

To get more insight in the effect a test and cull program has on different farms, in Figure 6 the true prevalence is shown without control or under the Standard Track for different levels of hygiene and management.

Figure 6 shows that on dairy farms with a ‘Bad’ management, a test and cull strategy has in absolute terms, a larger effect on the prevalence than on farms with a ‘Fair’ or ‘Good’ management. However, on farms with a ‘Bad’ management, the Standard Track is not capable to reduce the prevalence, where on ‘Fair’ and ‘Good’ management farms it is. So, in general, the effect of a test and cull strategy on a ‘Good’ management farm is relatively larger.

The effect of the Fast Track is smaller than of the Standard Track (see Figure 5) and therefor the lines of the ‘Fast Track’ in Figure 6 lie in between the line of ‘None’ and ‘Standard’ in Figure 6.

6.1.3 Contract Heifer Rearing

In Figure 7, the average true prevalence on a typical infected Pennsylvanian dairy farm is shown under different ‘heifer rearing contracts’ with different levels of hygiene and management on the dairy farm.
Figure 7 shows that ‘heifer contract rearing’, in contrast to the ‘test and cull’ strategies, is capable of reducing the average prevalence on a typical Pennsylvanian dairy herd. Figure 7 also shows a large difference in the effectivity of the various ‘rearing contracts’. The large differences are caused by (1) a difference in the start day of the contract and (2) the management on the dairy farm before the calves leave to the contract operation.

The effects of ‘heifer contract rearing’, on the prevalence of Johne’s disease is larger if the contracts starts at a younger age of the calves. This is clearly shown by the difference between the strategies ‘1-360 days’, ‘30-360 days’ and ‘180-360 days’. The earlier the control start, the more effect is has on the prevalence.

The ‘contract raising’ strategies, including a better management on the dairy farm (‘+Mngt’) reflect situations where the management on the dairy farms, before the calves leave to the contract operation, improves. As shown in Figure 7, the management during the first hours and days has a large influence on the prevalence of Johne’s disease. Because the calves are a shorter period on the dairy farm when the heifer contracting starts at a younger age, the influence of the management on the dairy farm becomes smaller.

Figure 8 shows the variation in the effectivity of ‘heifer contract rearing’ between farms, when the contract is started at an age of 1 day. Both a strategy without and with improvement of the hygiene on the dairy farm on day 1, are shown.
Figure 8. Variation in the true prevalence on an infected Pennsylvanian dairy herds under contract heifer rearing from day 1-360

Figure 8 shows there is a large variation between the prevalence of Johne’s disease between infected herds. Furthermore, Figure 8 shows that under both ‘heifer rearing contracts’ not only the average prevalence reduces, but also on farms with a very low or a high prevalence. In other words, ‘heifer rearing contract’ has an effect will reduce the prevalence of Johne’s disease on each farm type.

It is also shown that if the management around birth on the dairy farm (only the first day of life) is not changed accurately (without ‘+Mngt’), the prevalence will decrease much slower than when it is (‘+Mngt’). Because the simulation with a better management (‘+Mngt’) assumes an almost optimal hygiene, the decrease of the prevalence will probably lie between the two lines with or without ‘Mngt’, depending on the amount of effort a farmer uses to improve the management on day 1. However the importance of a better hygiene on day 1 is also shown by the following fact. Only 10% of the farms will eradicate Johne’s disease in 20 years when they do not improve the hygiene on day 1, but when then do, after 20 years 90% of the infected farms is free.

In general, also under the ‘heifer rearing contract’, which start with older calves the hygiene on the dairy farm, before the calves leave to the contract operation, has a large effect on the prevalence and is therefor very important.

6.1.4 Rank and evaluate management tools

A number of ‘management tools’ on a dairy farm are available against Johne’s disease, which can be used in the development of a statewide control program. Each of these control tools impacts Johne’s disease at a different point in it’s life cycle within a dairy herd. To determine the effect of each of the management tools, which are shown in paragraph 5.7, they are all simulated separately. In addition, they are also simulated all together and when they are used together with the Standard or Fast Track. The true prevalence under these strategies for farms with a ‘Bad’ Management is shown in Figure 9.
Figure 9. True prevalence on an infected ‘Bad’ management Pennsylvanian dairy herd, under different management tools or combination of control tools.

Figure 9 shows that a ‘Hygienic Calving Lot’, administering of ‘Colostrum own dam’ and a ‘Hygienic Raising’ almost have the same influence on the prevalence of Johne’s disease. If calves are given ‘Milk Replacer’, instead of pooled-, bulk- or rest milk (waste - treated) it has a large effect on the prevalence.

If the four management tools are combined (‘All Mngt’ together), the effect on the prevalence is large. So, an effective Johne’s control strategy should always include a limitation of all infection routes. In other words, never leave a chance opening for Johne’s disease to spread, because it will maintain the organism in the herd. The average prevalence (on ‘Bad’ management farms) when the management tools are combined, will decrease to 0% in around 15 years.

If the strategy ‘All Mngt’ is combined with the Fast or Standard Track, there is almost no increment in effectivity. It is also shown that, combined with an effective management strategy, there is almost no difference between the effectivity of the Fast or Standard Track.

6.1.5 Perfect information

The value of perfect test information (if assuming a 100% sensitivity and specificity) is determined by simulating both the Standard and the Fast Track using a perfect Elisa and Feces test. The effects of both strategies on the prevalence are shown in Figure 10.
Figure 10 shows the effect of the Fast Track strategies improves considerably when the test improves. Without any testing the prevalence will increase, where under the Fast Track, using a perfect test, the prevalence decreases rapidly, in 10 years the average prevalence is almost 0%. In contrast, the Standard Track, using a perfect test, does not eradicate Johne’s disease, the prevalence decreases gradually.

The reason for the large difference between the Fast and Standard Track, both with the perfect tests, is that with the Standard Track, in level 0 only 30 animals are tested, while with the Fast Track all animals are tested. Because of the 100% sensitivity, with the Fast Track all infected animals will be culled and prevalence will decline fast. However, with the Standard Track, when only part of the infected animal will be tested and culled, the rest will continue shedding *M. paratuberculosis* and therefore it is not very effective in reducing the prevalence.

### 6.2 Economical effects

#### 6.2.1 No Control

The losses due can be divided in losses due to (see also paragraph 5.6.1.):

1. Milk production losses;
2. Missed future income or clinical and sub-clinical animals;
3. Reduced slaughter value and treatment or test costs of infected animals.

The average total losses due to Johne’s disease for a typical infected Pennsylvanian 100-cows dairy farm, the variation of the total losses and the three different categories of losses are shown in Table 27.
Table 27. Total losses caused by Johne’s disease on an average infected typical infected 100-cows dairy farm without control and losses categories (in US$ per year)

<table>
<thead>
<tr>
<th>Year</th>
<th>Average</th>
<th>10%-perc.</th>
<th>Median</th>
<th>90%-perc.</th>
<th>Categorized losses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>1</td>
<td>3,434</td>
<td>67</td>
<td>2,288</td>
<td>8,354</td>
<td>308</td>
</tr>
<tr>
<td>2</td>
<td>2,819</td>
<td>65</td>
<td>1,677</td>
<td>7,836</td>
<td>341</td>
</tr>
<tr>
<td>5</td>
<td>3,795</td>
<td>80</td>
<td>2,539</td>
<td>9,612</td>
<td>449</td>
</tr>
<tr>
<td>10</td>
<td>5,239</td>
<td>141</td>
<td>4,022</td>
<td>13,033</td>
<td>556</td>
</tr>
<tr>
<td>15</td>
<td>6,234</td>
<td>217</td>
<td>4,970</td>
<td>14,180</td>
<td>674</td>
</tr>
<tr>
<td>20</td>
<td>7,202</td>
<td>418</td>
<td>6,054</td>
<td>14,937</td>
<td>750</td>
</tr>
<tr>
<td>Total not discounted</td>
<td>107,308</td>
<td>18,708</td>
<td>87,290</td>
<td>221,832</td>
<td>11,575</td>
</tr>
<tr>
<td>Total discounted</td>
<td>61,310</td>
<td>10,314</td>
<td>49,112</td>
<td>127,834</td>
<td>(11%)</td>
</tr>
</tbody>
</table>

The average **losses per cow** on an infected farm per year increase from **$35 till more than $72** per cow per year in year 20, which is in agreement with the increasing true prevalence (Figure 3). There is a large variation between the losses per cow on infected farm, shown by the 10% and 90% percentiles. At the moment, 80% of the infected farms have losses between $1 to more then $84 per present cow per year and this increase to losses between $4 to $150 per cow per year. Furthermore, on 10% of the infected farms the total losses per cow are more then $1,270 per cow in the first 20 years (discounted total).

Figure 3 shows that the average true prevalence on infected dairy herds without control increases from 22% to 49% in 20 years. This means that the average **losses per infected cow** are constantly around **$140-$150** per infected cow. Because only a small percentage of the infected cows become clinical infected, the total losses per clinical cow are much higher.

Table 27 also shows that a lower **milk production accounts for 11%** of the total losses by Johne’s disease (11,575 of 107,308). If a cow is prematurely culled, we miss her opportunity costs. Most of all losses of Johne’s disease occur due to losing these opportunity costs, also called **lost future income** (77%). Those opportunity costs are also called missed future income (Dijkhuizen and Morris, 1997). In addition around **12%** of the losses are a result of a **lower slaughter value** of culled infected animals and **treatment costs** of clinical infected cows (Table 30).

Table 28 shows the variation of the losses on a farm with a ‘Bad’ management and hygiene if there is no control program.

Table 28. Total losses caused by Johne’s disease on a ‘Bad’, management and hygiene level, infected 100-cows typical Pennsylvanian dairy farm without control (in US$ per year)

<table>
<thead>
<tr>
<th>Year</th>
<th>Average</th>
<th>10%-percentile</th>
<th>Median</th>
<th>90%-percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5,018</td>
<td>184</td>
<td>3,878</td>
<td>12,425</td>
</tr>
<tr>
<td>2</td>
<td>4,264</td>
<td>237</td>
<td>2,739</td>
<td>10,024</td>
</tr>
<tr>
<td>5</td>
<td>5,719</td>
<td>411</td>
<td>4,903</td>
<td>12,415</td>
</tr>
<tr>
<td>10</td>
<td>8,410</td>
<td>1,706</td>
<td>7,562</td>
<td>14,782</td>
</tr>
<tr>
<td>15</td>
<td>9,812</td>
<td>3,543</td>
<td>9,329</td>
<td>17,280</td>
</tr>
<tr>
<td>20</td>
<td>11,168</td>
<td>4,334</td>
<td>11,203</td>
<td>18,159</td>
</tr>
<tr>
<td>Total not discounted</td>
<td>168,393</td>
<td>83,414</td>
<td>165,512</td>
<td>270,942</td>
</tr>
<tr>
<td>Total discounted</td>
<td>95,733</td>
<td>43,973</td>
<td>88,531</td>
<td>164,590</td>
</tr>
</tbody>
</table>

Table 28 shows that on farms with a ‘Bad’ management where e.g. calves get whole milk instead of milk replacer, the losses can be very high. The average losses are $50 per cow per year and increase to more then $111 per cow per year in 20 years. However, on 10% of the farms, losses are higher then $124 per cow per year and in 20 years will be higher then $180.
6.2.2 Voluntary Johne’s Disease Herd Status Program

One of the major goals to start a control program is to reduce the losses due to Johne’s disease. The reduction of the losses caused by Johne’s disease and the costs of both the Standard and Fast track are shown in table 29. The reduction of the losses due to Johne’s, are equal to the benefits of a control strategy.

Table 29. Reduction of the losses due to Johne’s disease and costs of the ‘test and cull’ strategy (dollars/year)

<table>
<thead>
<tr>
<th>Year</th>
<th>Standard Track</th>
<th>Fast Track</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reduction (dollars/year)</td>
<td>Costs (dollars/year)</td>
</tr>
<tr>
<td>1</td>
<td>427</td>
<td>916</td>
</tr>
<tr>
<td>2</td>
<td>812</td>
<td>3,864</td>
</tr>
<tr>
<td>5</td>
<td>1,756</td>
<td>2,464</td>
</tr>
<tr>
<td>10</td>
<td>2,820</td>
<td>3,410</td>
</tr>
<tr>
<td>15</td>
<td>3,544</td>
<td>2,863</td>
</tr>
<tr>
<td>20</td>
<td>4,371</td>
<td>3,659</td>
</tr>
<tr>
<td>Total</td>
<td>57,368</td>
<td>62,915</td>
</tr>
<tr>
<td>Discounted</td>
<td>31,298</td>
<td>37,418</td>
</tr>
</tbody>
</table>

From table 29 it becomes clear that, in spite of the higher reduction of the losses with the Fast Track in the first years after starting a control program, in the long term the Standard track prevents more losses. Furthermore, the average total costs of the Standard Track are higher, mainly caused by the higher number of cows, being culled (see Table 31).

Furthermore Table 29 shows that in the first years the costs of control are considerably higher that the benefits, but in later years the benefits become higher then the costs.

In table 30 the Net Present Value (NPV) and the Benefit Costs Ratio (BC-ratio) for a 20 years period for both the Standard and Fast Track, are shown.

Table 30. Net Present Value and Benefit Costs-ratio of the Standard and Fast Track

<table>
<thead>
<tr>
<th>B/C-ratio</th>
<th>Standard Track</th>
<th>Fast Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.79</td>
<td>0.83</td>
</tr>
<tr>
<td>10%</td>
<td>0.31</td>
<td>0.32</td>
</tr>
<tr>
<td>50%</td>
<td>0.79</td>
<td>0.80</td>
</tr>
<tr>
<td>90%</td>
<td>1.24</td>
<td>1.36</td>
</tr>
<tr>
<td>B/C-ratio on sector level (all infected dairy farms)</td>
<td>0.84</td>
<td>0.85</td>
</tr>
</tbody>
</table>

From Table 30 it becomes clear that both tracks have an average B/C-ratio which is lower than 1, because the costs are higher then the benefits. A consequence is that the average NPV is negative.

On average the Fast Track is economical slightly more attractive than the Standard Track, in spite of the faster decline of the true prevalence with the Standard Track. The main reason for this, are the higher costs of the Standard Track because more animals are tested. Also, more test positive animals are culled (Table 34) with the Standard Track. Culling more animals does not only reduces the losses, but also causes higher control costs.

The variation of the economical consequences of ‘test and cull’ strategies between herds is large; on 10% of the herds the B/C-ratio is lower than 0.31 and 0.32 with respectively the Standard and Fast Track and on
10% it is higher then respectively 1.24 or 1.36. The latter means that on a proportion of the infected farms, the Standard of Fast Track is economical attractive, for each dollar invested the farmer gets more then $1.24 or $1.30 back.

Table 31 shows the average number of animals, which need to be culled on a 100-cow dairy farm under the Standard and Fast Track because of a positive test result and the variation in this number (median and 10% and 90% percentiles).

**Table 31. Number of test positive animals that is culled on 100-cow dairy herds (20 years period)**

<table>
<thead>
<tr>
<th></th>
<th>Standard Track</th>
<th>Fast Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>27.6</td>
<td>23.0</td>
</tr>
<tr>
<td>10%</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Median</td>
<td>23</td>
<td>16</td>
</tr>
<tr>
<td>90%</td>
<td>58</td>
<td>54</td>
</tr>
</tbody>
</table>

On average around 25 animals need to be culled under both tracks. This means that about 5 animals in 4 years are culled because of a positive test result.

Furthermore, Table 31 shows a large variation in the number of test positive animals that must be culled. With e.g. the Standard Track, the average number of test positive cows that need to be culled in 20 years is 27.6, but on 10% of the farms only 3 or less animals need to be culled. On the other hand, on 10% of the farms 58 or more cows needs to be culled, which is on average almost 3 per year, about 2½ times more animals then on an average farm.

### 6.2.3 Heifer Contract Rearing

‘Heifer contract rearing’ reduces the losses due to Johne’s disease. The reductions of the losses due to Johne’s disease under different contracts are shown in table 32. Also the Net Present Value (NPV) and it’s variation between farms are shown in this Table.

**Table 32. Reduction of the losses due to Johne’s disease (dollars/year)**

<table>
<thead>
<tr>
<th></th>
<th>Same management</th>
<th>Better management on dairy farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>Day 1-360</td>
<td>Day 30-360</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>716</td>
<td>191</td>
</tr>
<tr>
<td>10</td>
<td>3,019</td>
<td>792</td>
</tr>
<tr>
<td>15</td>
<td>4,420</td>
<td>1,356</td>
</tr>
<tr>
<td>20</td>
<td>5,749</td>
<td>2,012</td>
</tr>
<tr>
<td>Total</td>
<td>59,931</td>
<td>19,304</td>
</tr>
</tbody>
</table>

**NPV**

<table>
<thead>
<tr>
<th></th>
<th>Same management</th>
<th>Better management on dairy farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>29,905</td>
<td>9,421</td>
</tr>
<tr>
<td>10% perc.</td>
<td>4,319</td>
<td>1,620</td>
</tr>
<tr>
<td>Median</td>
<td>19,465</td>
<td>8,135</td>
</tr>
<tr>
<td>90% perc.</td>
<td>68,485</td>
<td>19,402</td>
</tr>
</tbody>
</table>

*The NPV is equal to the total discounted reduction of the losses due to Johne’s disease*

First Table 32 shows that, the reduction in losses under the different ‘Heifer Contracts’ without improving the management on the dairy farm, increase substantially if the heifers leave to the contract heifer operation at a younger age. This is in agreement with Figure 7 where the true prevalence decrease faster under contracts, which start at a younger age.

Secondly, if in addition to ‘heifer contract rearing’ the dairy farm has a better level of hygiene, the differences between the Net Present Values of the different contracts are smaller. In other words, with a
better management on the dairy farm, the influence of the age when starting the contract becomes smaller. An important note hereby is that, probably for a dairy farmer it is much easier to remove all heifers to the contract operation at a very young age then to improve the management of the calves and work more hygienic. An important reason for this is that, when heifers are contracted at a young age, the dairy farmer needs to concentrate on the hygiene of the newborn calves for only a few days until they leave the farm.

Improving the management has an economical advantage of $14,000 with a ‘heifer rearing contract’ starting at day 1 to more then 34,000 with a ‘heifer rearing contract’ starting at day 180. So, improving the hygiene before the calves leave the dairy farm is economical very attractive.

The variation between the NPV’s of dairy herds with a ‘1-360days contract’ is large; on 10% of the herds the NPV with a ‘1-360 days contract’ is equal or less then $ 4,300, but on another 10% of the herds the NPV is higher then $ 68,500 ($68 per cow).

### 6.2.4 Rank and evaluate management tools

The reduction of the losses of Johne’s disease with the different ‘management tools’ and the Mngt & test combined, are shown in Table 33.

<table>
<thead>
<tr>
<th>Year</th>
<th>Calving area</th>
<th>Colostrum</th>
<th>Milk replacer</th>
<th>Hygiene raising</th>
<th>All Mngt.</th>
<th>Mngt &amp; Tests</th>
<th>Mngt &amp; Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>own dam</td>
<td></td>
<td></td>
<td></td>
<td>Mngt &amp; Standard</td>
<td>Mngt &amp; Fast</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>542</td>
<td>1,511</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1,032</td>
<td>1,538</td>
</tr>
<tr>
<td>5</td>
<td>306</td>
<td>282</td>
<td>778</td>
<td>277</td>
<td>2,034</td>
<td>3,950</td>
<td>3,487</td>
</tr>
<tr>
<td>10</td>
<td>1,350</td>
<td>1,476</td>
<td>3,941</td>
<td>1,074</td>
<td>7,749</td>
<td>8,356</td>
<td>8,081</td>
</tr>
<tr>
<td>15</td>
<td>1,411</td>
<td>2,249</td>
<td>5,231</td>
<td>1,896</td>
<td>9,734</td>
<td>9,902</td>
<td>9,765</td>
</tr>
<tr>
<td>20</td>
<td>1,462</td>
<td>2,525</td>
<td>6,737</td>
<td>2,202</td>
<td>11,321</td>
<td>11,336</td>
<td>11,285</td>
</tr>
<tr>
<td>Total</td>
<td>29,905</td>
<td>27,024</td>
<td>72,807</td>
<td>25,086</td>
<td>136,975</td>
<td>151,552</td>
<td>148,694</td>
</tr>
</tbody>
</table>

| NPV * | Average | 11,440 | 13,396 | 36,217 | 12,306 | 69,965 | 80,975 | 79,325 |
| 10% perc. | -794 | 2,367 | 15,165 | 2,370 | 34,655 | 40,146 | 35,978 |
| Median | 10,357 | 11,954 | 37,050 | 11,322 | 71,808 | 81,981 | 79,011 |
| 90% perc. | 25,337 | 25,094 | 55,359 | 24,241 | 101,906 | 117,077 | 125,687 |

* The NPV is equal to the total discounted reduction of the losses due to Johne’s disease

Table 33 shows that in general the reduction of the losses (benefits) show up after about 5 years. The benefits of feeding milk replacer instead of whole pooled or rest milk (waste – treated) are for an average infected farm more then $36,000 (discounted total in 20 years). This is in addition to the benefits of feeding milk replacer, which are not related to Johne’s disease.

The benefits of all management tools combined (All Mngt) are on average $70,000. There is a large variation between the benefits of this strategy, 10% of the infected farms have less then $35,000 benefits and 10% more then $117,000.

In addition, two Mngt & Test strategies were simulated. The extra benefits when combining all management tools with the Standard or Fast track are not large. This is also shown in Figure 9. An important factor is however that the losses due to Johne’s disease reduce already the first years after starting the program, in contrast to the control programs where no tests are being used.
6.3 Sensitivity analyses

The sensitivity analyses is performed on one specific type of management, which is the ‘Fair’ management type. The level of hygiene and management on these farms is about average and lies between the ‘Bad’ and ‘Good’ management, and is therefor chosen for this purpose.

1. First, in all results, shown above, an exponential decrease of the susceptibility is assumed (default). Because of the lack of literature and knowledge about this, in the sensitivity analyses a linear decrease is assumed.
2. Secondly, in the default situation, the milk price is assumed to be $13, where in the sensitivity analyses a simulation has been done with a milk price of $17 per 100 lbs. This will change both the Retention Pay Off-values of the cows, and the losses associated with a lower milk production.

The true prevalence for the default situation and for both ‘other’ situations is shown in Figure 9.

![Figure 9. True prevalence without control or with contract heifer rearing from day 1-360 in the default situation and in the sensitivity analyses](image)

In figure 9 a small difference in the true prevalence can be seen when the milk price is $17 per 100 lbs. instead of $13. This different is caused by a difference in the Retention Pay Off values of the cows. This causes a small difference in the voluntary culling, which causes a small difference in the average true prevalence without control.

When a linear decrease of the susceptibility of young calves to Johne’s disease is assumed, the true prevalence is also higher then when we assume an exponential decrease. With an exponential decrease, fewer animals are getting infected, because calves are becoming resistant at a younger age (Figure 2). However, the difference between the true prevalence under both assumptions is not large and under a control strategy even smaller than without a control strategy (Figure 9).
Table 34. Reduction of the losses due to Johne’s disease in the sensitivity analyses under a heifer contract from day 1 to 360.

<table>
<thead>
<tr>
<th>Year</th>
<th>Default</th>
<th>Milkprice $17</th>
<th>Linear decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>270</td>
<td>376</td>
<td>304</td>
</tr>
<tr>
<td>10</td>
<td>1,019</td>
<td>1,426</td>
<td>1,126</td>
</tr>
<tr>
<td>15</td>
<td>1,909</td>
<td>2,371</td>
<td>1,941</td>
</tr>
<tr>
<td>20</td>
<td>2,799</td>
<td>3,911</td>
<td>2,980</td>
</tr>
<tr>
<td>Total</td>
<td>23,839</td>
<td>32,425</td>
<td>25,398</td>
</tr>
</tbody>
</table>

NPV *

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>NPV $17</th>
<th>Linear decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% perc.</td>
<td>3,542</td>
<td>4,769</td>
<td>3,741</td>
</tr>
<tr>
<td>Median</td>
<td>11,228</td>
<td>14,900</td>
<td>11,830</td>
</tr>
<tr>
<td>90% perc.</td>
<td>22,184</td>
<td>30,021</td>
<td>22,351</td>
</tr>
</tbody>
</table>

* the NPV is equal to the total discounted reduction of the losses due to Johne’s disease

From Table 34 it becomes clear that, if the milk price increases to $17/100 lbs., the reduction of the losses due to the control of Johne’s disease (equal to the NPV) will increase considerably and therefor control of Johne’s disease will become more attractive. The higher benefits of controls are caused by the higher Retention Pay Off values of the cows, the higher losses per lbs. of milk and the slightly higher prevalence without control.

Under the assumption that the susceptibility of the calves follows a linear decrease, the NPV’s of the control program will increase a little. This is caused by the slightly higher susceptibility, assuming a linear decrease (Figure 2), and therefor a little bit faster spread of Johne’s disease without control (Figure 9).
7 Discussion and conclusion

7.1 Epidemiological effects of the control of Johne’s disease

7.1.1 ‘Voluntary Johne’s Disease Herd Status Program’

The results of the simulation model shows that when using only a ‘test and cull’ strategy, and not changing the hygiene and management, the prevalence of Johne’s disease will not decrease. In literature many attempts to eradicate paratuberculosis from different herds by use of fecal culture examinations and/or serological tests have been reported unsuccessful before, because of the lack of reliable serological tests for use in detecting cattle with sub-clinical Johne’s disease (Ringdal, 1965; Thoen et al., 1983). This has also been observed in several other studies (Benedictus, 1987; Whitlock and Buergelt, 1996). In 1999, the Subcommittee on Education of the Nat. Johne’s Working Group (NJWG) stated that during control of Johne’s disease management changes are essential to the success. For the ‘test and cull’ options to work always requires adoption of the improved management practices (NJWG, 1999). However, there is only a small effect of a ‘test and cull’ strategy, especially when it is used in combination with management tools.

Two important attributes of a test are the sensitivity and the specificity. In spite of many studies, which are done to determine the sensitivity and specificity of different ELISA and fecal tests, there is still uncertainty about these parameters. The sensitivity, used in the simulation model (table 9) is based on both literature and estimates of Johne’s experts.

One of the major reasons for the poor performance of a ‘test and cull’ strategy is the low sensitivity of ‘sub-clinical’ animals. Whitlock and Buergelt (1996) concluded that the clinical Johne’s disease case is only the tip of the iceberg in terms of the total number of infected animals on the farm. If the clinically infected animal was born on the farm, a minimum of 25 other animals are probably infected and less than 30% of those will be detectable by currently available tests. The lack of test sensitive enough to detect infected animals in the early stages of disease is a serious obstacle to eradication of Johne’s disease with a ‘test and cull’ strategy (Whitlock and Buergelt, 1996). Also Whitlock et al. (1997) concluded that around 70%-75% of the infected animals are pre-patent and pre-clinical (not yet shedding adequate organisms to be detectable by culture) in a typical dairy herd. They stated that probably this was even clearly an underestimate. The fraction of low, mid and high shedders and clinical cases was found to be respectively 70%, 5%, 20% and 5% (Whitlock et al., 1997). This is in agreement with the results from the model where between 70 to 80% of the animals are in the ‘latent infected’ group (none shedding and sub-clinical) and where around 25% of the shedders are heavy shedders, so the rest of the shedders (75%) are low shedders.

If we assume a 100% sensitivity and specificity for both the Elisa and faces test, used in the Standard and Fast track, the effect of the Fast Track on the prevalence is larger (Figure 10). With a perfect test under the Standard it was not possible to eradicate Johne’s disease in 20 years because not all cows are tested, in contrast to the Fast Track.

7.1.2 ‘Heifer contract rearing’

Using ‘heifer contract rearing’ as a control strategy against Johne’s disease is a useful method to decrease the prevalence of Johne’s disease. The younger the calves leave the dairy farm, the larger the effects on the Johne’s disease prevalence and the higher the economical benefits. Especially the first months of age are very critical, so the younger the calf leaves the dairy farm, the better. This becomes especially very clear from the difference between the ‘1-360 days’ and 30-360days’ contracts. Starting the

Furthermore, the management on a dairy farm, before the calves leave to the ‘heifer contract rearing operation’ is very important. Even when the calves leave to the ‘contract operation’ at the 1st day, there is a quite large difference between the strategy with or without accurate management on day 1 (Figure 7). It is concluded that the younger the calves, the more important it is to have an accurate hygiene and management. A main reason for this is that, at a young age a calf is not only less resistant but there are also more infection routes.
So, an important factor with ‘heifer contract rearing’ is that, the younger the calves are leaving the dairy farm, the shorter the ‘critical period’ when the farmer has to concentrate on the level of hygiene of the calves and the easier and more effective the Johne’s control program will be. If contract heifer rearing is combined with a better management on the dairy farm, the ‘contract raising’ strategy is very effective in reducing the prevalence and the losses of Johne’s disease.

The higher susceptibility of young calves compared with that of adult cattle has been reported previously (Larsen et al., 1975). Therefore, segregation of young calves from adult cattle is an important tool in reducing exposure to *M. paratuberculosis*. Little is known of how fast the susceptibility decreases when calves get older. Therefor, both an exponential and a linear decrease where assumed in this simulation study. As shown in the sensitivity analyses, there was only a small different between the spread of Johne’s disease, with an exponential of linear decrease in the susceptibility of young calves.

### 7.1.3 Rank and evaluate management tools

The results of the simulation model show that when only one management tool is used to control Johne’s disease, the prevalence will not decrease. Using milk replacer instead of rest (waste – treated) and pooled milk has a relatively large influence on the prevalence of Johne’s disease. The reason for this is that whole milk can be a very effective transmission route in herd, many calves can drink infected milk from the same cow and therefore one infected cow can infect many calves.

The results of this study show that better hygiene and management are essential to prevent the spread of Johne’s disease. Secondly, better hygiene and management is much more effective in reducing the spread of Johne’s disease than a ‘test and cull’ strategy is. This is in agreement with McCaughan’s conclusion (1989). Also in a study of Thoen and Moore (1989) the fecal prevalence and economic losses due to Johne’s disease decreased considerable after segregation of the calves. However, within 6 year eradication did not occur. Also in this study, both the prevalence and the losses of Johne’s disease decrease after different management control strategies. Many papers state that eradication of Johne’s disease will take many year (Ringdal, 1965; Moyle, 1975; Thoen et al., 1993; Collins and Morgan, 1992; NJWG, 1999), which is also in agreement with results of the simulation model.

Only when all necessary tools are used, the prevalence of Johne’s will decrease fast. In other words, taking only ‘half steps’ will not eradicate Johne’s disease because the disease will find a way to spread in the herd, but good hygiene and accurate management will result in a relatively fast decrease and eradication of Johne’s disease.

### 7.1.4 General

The Reed-Frost method, which is used to calculate the infection probability via environmental contamination, assumes a correlation between the prevalence and infection probability. Rosenberger et al. (1991) concluded that the environmental contamination was very closely correlated to the herd prevalence of Johne’s disease and the number of colony forming units of *M. Paratuberculosis* present in the manure of infected cattle. Their conclusions support the assumption that the prevalence and the infection probability are positively correlated. Furthermore, Collins and Morgan (1991) showed that the assumptions, used in the Reed-Frost models, are an acceptable simplification for Johne’s disease. In the current model, several other infection routes exist to represent the transmission of Johne’s disease accurately.

Collins and Morgans model (1991) was most sensitive to changes in the number of effective cow-calf contacts per year. This is consistent with the current model where differences in hygiene and management have a large effect on the transmission rate of Johne’s disease on a farm (figure 31). Furthermore, their model also estimated an increase of the prevalence of Johne’s disease. In their model they also observed a generally plateau at 40-60% of the herd, where in the current model some herds can get a true prevalence near 100%.

The spread of Johne’s disease between farms is included the model, but for better estimates on the effects, refinement of the model and better data on the spread between herds are necessary. The current model
assumes a spread between herds, which changes in time but is the same for all herds. However, in practice, there is a lot of variation in e.g. the number of animals a farmer buys per year. Ott et al. (1999) concluded that Johne’s high clinical herds were at least as likely to sell replacement cows to other producers than Johne’s base negative herds. This can serve as a warning to producers to be careful about purchasing cattle and to select cows only from herds free from Johne’s. Test results will tell less about the infection status of a cow than the infection status of the herd does (Galligan, 1999).

The current simulation model is based both on data from literature and estimates from Johne’s experts. Because a lack of quantitative data on the spread and dynamics of Johne’s disease, the disease spread is partly based on expert estimates, which are based on literature, experiences and discussions. In spite of this lack of hard data, the results of the current simulation model are consistent with observations of paratuberculosis spread and control, made by other investigators (McCaughin, 1992; Thoen et al., 1993; Collins and Morgan, 1992; Benedictus et al., 1983).

Validation of this model with field data is difficult in that M. paratuberculosis infected herds have not been monitored, without and with intervention to control the disease, over this extended time periods needed to follow the epidemic. However, the simulation model has been validated with data of the spread of Johne’s disease, on different dairy farms in the Netherlands. From both the field data and from the model, the \( \beta \)-values (average, percentiles and extremes) were calculated (measurement of the transmission rate of a disease) and compared. In addition to this, assumptions of the model where discussed with Johne’s experts thoroughly. The model was consistent with observations on paratuberculosis without or with control made by Johne’s experts and other investigators (McCaughin, 1992; Thoen et al., 1993; Collins and Morgan, 1992; Benedictus et al., 1983).

7.2 Economical effects of the control of Johne’s disease

7.2.1 No control

In this study, the average losses due to Johne’s disease on an infected 100-cow dairy farm are $3,500 per year, which is $35 per cow per year. However, the average losses increase to $52 and $71 per cow per year in respectively 10 and 20 years from now. There is a large variation in the losses on infected farm, currently 10% of the farms having losses, which are higher then $85 per cow per year and in a 20-year period $1,280 (not discounted total is $2,200). The average losses are lower then estimated by Chiodine et al. (1986) who estimated the annual economic loss per 100 cows in herds with Johne’s disease infection to be $7,659 but they are within the interval where the losses of 80% of all infected farms are.

Ott et al. (1999) calculated that the current losses of Johne’s were over US$ 200 per cow for herd that reported at least 10% of their cows as having clinical signs consistent with Johne’s disease. The losses were standardized to a common milk price (but not correcting for a lower feed intake) and, when possible, too common cull cow prices for clinical cases. For Johne’s positive herds, compared to Johne’s negative herds, the average losses were estimated on US$ 100 per cow, which is $10,000 for a 100-cow infected herd. This is higher then the losses, calculated in this study because of several reasons. There are two mayor reasons for this difference, the first is that Ott et al. (1999) did not include any feed costs in their calculation of the losses. A second important reason is that Ott et al. (1999) compared the difference between dairy farms, which have a different Johne’s prevalence. Consequently, if there is a relation between the management on a dairy farm and the prevalence of Johne’s disease, not only the influence of a higher prevalence of Johne’s disease is included in the milk production losses, but also the influence of a worse management on dairy farms. Especially the second factor might have given a large over-estimation of the losses of Johne’s disease due to a reduction of the milk production. In the simulation model only the effects of Johne’s disease on the milk production are calculated and the only relation between the management and the milk production losses are possible because with a worse management Johne’s disease will be more prevalent.

Furthermore, Ott et al. (1999) calculated that the average losses due to Johne’s disease across all herds are US$ 22 to US$ 27 per cow. Other estimates of the economic impact of Johne’s disease in the Netherlands ranged from $389 to $959 per infected cow with clinical signs of Johne’s disease and $123 to $696 per infected cow not showing any clinical signs (Benedictus et al., 1987). The average losses per infected cow
are about $140 to $150 per year, which is in agreement with the findings of Benedictus et al. (1987). An important note is that the farms where they calculated the losses where all heavily infected farms.

Three important reasons for the large variation of losses due to Johne’s disease per farm are the differences of (1) the prevalence, (2) the management and (3) the size of the farm (Benedictus et al., 1987; Ott et al., 1999). In this study this variation is included by simulating herds, having a different prevalence, management and herd size. Most of the shown estimated losses are higher than we find in the current study. One reason for this may be that in the current study also infected farm with a test prevalence, which is 0, are included where in the other studies only test positive farms are. Furthermore, in the current study a correction is made for feed costs, where in other studies it is not.

The larger the herd is, the higher the losses due to Johne’s disease are. The reason for this is that Johne’s disease spreads easier and faster in larger herds because of the discontinuous spreading of the M. paratuberculosis bacteria of infected cows. This is in contrast of results of Collins and Morgan’s model (1991), where paratuberculosis progressed faster in smaller herds. They state however that this phenomenon could be caused by some wrong underlying assumption of parameters in their model.

The model show that most of the losses due to Johne’s disease (around 77%) are caused by premature culling of clinical cows and cows, which are culled due to a lower milk production caused by Johne’s disease. The losses due to a lower milk production are only 10-15% of the total losses. Jones (1992) also states that the major costs of Johne’s disease are indirect costs, which are related to replacements costs and unrealized future income. Because around 70-90% of the infected cows are sub-clinical, in field studies the losses due to premature culling are very difficult to determine. The result of the model are not in agreement with the result of the study of Ott et al. (1999) who calculated that around 80 - 90% of the losses due to Johne’s disease are caused by a lower milk production. Two important reasons for this high percentage are stated above.

7.2.2 Voluntary Johne’s Disease Herd Status Program

Control of Johne’s disease does reduce the losses caused by Johne’s disease and therefor can be economical attractive. In the Cost-Benefit analyses, the costs of control are compared with the reduction of the losses caused by Johne’s disease.

As shown in Table 33, both of the two tracks of the Voluntary Program were on average not economical attractive for infected farms on a 20-year period. However the average benefits after 10-20 years are higher then the costs, which means that in a longer period control may be attractive.

Furthermore, due to the variation between farms, on a proportion of the farms, the NPV is positive and therefor control economical attractive. This is shown in Table 33 where the 90% percentile is 1.3, which means than 10% of the farms have an BC-ratio which is higher then 1.3.

The increment of a ‘test and cull’ strategy becomes smaller when it is combined with an improvement in the management. Because only management tools are capable of reducing the prevalence, they are necessary critically. ‘Test and cull’ strategy should therefor never be used alone to eradicate Johne’s disease, the main effort should be focused on an improvement of the hygiene.

7.2.3 Heifer contract rearing

All ‘heifer contract rearing’ strategies have a positive Net Present Value. Two main factors do increase the effectivity of a ‘heifer contract rearing program’. First of all, the younger the calves leave the dairy farm to go to the ‘contract operation’, the more effectively the program and the higher the economical benefits. Secondly, combining ‘contract heifer rearing’ with ‘better management does also increase the effectivity and economical benefits (Table 34). E.g. the average NPV of contract heifer rearing from 1-360 days without or with ‘better management’ is respectively $30,000 and $44,000 for a 20-year period.
The economical benefits of the strategies, without using a ‘test and cull’ strategy, are equal to the discounted reduction of the losses due to Johne’s disease. For this reason, the Net Present Values of those strategies can be seen as the amount of money that can be spend on the control program. For ‘contract heifer strategies’ this means that, irrespective of all the other economical benefits of contract heifer rearing, the reduction of the losses due to Johne’s disease will make ‘contract heifer rearing’ economical more attractive. The extra profits from a 1-360 day ‘heifer raising contract’ including a better management on day 1, increase from $0 in year 1 to more then $4,800 and 7,200 per year after respectively 10 and 20 years on a 100 cows dairy farm.

The ‘extra’ economical benefits of heifer contract raising, combined with the relative easy way of controlling Johne’s disease, can encourage farmers to start contracting their heifers. Important is that their contract should start as young as possible and that the hygiene and management during the first day is optimal.

7.2.4 Rank and evaluate management tools

The reduction of the losses due to Johne’s disease using only management tools start to occur after about 5 years (Table 36) where, combined with a test and cull strategy the losses are also reduced in the first years. The management tools have a influence on the probability on new infections and the losses due to those new infections will not occur within the first years. However, a test and cull strategy does not have a large effect on the total benefits of a control program.

Feeding milk replacer instead of whole milk is economical a very attractive management tool. In addition to the fact that feeding milk replacer is cheaper than feeding whole milk (paragraph 5.6.2.2) it will reduce the losses due to Johne’s disease considerably. However, also the other three management tools have high economical benefits. Combining all management tools does result in $70,000 (35,000 to 102,000) benefits in 20 years, or on average $113 per cow per year in year 20.

7.3 Further research

The simulation model gives several directions for further research. First of all, an important effect could be that of expanding the dairy herds. With many dairy herds expanding and keeping most of their own heifers, the spread of Johne’s disease could differ from those herds with that of herds with a constant number of dairy cows. Also the introduction of Johne’s disease due to buying infected animals, possibly related to expansion of a herd, should be studied more precise.

In the current study, only the economical benefits of contract heifer rearing and a better management are calculated, which are related to Johne’s disease. Other benefits of these strategies might be reductions in the losses due to other diseases, e.g. BVD, Corona and Rota viruses, *E. coli*, and Salmonella bacteria. The reduction of the losses of these diseases needs to be calculated too, to determine the total benefits of the different control strategies.

Furthermore, the economical effects of a reduction in the milk price due to consumers’ concern due to the possibly relation between Johne’s disease and Crohn’s disease, should be calculated. If indeed Johne’s disease becomes a food safety issue, a reduction in the milk price due to Johne’s disease can occur. In this case the losses may be so high that a national Johne’s disease eradication program is be economical attractive.

Vaccination reduces clinical disease but, without strict management, infection in herds continues and is maintained at an unknown level. Vaccination may therefor be an option for any heavily infected herds to reduce the economic impact of the disease (NJWG, 1999). In the simulation model, vaccination could also be incorporated, having different effects on the epidemiology of Johne’s disease. In this way, the most important attributes of a vaccine could be determined, which is helpful for further research on vaccine development against Johne’s disease. Also the economic costs and benefits of vaccination can be calculated.
More Johne’s disease control programs could be evaluated with the current model to determine their epidemiological and economical effects. This can be used to optimize the recommended control programs and possibly have different control programs for different farm types or farms with a different prevalence.

The spread of Johne’s disease may become more important for individual herds when the Johne’s prevalence is decrease. A more precise simulation of the spread of Johne’s between herd will be useful to study the importance of the inter-herd spread.

7.4 Conclusion summary

It is concluded that the prevalence of Johne’s disease can only be reduced with better hygiene and management, which reduce the spread of Johne’s disease. ‘Test and cull’ control programs alone, on average do not decrease the prevalence. They should be combined with improvements in the management to reduce Johne’s disease. For instance the use of milk replacer over whole milk is an economical very attractive control tool. Only real and complete improvement of the management can reduce the prevalence so eradication is possible within 20 years. The increment of a ‘test and cull’ strategy decreases if the management and hygiene is better.

An effective, cheap and therefore attractive way of reducing the spread of Johne’s disease is to send calves at a young age to a contract heifer operation. If this strategy is combined with good hygiene around birth on the dairy farm, the effects on the prevalence of Johne’s disease are even greater. In addition, there are high ‘extra’ economic benefits of ‘heifer contract rearing’, related to Johne’s disease.

The results of this study are, in rough lines, in agreement with former studies and with data from infected farms. The results are consistent throughout different situations and therefore, the simulation model showed to be a powerful tool to study many different situations and strategies to control Johne’s disease and determine the critical points.
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9 Literature


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