An Incentive System for *Salmonella* Control in the Pork Supply Chain

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Selected paper prepared for presentation at the American Agricultural Economics Association Annual Meeting, Portland, OR, July 29- August 1, 2007

Abstract

This paper presents a dynamic principal-agent analysis of an incentive system for *Salmonella* control in the pork supply chain. The incentive system determines quality premiums to the producer, testing frequencies for hogs delivered, as well as charges to the producer for testing and penalties. Using cost estimates and technical parameters, we evaluate the cost effectiveness of plant and farm control measures and trade-offs between prevalence reduction and related costs and gains. We also assess the impact of ownership structure on incentive system parameters and performance for a wide range of prevalence threshold levels. Differences in control actions, bacteriological prevalence and the overall welfare gain for the chain are very small across ownership structures. Changes in the prevalence threshold level lead to substantial changes in the use of farm and plant control packages and performance measures.

Keywords: dynamic programming, food quality, principal-agent

1. Introduction

Consumers in developed countries take an interest in the way their food is produced. Besides ethical issues and convenience considerations, consumers are concerned about health risks from food borne illnesses. By far the most frequently reported zoonotic diseases in humans are salmonellosis and campylobacteriosis. In 2004, a total of 192,703 cases of salmonellosis were reported the EU Member States. The incidence was 42.2 cases per 100,000 of population (European Food Safety Authority, 2006). A substantial share of the finishing pigs herds are infected with *Salmonella* (van der Wolf et al., 2001). Infection of pigs with *Salmonella* can occur on the farm. Pigs can also be infected during transport and lairage, and meat can be contaminated during slaughter. One out of four cases of human salmonellosis is caused by a serotype occurring in pigs (van Pelt and Valkenburg, 2001). Therefore, pork can be regarded as an important source of food borne salmonellosis.

Starting in 2008, it will be mandatory for all member states of the European Union to test pork and pork products for all *Salmonella* serotypes with public health significance and to certify such products for trade. To meet these statutory demands, each country will be required to implement a control program in the pork supply chain. But there is a need for more information on the cost effectiveness of control measures and on trade-offs between prevalence reduction and related gains and costs.

Trade-offs in pork and dairy chains are reported for a wide range of food safety measures (van der Gaag, 2004a; Valeeva *et al.*, 2006). At present, however, pork supply chains in most European countries have neither a formal control system that spans the entire chain nor payment differentials based on *Salmonella* contamination. A mandatory *Salmonella* control program has already been in place in Denmark since 1995. Its main focus is on *Salmonella* control in the primairy production. The Dutch pork chain has no differentiation in payments to producers with respect to the contamination of the product with *Salmonella*, so there is no direct incentive for producers to reduce the *Salmonella* prevalence.

Nielsen *et al*. (2005) analysed the cost effectiveness of the Danish *Salmonella* control program. They concluded that further on-farm initiatives cannot reduce the *Salmonella* prevalence in Danish pork sufficiently. Only intensified focus on slaughterhouse measures can further reduce the prevalence of *Salmonella* in pork (Alban and Goldbach, 2005). The Dutch pig industry focuses on developing private quality control systems which can qualify for less intensive public control for *Salmonella* and other food related hazards by inspectors of the government (de Bakker, 2007).

This paper presents results of an analysis of an incentive system for *Salmonella* control in a two segment pork supply chain. The model described here is a direct extension of a dynamic principal-agent model developed by King, Backus, and van der Gaag (2007) that allows for explicit consideration of the producer's performance history in controlling serological *Salmonella* herd prevalence. In this study we add the possibility of plant control measures that reduce bacteriological *Salmonella* carcass prevalence. The producer incentive system determines *Salmonella* testing frequencies for pigs delivered to the slaughter plant, as well as charges to the producer for testing and penalties for substandard *Salmonella* control. Plant level control measures are one-time investments made at the time the plant chooses parameters for the producer incentive system. Using cost estimates and technical parameters based on Dutch experts and Danish data, we use the model to evaluate the cost effectiveness of plant and farm control measures and trade-offs between prevalence reduction and related costs and gains. We also assess the impact of ownership structure on performance for a wide range of prevalence threshold levels.

2. *Salmonella* testing procedures and control measures

Pork can become contaminated with *Salmonella* in different ways, and at different points in the pork supply chain. Control measures to decrease the risk from *Salmonella* contamination should be considered on the farm and at the slaughterhouse (Beloeil et al., 2004).

Two types of testing, serological and bacteriological, are used to assess *Salmonella* prevalence. Serological tests determine the level of *Salmonella* antibodies in blood samples typically taken at slaughter. Serological sampling of finishing herds is possible at the farm or at the slaughterhouse, since the serological status does not change after pigs leave the farm. Bacteriological tests determine whether *Salmonella* bacteria are present in manure or in a tissue sample from a carcass. The bacteriological testing of carcasses is the most important indicator for food safety.

The plant's bacteriological prevalence level is related to farm-level serological prevalence levels. In general, bacteriological prevalence levels are lower than serological prevalence levels because (i) serological prevalence often indicates a past infection that is no longer active and (ii) control measures taken at the plant level may influence bacteriological contamination on carcasses by contributing to or minimizing cross-contamination.

The relation between herd serology and the prevalence of *Salmonella* bacteria measured at the carcass surface is described for three Danish abbatoirs by a 1.4% increase in the probability of *Salmonella* positive carcasses for a 10 percentage point increase in herd serological prevalence. The Spearmann correlation between carcass prevalence and serological prevalence was 0.29 (Sorensen et al., 2004). Swanenburg *et al*. (2001a) report also that the prevalence of *Salmonella* lower is in pork samples of sero-negative herds than in samples of sero-positive herds

Salmonella contamination of carcasses after slaughter is partially caused by *Salmonella*-infected herds that were slaughtered before, and partially by residential flora of the slaughterhouse. Slaughter hygiene, including careful removal of the intestinal tract from the carcass and cleaning and disinfection, can reduce cross-contamination by residential flora from the slaughterline. The carcass splitter in the slaughter line is the most important contamination source for carcasses of pigs from both sero-negative and sero-positive herds. Logistic slaughter, or separate slaughter of sero-negative pig herds, can also be useful to decrease the *Salmonella* prevalence of pork after slaughter (Swanenburg *et al*., 2001b).

3. Model Description

The model developed for this study is a direct extension of the dynamic principal-agent model presented in King, Backus, and van der Gaag (2007), and our description here draws heavily on the description in that paper (pp. 85-92). That model identifies Nash equilibrium farmer incentive system parameters and associated farm-level *Salmonella* control policies for a two segment supply chain that includes producers and a slaughter plant. The model described here adds the possibility of plant control measures that reduce bacteriological *Salmonella* prevalence.

Of the two incentive systems described in King , Backus, and van der Gaag (2007), we use the cumulative experience system in this analysis. The parties in control under IOF and COOP ownership structures have a uniform preference for the cumulative experience system. That is due largely to lower testing costs. Consistent with results presented by Starbird (2005), a random testing regime makes it possible to reduce testing costs without sacrificing product quality.

We assume a homogeneous group of hog producers, each of whom is treated as an independent agent in the model developed for this study. Each producer delivers a fixed number of hogs once each month to a slaughter plant that has a *Salmonella* control program. All producers have identical costs for inputs not related to *Salmonella* control, **PC**, and receive an identical base price, **PH**, per hog delivered. They also receive a producer quality premium, $\boldsymbol{\alpha_0}$, per hog delivered that is a reward for participation in the plant's *Salmonella* control program. Each month, the producer chooses one package from a set of three *Salmonella* control measure packages, $\mathbf{x_t} \in \{\mathbf{x_1}, \mathbf{x_2}, \mathbf{x_3}\}$, with an associated cost, $\mathbf{c(x_t)}$, that increases with the intensity of the control measures. At slaughter, a sample of the producer's hogs may be serologically tested for *Salmonella* prevalence, $\mathbf{prev_t} \in \{\mathbf{0, 10, 20, \ldots, 100}\}$. The probability distribution of prevalence levels is a function of the current *Salmonella* control package and is denoted by the discrete probability function $\mathbf{h(prev_t|x_t)}$.[1] If hogs are tested, the test results become part of the producer's production history, which is summarized by a production history indicator level, $\mathbf{R_t}$, a scalar defined as the number of consecutive months (up to a maximum of $\boldsymbol{\alpha_1} \in \mathbf{\{0, 1, 2, \ldots, 24\}}$) the producer has delivered hogs prior to the current period without having a *Salmonella* prevalence test level exceeding the *Salmonella* serological threshold level, $\boldsymbol{\alpha_7} \in \mathbf{\{10, 20, 30, 40\}}$, set by the slaughter plant.

The probability that the producer's hogs will be tested on delivery, $\mathbf{t}(\mathbf{R_t})$, declines as $\mathbf{R_t}$ increases according to the following relationship:

(1) $$\mathbf{t}(\mathbf{R_t}) = \max((a_2 \mathbf{e}^{-a_3 \mathbf{R_t}}), a_4),$$

where $\boldsymbol{\alpha_2}$ is the maximum probability of being tested, $\boldsymbol{\alpha_3}$ is a testing probability reduction parameter, and $\boldsymbol{\alpha_4}$ is the minimum probability of being tested. The evolution of the production history indicator is described by the following expression:

(2) $$\mathbf{R_{t+1}} = \begin{cases} \min((\mathbf{R_t}+1), a_1) & \textbf{if } \mathbf{Test_t Fail(x_t)} = 0 \\ 0 & \textbf{if } \mathbf{Test_t Fail(x_t)} = 1 \end{cases},$$

where $\mathbf{Test_t}$ is a binary variable equal to one if the producer's hogs are tested in period t and zero otherwise, and $\mathbf{Fail(x_t)}$ is a binary variable equal to one if the producer's hogs are tested in period t and

[1] We assume the prevalence of *Salmonella* at t=1 is independent of prevalence at t=0. Field tests reveal a low correlation between consecutive monthly prevalence test results. However, there is some evidence that a low on-farm *Salmonella* prevalence at t=0 is associated with a higher probability of a low on-farm *Salmonella* prevalence at t=1. We attribute this to irreversible control measures, such as investments in farm buildings and equipment aimed at improving herd health hygiene, which are not considered here. Seasonal effects could also be a factor, but these are also outside the scope of our analysis.

have a prevalence test result above the allowable threshold and zero otherwise. Therefore, $\mathbf{R_{t+1}}$ is a random variable that depends not only on the control package used by the producer but also on the probability of testing determined by the current production history indicator. The probability that the prevalence test result will be below the plant's *Salmonella* threshold level, $\mathbf{s(x_t)}$, is calculated for each control package by summing values of the prevalence probability function, $\mathbf{h(prev_t|x_t)}$, over prevalence levels less than or equal to the *Salmonella* threshold, $\boldsymbol{\alpha_7}$. This incentive system has two additional parameters: $\boldsymbol{\alpha_5}$ is the share of the expected testing cost paid by the producer , and $\boldsymbol{\alpha_6} \in \mathbf{[0,1]}$ is the size of the producer penalty per hog for a prevalence test result that exceeds the plant's S*almonella* threshold level. The single period return for the producer, $\mathbf{f(x_t, R_t)}$, is defined by the following expression:

$$(3)\quad \mathbf{f(x_t, R_t)} = a_0 - \mathbf{c(x_t)} - a_5\mathbf{t(R_t)TC} - a_6\mathbf{Test_t Fail(x_t)}$$

The producer pays the expected testing cost, regardless of whether his hogs are actually tested. The producer's choice of a *Salmonella* control package, $\mathbf{x_t}$, influences the distribution of current returns not only through control costs but also through its effect on the probability of paying a penalty for a prevalence test above the allowable threshold. The current control package also influences future returns through its effect on the production history indicator level, which affects testing costs and the probability of having one's hogs tested.

The producer's problem is solved by dynamic programming, with the *Salmonella* control package as the control variable and the production history indicator level as the state variable. Producers are assumed to be risk averse with an infinite planning horizon. Preferences are represented by an additively time separable constant absolute risk aversion (CARA) utility function, and the model does not allow for saving. Producers consider the plant's investments in *Salmonella* control measures and the incentive system to be exogenously determined and fixed. Each period, the producer chooses a *Salmonella* control package and realizes a net gain from participation in the *Salmonella* control program that is equal to the quality premium minus costs for quality control measures and *Salmonella* testing and, possibly, a penalty for a *Salmonella* prevalence level that exceeds thresholds set by the slaughter plant.[2]

The producer's dynamic programming problem can be formally stated as:

$$\max_{\{\mathbf{x_t}\}_{t=0}^{\infty}} \mathbf{E}[\sum_{\mathbf{t}=0}^{\infty} \delta^{\mathbf{t}} (-\mathbf{e}^{-\lambda \mathbf{f}(\mathbf{x_t},\mathbf{R_t})})]$$

(4) **s.t.**

$$\mathbf{R}_{t+1} = \begin{cases} \min((\mathbf{R_t} + 1), a_1) & \textbf{if Test}_{\mathbf{t}}\textbf{Fail}(\mathbf{x_t}) = 0 \\ 0 & \textbf{if Test}_{\mathbf{t}}\textbf{Fail}(\mathbf{x_t}) = 1 \end{cases}$$

where **E** is the expectations operator, **δ** is a monthly discount factor and **λ** is the producer's constant level of absolute risk aversion. The optimal solution to this problem yields a steady state *Salmonella* control package for each production history indicator state. The solution also yields probabilities that the producer will be in each state, expected control and testing costs, and expected penalties assessed to the producer. If the certainty equivalent of the net gain from participation in the *Salmonella* control program falls below zero, the producer will terminate his relationship with the slaughter plant and will deliver his hogs to another plant that does not offer a producer quality premium because it sells its product in markets that do not restrict *Salmonella* prevalence.

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[2] Production costs not related to *Salmonella* control, **PC**, and the base price per hog, **PH**, are treated as deterministic in this analysis. Therefore, the base net return for hog production can be treated as a fixed component of overall returns that include gains from participation in the *Salmonella* control program. With a CARA utility function, this fixed component does not affect the optimal choice of a control package and so can be disregarded.

The manager of the slaughter plant is treated as the principal in this model. She cannot directly observe producers' quality control efforts, but she can influence their behavior through the design of the compensation/testing system. Specifically, she can choose the structure of the incentive system and the values of elements in the parameter vector, $\boldsymbol{\alpha}$, that determine the producer quality premium, testing probabilities, serological prevalence threshold, penalties, the incidence of testing costs, and the evolution of production history indicator levels. The plant manager can also choose one package from a set of three S*almonella* plant control measure packages, $\boldsymbol{\gamma_t} \in \{\boldsymbol{\gamma_1, \gamma_2, \gamma_3}\}$, with an associated cost, $\mathbf{c(\gamma_t)}$. The slaughter plant receives an exogenously determined quality premium equivalent to **QPS** per hog from its downstream customers if the plant level mean bacteriological prevalence of *Salmonella* for all hog carcasses produced by the plant on a given day, **pprev**, is less than or equal to an exogenously determined bacteriological threshold, $\mathbf{BPREV^*}$. The plant's bacteriological prevalence level, for a given plant control package, depends on the distribution of bacteriological prevalence levels for hogs delivered by producers. This, in turn, is related to farm-level serological prevalence levels, which depend on the farm-level control measures used by producers. Therefore, the bacteriological prevalence measure for a group of hogs delivered by a producer, **bprev**, is a random variable with a probability function, $\mathbf{m(bprev|prev_t, \gamma_t)}$, that is conditional on the producer's serological prevalence level and the plant-level *Salmonella* control package.

The slaughter plant's bacteriological prevalence level, **pprev**, is a measure of the mean bacteriological prevalence level for all hog carcasses produced during a day. As in King, Backus, and van der Gaag (2007), we assume that there are daily hog deliveries by **dhogd** homogeneous producers. Due to past random events, these producers are distributed over production history states and so may have used a distribution of control packages, though any individual producer will be in a single state and will have used a single control package. Therefore, the population of producers will deliver hogs with a bacteriological prevalence distribution associated with the mix of control packages reflecting the steady state distribution of producers over production history states and the plant's own control package. Let $\mathbf{cp_i}$, $\boldsymbol{\mu}_{\mathbf{ij}}$, and $\boldsymbol{\sigma}_{\mathbf{ij}}^{\mathbf{2}}$ be the percentage of producers using control package **i** and the mean and variance of producer level bacteriological prevalence for package **i**, where $\mathbf{i} \in \mathbf{\{1, 2, 3\}}$, when the plant has selected plant control package **j**, where $\mathbf{j} \in \mathbf{\{1, 2, 3\}}$. Assuming producer level prevalence is identically and independently distributed for producers using the same control package, the plant-level expected bacteriological prevalence for this group of producers will be normally distributed with mean and variance, $\boldsymbol{\mu}_{\mathbf{Sij}}$, and $\boldsymbol{\sigma}_{\mathbf{Sij}}^{\mathbf{2}}$, defined by the following expressions:

(5) $$m_{\mathbf{Sij}} = m_{\mathbf{ij}}$$

(6) $$s_{\mathbf{Sij}}{}^{2} = s_{\mathbf{ij}}{}^{2} / (\mathbf{cp}_{\mathbf{i}}\mathbf{dhogd})$$

The overall plant-level expected bacterological prevalence will also be normally distributed with mean and variance, $\boldsymbol{\mu}_{\mathbf{Sj}}$, and $\boldsymbol{\sigma}_{\mathbf{Sj}}^{\mathbf{2}}$, defined by the following expressions:

(7) $$m_{\mathbf{Sj}} = \sum_{\mathbf{i}=1}^{3} \mathbf{cp}_{\mathbf{i}} m_{\mathbf{Sij}}$$

(8) $$s_{\mathbf{Sj}}{}^{2} = \sum_{\mathbf{i}=1}^{3} \mathbf{cp}_{\mathbf{i}}{}^{2} s_{\mathbf{Sij}}{}^{2} = \sum_{\mathbf{i}=1}^{3} \mathbf{cp}_{\mathbf{i}} s_{\mathbf{ij}}{}^{2} / \mathbf{dhogd}$$

The plant receives no premium when the plant level prevalence in hogs delivered exceeds $\mathbf{BPREV^*}$. Knowing the plant-level bacteriological prevalence distribution, the expected slaughter plant premium is the product of **QPS** and the probability the plant-level prevalence will be less than or equal to $\mathbf{BPREV^*}$. The plant pays *Salmonella* control costs, quality premiums to producers and *Salmonella* testing costs not paid for by the producers. The plant also receives penalties assessed to producers. Otherwise, the plant's processing margin per hog is fixed.

The manager chooses a compensation/testing system, $\boldsymbol{\alpha}$, and plant level control package, $\boldsymbol{\gamma}_t$, that optimizes her relevant performance measure, subject to producers' optimal behavior under the incentive system and the participation constraint that the certainty equivalent of each producer's expected net gain from participation in the *Salmonella* control program must be greater than or equal to zero. The manager's relevant performance measure depends on the ownership structure for the slaughter plant. We consider two structures: ownership by non-producer investors (IOF) and ownership by a producer cooperative (COOP).

Under the IOF structure, the manager maximizes the plant's expected gain from participation in a *Salmonella* control program, which is defined as the expected premium received from downstream customers plus expected penalties paid to the plant by producers minus plant control costs, producer quality premiums and S*almonella* testing costs paid by the plant. Under the COOP structure, the manager maximizes the certainty equivalent of the representative producer's net gain from participation in the *Salmonella* control program subject to the constraint that the plant's expected gain from participation in the *Salmonella* control program is greater than or equal to zero.

We also consider the case where the manager chooses incentive system parameters to maximize net gains from *Salmonella* control for the entire two segment chain (CHAIN). In this case, which serves as an overall efficiency benchmark for chain operations with decentralized decision making, the objective is to maximize the plant's expected quality premium minus control and testing costs. Penalties paid by producers to the slaughter plant are not considered explicitly in the function to be maximized, since they are simply within-chain transfers between parties. Because these penalties are stochastic and producers are risk averse, however, the incidence of penalties does indirectly affect overall chain performance. The model accounts for this. Optimal incentive system parameters under CHAIN ownership structure may not be optimal from the perspective of the producer or the plant, but they do maximize expected gains for the chain.

With the behavioral assumptions in this analysis, along with the assumptions that incentive system parameters will be fixed over the entire planning horizon and that the manager will be honest in applying the incentive system parameters she chooses under a particular incentive system design and ownership structure, the incentive system parameters and the associated optimal *Salmonella* control policies of the plant and the producers represent a Nash equilibrium. Given the other party's optimal response, neither the producer nor the manager can be made better off by deviating from his or her optimal solution.

4. Model Parameters

Model parameters for this analysis are based on current conditions for hog finishing operations in the Netherlands, with non-*Salmonella* control-related variable production costs, **PC**, of €90.90 per hog and a base price, **PH**, of €115.00 per hog. Each producer is assumed to deliver 200 hogs per month, but all analysis is done on a per-hog basis. If hogs are tested, blood samples are analyzed for ten of the 200 hogs delivered. The cost of serological testing is €2.00 per sample, so the testing cost for the entire group, **TC**, is €0.10 per hog. The farmer's monthly discount factor, **δ**, is assumed to be 0.9967, which implies an annual discount rate of 4%. The farmer's constant absolute risk aversion level, **λ**, is set at 0.10, a level that implies a risk premium equal to between 4% and 6% of the expected net gain for the entire chain from participation in the *Salmonella* control program.

The slaughter plant's quality premium for participation in the *Salmonella* control program, **QPS**, is €4.25 per hog processed. The exogenously determined threshold for the average bacteriological prevalence of hogs delivered by all producers, $\mathbf{BPREV}^*$, is allowed to vary in this analysis from a high of 3.5% to a low of 0.5%.

The three *Salmonella* control packages available to producers are those defined by King, Backus, and van der Gaag (2007). They include only reversible control measures. All three packages contain basic control measures like control of rodents, hygiene protocols, disinfecting and cleaning. Package 2 adds strict all-in/all-out procedures and separate routes for different suppliers. Package 3 adds acidification of feed and/or water, a highly effective but expensive measure. Costs for farm control packages 1, 2 and 3 are estimated to be €0.72, €1.14, and €2.92 per hog (King Backus, and van der Gaag, 2007). Farm-level serological prevalence probability distributions for the three control packages – i.e., $\mathbf{h(prev_t|x_t)}$ – are shown in table 1. The prevalence distribution for Package 1 is quite dispersed and is centered around 50%. The distribution for Package 2 is more concentrated and has most of its probability mass at levels below 30%. The distribution for Package 3 is still more concentrated at the lower end of the prevalence range, with the probability of a test result of zero exceeding 70%. These discrete prevalence distributions are used to determine elements of the state transition matrices required for solution of the producer's dynamic programming problem.

Three plant level *Salmonella* control packages are considered in this study. Package 1 contains strict hygienic practices at slaughter & processing (cleaning and disinfection) induced by the investor owner or cooperative through monitoring the plant manager's effort. Package 2 adds acidification of slaughter equipment in cleaning and disinfecting procedures. Package 3 adds logistic slaughter of sero-negative pig herds. Logistic slaughter includes testing all pig herds and slaughtering positively tested herds either at the end of the day or at another location to reduce cross-contamination in the slaughterhouse. Logistic slaughter only reduces the prevalence of *Salmonella* effectively when the delay between sampling pig herds at the farm and delivery to the slaughterhouse is at a minimum.

Cost estimates are based on figures provided by Dutch experts from the Vionfood company. The cost of monitoring the plant manager's effort to avoid cross-contamination of carcasses are included in all three plant control packages and set at zero costs. The costs of plant control packages 2 and 3 are estimated to be €0.10 and €0.40 per hog[3].

Bacteriological prevalence distributions for plant control package, $\boldsymbol{\gamma_t}$, are shown in table 2. Each row of the probability matrix for a given plant control package is associated with a serological prevalence level, and each column is associated with a bacteriological prevalence level. The matrix elements are bacteriological prevalence probabilities derived from a Danish study in three Danish abattoirs (Sorensen et al., 2004). First, a probability matrix was constructed based on odds of 1.4 for *Salmonella* positive carcasses for each 10% point increase in herd serology, together with an increasing dispersion of the probability distribution when serological prevalence levels increase[4]. It was estimated that monitoring the plant manager's effort to reduce *Salmonella* by the investor owner or cooperative results for plant control package 1 resulted in a 50% reduction of the values in the probability matrix, except for the zero bacteriological prevalence level (Urlings, 2007). Acidification of slaughter equipment in cleaning and disinfecting procedures under plant control package 2 results in an additional 50% reduction of the probability matrix values, again except for the zero bacteriological prevalence level, compared to plant control package 1. This results in higher probabilities for a bacteriological prevalence level of 0%. Adding logistic slaughter of sero-negative pig herds as control measure results in a probability matrix equal to that for control package 2, except for the zero serological herd prevalence level, in which the probability for a zero bacteriological probability is 1.

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[3] Within the "Control of Control program" Dutch slaughter companies seek to qualify for less intensive public control for food related hazards by inspectors of the government. The reduced costs of less public inspection are assumed to outweigh the costs of implementing and maintaining own control systems. The costs of logistic slaughter of *Salmonella*-free herd are estimated for the Dutch Vionfood company. The company has six plants in the Netherlands. It was considered not feasible to slaughter *Salmonella*-free herds at specific plants. Positively tested herds will be slaughtered at the end of the day. Costs of logistic slaughter include an estimated 10 % increase in transportation costs.

[4] The authors wish to express their gratitude to Liz Alban from Danmark for providing the original data of this study.

The probability distribution for package 1 has most of its probability mass at a bacteriological prevalence level of 0%. With higher serological herd prevalence levels the probability distribution is more dispersed with non-zero probabilities up to bacteriological prevalence levels of 80%.

5. Solution Procedures

General purpose MATLAB routines developed by Miranda and Fackler (2002: 155-188) were adapted to solve the producer's stochastic discrete time/discrete state infinite horizon dynamic programming problem for a given set of parameters. The program uses policy iteration to identify an optimal steady state control policy – i.e., the optimal *Salmonella* control package for each possible production history state. The solution procedure also identifies the state transition matrix associated with the optimal policy, which can be used to determine a long-run probability for each possible state under the optimal policy. This, in turn can be used along with the optimal policy to calculate expected control costs, testing costs, penalties, and prevalence levels for a representative producer operating under the optimal policy.

In order to solve the slaughter plant manager's problem of selecting an optimal plant control package and set of incentive system parameters, the producer problem for each system was embedded in a grid search program that systematically explored the relevant plant control package and incentive parameter space, as defined in table 3.

The optimal parameters for the manager problem combined with the optimal producer control policy for those parameters, define a Nash equilibrium. As noted in the description of the model, we consider two ownership structures – denoted IOF and COOP – as well as an efficiency benchmark for the production chain operations – denoted CHAIN. The relevant performance measure for the manager depends on the ownership structure for the slaughter plant, and all the revenues and costs for the producer and the slaughter plant are readily calculated using the output from the producer model.

6 Results

Nash equilibrium incentive system parameters and key performance measures for bacteriological threshold values **BPREV*** $\in$ **{0.5, 1.0, 1.5, …, 3.5}** under each of the three ownership structures are presented in table 4. All expected performance measures are calculated using the producer's optimal S*almonella* control policies, the plant's optimal S*almonella* control policy and the associated steady state probabilities for each possible production history state. The dynamic programming solution identifies an optimal control package for each production history level and a steady state probability that a producer will be in each of the $\boldsymbol{\alpha_1 + 1}$ possible production history states. Multiplying the costs of the optimal control package for each state by the associated steady state probability and summing over all $\boldsymbol{\alpha_1 + 1}$ states yields the expected farm control cost.

Changes in the bacteriological prevalence threshold level lead to changes in control actions, incentive parameter values, and performance results. The producer always pays for testing costs under IOF and CHAIN ownership, and the slaughter plant pays for testing costs under COOP ownership. Farmer cost are high and farmer certainty equivalent of gain is low under IOF ownership. The pattern is reversed under COOP ownership, and intermediate values are taken under CHAIN ownership.

The use of farm and plant control packages changes with varying bacteriological threshold levels, but is very similar across ownership structures. For bacteriological threshold values of 3.5% and 3.0% , the optimal producer policy always calls for control package 1. Lowering the bacteriological plant threshold from 3.5% or 3.0% to 2.5% induces more producers to use control package 2 with strict all-in/all-out procedures under all three ownership structures. Farm control package 2 is applied by all producers under the three ownership structures when the threshold values are 1.5% or 1.0%. The increased use of farm control package 2 is induced by a higher value of the producer penalty parameter. Additional plant level control measures with acidification of slaughter equipment in cleaning and disinfecting procedures are in effect for all presented Nash equilibrium cases[5]. For all ownership structures, plant control package 2 is implemented before farm control package 2 becomes part of the optimal solution.

The farm serological threshold level decreases to 10% when the bacteriological threshold level falls to 0.5%, and the producer penalty remains high under all three ownership structures, inducing producers to use farm control package 3. The producer quality premium increases to allow for the use of farm control package 3 when the prevalence threshold value falls to 0.5 per cent. The cost effectiveness of farm control package 3, with a high probability of a zero seroprevalence, is related to the use of plant control package 3, with a probability of 100% for a zero bacteriological prevalence when the seroprevalence is zero. Under all three ownership structures, plant control package 3 requires that all herds are tested and associated parameter values are 0 for the production history indicator level, 1 for the maximum testing probability, and 0 for the testing probability reduction, thus making a static incentive system optimal when the bacteriological threshold is 0.5 per cent. These expensive plant and farm control measures prevent a dramatic increase in expected penalties and result in a lower expected prevalence level. Expected welfare and monetary gains fall accordingly.

The optimal values of the production history indicator level, maximum testing probability, testing probability reduction, producer penalty, and farm serological threshold are the same across all three ownership structures when bacteriological threshold values are 3.5% or 3.0%. The optimal values of the maximum testing probability and the optimal testing probability reduction parameter value are 0, resulting in zero testing costs. The optimal performance of the incentive system is not affected by

[5] Only for bacteriological threshold values higher than 5.5 plant control package 1 is part of the optimal solution.

changes in the serological threshold value, the producer penalty parameter, the producer share of testing cost, and the optimum value of the production history indicator level when bacteriological threshold values are 3.5% and 3.0%. The producer quality premium shifts gains between producers and the slaughter plant without affecting risk. It is €0.80 per hog under IOF ownership. Under COOP ownership, the producer premium decreases from €4.10 to €4.00 per hog when the bacteriological threshold decreases from 3.5% to 3..0%. This allows the plant to pay the higher expected slaughter penalty associated with the lower threshold. The optimal values of the producer quality premium range from €0.80 to €4.10 per hog and from €0.80 to €4.00 per hog when the threshold levels are 3.5% or 3.0% under CHAIN ownership. Within these intervals, changes in the optimal producer quality premium simply result in transfers between the producers and the slaughter plant, but they do not affect the expected welfare gain for the chain.

The producer history indicator level is 24 when the plant threshold level ranges from 2.5% to 1.0%. The value of the producer penalty parameter is in the range €1.30-€1.70 per hog for bacteriological threshold levels from 2.5% to 2.0%, and the maximum testing probability ranges from 0.47 to 0.57 under all three ownership structures. The testing probability parameter value is 0.10 or 0.11 for a bacteriological threshold value of 2.5% and ranges from 0.04 to 0.06 for a threshold value 2.0% under all thee ownership structures.

The producer quality premium is low and in the range of €1.30-€1.50 per hog under IOF and CHAIN ownership for bacteriological threshold values ranging from 2.5% to 1.0%. It takes a high value just above €4.00 per hog under COOP ownership when plant threshold values are 1.5% or higher. This keeps the producer share of gains from S*almonella* control high under COOP ownership. This effect is strengthened by the fact that producers pay all testing costs under IOF ownership, while the plant pays all testing costs under COOP ownership. With further lowering the bacteriological threshold value from 1.5% to 1.0%, the producer quality premium is partly shifted to the slaughter company to allow for paying the expected slaughter penalty under COOP ownership.

The optimal serological threshold value for the producers is 30 under IOF and COOP ownership when the plant threshold ranges from 2.5% to 1.0% or less. It increases to 40 when the plant threshold decreases from 2.5% or 2.0% to 1.5% or 1.0% under CHAIN ownership. This seems counterintuitive, but more frequent use of farm level control package 2 is not induced by the serological farm threshold value but by the producer penalty parameter and the probability of being tested.

Because there is some uncertainty over testing costs under this incentive system, shifting this uncertainty to the risk neutral slaughter company lessens the risk borne by the risk averse producer. In turn, this reduces the risk premium in the system and so increases efficiency. The slaughter company does not bear testing costs under IOF ownership, however, because shifting risk to the producer makes it easier to induce the use of less risky, more effective control packages.

Differences in the main performance measures, bacteriological prevalence and the welfare gain for the chain, are very small across ownership structures. Values of the expected monetary and welfare gains for the chain under IOF and COOP ownership are very close to those gains under CHAIN ownership. Expected testing costs increase with a decreasing plant threshold but always remain under €0.036 per hog, except for a plant threshold level of 1.0% with testing costs of €0.10 per hog. The expected slaughter penalty increases to €0.944 when the plant threshold value fall to 1.0% under all ownership structures. A further decrease of the plant threshold value to 0.5% induces more stringent plant and farm control measures, with associated high expected control cost and the expected slaughter penalty falls accordingly.

Changes in the bacteriological threshold level lead to substantial changes in performance measures. Expected bacteriological *Salmonella* prevalence decreases by 56%, and expected overall welfare gains for the chain decrease by 17% when the plant threshold decreases from 3.5% to 1.5%. Expected bacteriological *Salmonella* prevalence decreases by 91%, and expected overall welfare gains for the chain decrease by 82% when the plant threshold decreases from 3.5% to 0.5%.

7. Concluding comments

This paper presents a dynamic principal-agent model for *Salmonella* control in the pork supply chain. Analysis based on this model clearly indicates the value of evaluating the cost effectiveness of plant and farm control measures, and trade-offs between prevalence reduction and related costs and gains for a wide range of prevalence threshold levels. Our results show that the optimal incentive system parameters and the overall performance in a supply chain can vary considerably with the bacteriological threshold level.

It must be emphasized here that specific findings presented here depend on underlying behavioral and technical assumptions and on the particular sets of farm and plant control packages considered. While these findings might be reasonable for the Dutch pork supply chain, where slaughter companies seek to qualify for less intensive public control for food related hazards by inspectors of the government, slaughter plants in other EU member states may have different *Salmonella* prevalence levels.

Both farm and plant control measures can be used to reduce *Salmonella* prevalence. The optimal values of the producer penalty parameter are lower in this study, compared to the earlier study of King, Backus and van der Gaag (2007), allowing plant control measures to be intensified first when plant threshold levels fall. It is also noteworthy that the cost effectiveness of farm control package 3 is strongly related to the use of plant control package 3. It is therefore considered reasonable to assume that plant managers are honest in applying the incentive system parameters they choose when plant threshold levels are low.

The need to simplify the analysis has resulted in at least three important limitations. First, although this analysis gives useful insights in the trade-offs between prevalence reduction and related costs and gains, it must be emphasized that for determining the appropriate bacteriological threshold level also public health aspects have to be considered.

Second, in evaluating incentives for *Salmonella* control, the food safety externalities caused by joint production of quality attributes are often overlooked but may alter the willingness of a firm to adopt food safety controls (Roberts, 2005).

Finally, plants using logistic slaughter are considered to test all herds for *Salmonella* and slaughter positively tested herds at the end of the day instead of at another location. Logistic slaughter only reduces the prevalence of *Salmonella* effectively when the delay between sampling pig herds at the farm and delivery to the slaughterhouse is at a minimum. In the future, the analysis could be extended to determine how the geographic distribution of plant capacity affects the choice between slaughtering positively tested herds at the end of the day instead or at another location. And with the development of faster testing technologies one might expect that production history performance information also contributes to the cost effectiveness of logistic slaughter.

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Table 1. Expected Serological Prevalence for *Salmonella* Farm Control Packages

Serological prevalence	Farm Control Package		
	1	2	3
0	0.03	0.18	0.72
10	0.06	0.24	0.17
20	0.09	0.22	0.06
30	0.12	0.15	0.03
40	0.18	0.10	0.02
50	0.21	0.06	0.00
60	0.15	0.03	0.00
70	0.08	0.01	0.00
80	0.05	0.01	0.00
90	0.02	0.00	0.00
100	0.01	0.00	0.00
Expected prevalence level (%)	45.1	21.6	4.6
Variance of prevalence level	442.99	311.44	78.84
Probability of exceeding 20% prevalence	0.82	0.36	0.05

Table 2. Bacteriological Prevalence Probability Distributions for Plant Control Package γ_1.

Bacteriological prevalence	0	10	20	30	40	50	60	70	80	90	100
Seroprevalence 0	0.95	0.05	0	0	0	0	0	0	0	0	0
Seroprevalence 10	0.94	0.05	0.01	0	0	0	0	0	0	0	0
Seroprevalence 20	0.927	0.053	0.015	0.005	0	0	0	0	0	0	0
Seroprevalence 30	0.8978	0.0747	0.02	0.0075	0	0	0	0	0	0	0
Seroprevalence 40	0.86792	0.09208	0.025	0.01	0.005	0	0	0	0	0	0
Seroprevalence 50	0.818588	0.128912	0.03	0.0125	0.0075	0.0025	0	0	0	0	0
Seroprevalence 60	0.78395	0.135	0.035	0.0225	0.015	0.0075	0.00105	0	0	0	0
Seroprevalence 70	0.73255	0.14	0.06	0.035	0.015	0.0075	0.005	0.00495	0	0	0
Seroprevalence 80	0.666	0.135	0.095	0.05	0.025	0.015	0.01	0.004	0	0	0
Seroprevalence 90	0.63	0.105	0.09	0.065	0.05	0.03	0.015	0.01	0.005	0	0
Seroprevalence 100	0.5817	0.08	0.08	0.075	0.06	0.05	0.035	0.025	0.0133	0	0

Table 3. Allowable Parameter Values for the Slaughter Plant Optimisation Problem*

Parameters	min	max	step size
α_0 – Producer quality premium	0.50	4.25	0.05
α_1 – Production history indicator level	1	24	1
α_2 – Maximum testing probability	0.00	1.00	0.01
α_3 – Testing probability reduction	0.00	0.20	0.01
α_4 – Minimum testing probability	0.00	0.50	0.10
α_5 – Producer share of testing cost	0.00	1.00	1.00
α_6 – Producer penalty	0.00	4.25	0.10
α_7 – Serological threshold value	0	30	10
$g(\gamma)$ – Plant level *Salmonella* control	1	3	1

* All pig herds are tested with a value of 1.00 for α_2 and α_4 and a value of 0.00 for α_3 when plant control package γ_3 is used.

Table 4. Optimal Incentive System Parameters and Performance Measures (λ = 0.10 and dhogd = 50)

	ß ----Investor Owned Firm---- à							ß ----Cooperative---- à							ß ----Chain---- à						
Bacteriological threshold value	3.5	3.0	2.5	2	1.5	1	0.5	3.5	3	2.5	2	1.5	1	0.5	3.5	3	2.5	2	1.5	1	0.5
Parameters																					
α_0 – Producer quality premium	0.80	0.80	1.05	1.30	1.40	1.40	3.55	4.10	4.00	4.10	4.15	4.15	3.35	4.05	[0.80-4.10]	[0.80-4.00]	1.90	1.30	1.50	1.50	4.00
α_1 – Production history indicator level	[0-24]	[0-24]	24	24	24	24	0	[0-24]	[0-24]	24	24	24	24	0	[0-24]	[0-24]	24	24	24	24	0
α_2 – Maximum testing probability	0.00	0.00	0.52	0.47	0.49	0.49	1.00	0.00	0.00	0.57	0.53	0.40	0.60	1.00	0.00	0.00	0.51	0.51	0.99	0.99	1.00
α_3 – Testing probability reduction	0.00	0.00	0.10	0.04	0.05	0.05	0.00	0.00	0.00	0.11	0.06	0.03	0.07	0.00	0.00	0.00	0.10	0.05	0.10	0.10	0.00
α_4 – Minimum testing probability	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
α_5 – Producer share of testing cost	[0-1]	[0-1]	1	1	1	1	1	[0-1]	[0-1]	0	0	0	0	0	[0-1]	[0-1]	1	1	1	1	1
α_6 – Producer penalty	0.00	0.00	1.30	1.70	3.10	3.10	3.80	0.00	0.00	1.30	1.50	3.00	3.20	3.90	0.00	0.00	1.30	1.50	4.00	4.00	3. 70
α_7 – Serological threshold value	[10-40]	[10-40]	30	30	30	30	10	[10-40]	[10-40]	30	30	30	30	10	[10-40]	[10-40]	30	30	40	40	10
$g(\gamma)$ – Plant level *Salmonella* control	2	2	2	2	2	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	3
Performance Measures																					
Expected bacteriological prevalence	1.46	1.46	1.07	0.76	0.64	0.64	0.13	1.46	1.46	1.10	0.83	0.64	0.64	0.13	1.46	1.46	1.08	0.78	0.64	0.64	0.13
Expected serological prevalence	45.10	45.10	33.87	25.17	21.60	21.60	4.60	45.10	45.10	34.69	26.96	21.60	21.60	4.60	45.10	45.10	34.07	25.73	21.60	21.60	4.60
Producer gain (€/hog)																					
- producer quality premium	0.800	0.800	1.050	1.300	1.400	1.400	3.550	4.100	4.000	4.100	4.150	4.150	3.350	4.050	[0.800-4.100]	[0.800-4.000]	1.900	1.300	3.500	3.300	4.000
- expected control cost	0.720	0.720	0.921	1.076	1.140	1.140	2.920	0.720	0.720	0.907	1.044	1.140	1.140	2.920	0.720	0.720	0.917	1.066	1.140	1.140	2.920
- expected testing cost	0.000	0.000	0.018	0.034	0.027	0.027	0.100	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.018	0.036	0.019	0.019	0.100
- expected penalty to plant	0.000	0.000	0.069	0.144	0.172	0.172	0.418	0.000	0.000	0.067	0.125	0.175	0.169	0.429	0.000	0.000	0.067	0.126	0.085	0.085	0.407
- expected total cost	0.720	0.720	1.008	1.254	1.339	1.339	3.438	0.720	0.720	0.972	1.169	1.315	1.309	3.349	0.720	0.720	1.002	1.226	1.245	1.245	3.427
- expected monetary gain	0.080	0.080	0.043	0.046	0.061	0.061	0.112	3.380	3.280	3.128	2.981	2.835	2.041	0.701	[0.080-3.380]	[0.080-3.280]	0.898	0.074	0.255	0.055	0.573
Farmer certainty equivalent of gain	0.047	0.047	0.002	0.001	0.000	0.000	0.001	3.347	3.247	3.088	2.937	2.775	1.979	0.585	[0.047-3.347]	[0.047-3.247]	0.858	0.030	0.203	0.203	0.466
Slaughter plant gain (€/hog)																					
- slaughter plant price premium	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250
- slaughter plant control cost	0.100	0.100	0.100	0.100	0.100	0.100	0.400	0.100	0.100	0.100	0.100	0.100	0.100	0.400	0.100	0.100	0.100	0.100	0.100	0.100	0.400
- quality premium paid to producers	0.800	0.800	1.050	1.300	1.400	1.400	3.550	4.100	4.000	4.100	4.150	4.150	3.350	4.050	[0.800-4.100]	[0.800-4.000]	1.900	1.300	1.500	1.500	4.000
- expected penalty from producers	0.000	0.000	0.069	0.144	0.172	0.172	0.418	0.000	0.000	0.067	0.125	0.175	0.169	0.429	0.000	0.000	0.067	0.126	0.085	0.085	0.407
- expected testing cost	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.018	0.032	0.028	0.025	0.100	0.000	0.000	0.000	0.000	0.000	0.000	0.000
- expected slaughter penalty	0.033	0.145	0.082	0.050	0.147	0.944	0.123	0.033	0.145	0.098	0.091	0.147	0.944	0.123	0.033	0.145	0.085	0.061	0.147	0.944	0.123
Expected monetary slaughter gain	3.317	3.205	3.087	2.944	2.775	1.979	0.595	0.017	0.005	0.001	0.002	0.000	0.000	0.006	[3.317-0.017]	[3.205-0.005]	2.232	2.915	2.588	1.791	0.134
Overall chain gain (€/hog)																					
- slaughter plant price premium	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250	4.250
- expected farm control cost	0.720	0.720	0.921	1.076	1.140	1.140	2.920	0.720	0.720	0.906	1.044	1.140	1.140	2.900	0.720	0.720	0.917	1.066	1.140	1.140	2.920
- slaughter plant control cost	0.100	0.100	0.100	0.100	0.100	0.100	0.400	0.100	0.100	0.100	0.100	0.100	0.100	0.400	0.100	0.100	0.100	0.100	0.100	0.100	0.400
- expected testing cost	0.000	0.003	0.018	0.034	0.027	0.027	0.100	0.000	0.000	0.018	0.032	0.028	0.025	0.100	0.000	0.000	0.018	0.036	0.019	0.019	0.100
- expected slaughter penalty	0.033	0.145	0.082	0.050	0.147	0.944	0.123	0.033	0.145	0.098	0.091	0.147	0.944	0.123	0.033	0.145	0.085	0.061	0.147	0.944	0.123
- expected monetary gain for the chain	3.397	3.285	3.130	2.890	2.836	2.040	0.707	3.397	3.285	3.128	2.983	2.835	2.041	0.707	3.397	3.285	3.130	2.990	2.843	2.047	0.707
Expected welfare gain for the chain	3.364	3.252	3.089	2.944	2.775	1.979	0.596	3.364	3.252	3.088	2.939	2.775	1.980	0.591	3.364	3.252	3.089	2.946	2.791	1.994	0.600