Incentive Systems for *Salmonella* Control in Pork Production

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This paper presents a dynamic principal-agent analysis of incentive systems for *Salmonella* control. Based on the producer's performance history in controlling *Salmonella*, the incentive systems analysed determine 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 two dynamic incentive systems. We also assess the impact of ownership structure on performance. The more efficient incentive system economises on testing costs by reducing the probability of testing in response to a favourable production history and is preferred under all ownership structures.

1. Introduction

Often the food safety and quality attributes consumers seek are difficult to verify, especially when those attributes are derived from the actions of numerous, spatially dispersed producers. Direct monitoring of farm production processes is prohibitively expensive in most cases. Recent advances in testing technologies will provide better information at lower cost and in a shorter time, but laboratory tests to measure critical attributes can still be quite costly. The inherent riskiness of agricultural production further complicates the problem. Even if product quality can be assessed at a reasonable cost, it may be difficult to determine whether quality problems are due to lack of care and effort by the primary producer or to factors outside his control. A variety of incentive mechanisms for addressing these agency problems have been proposed, analysed and implemented. The basic principal-agent models used in these studies consider incentives, actions and performance for a single period. This paper presents a dynamic analysis of incentive systems for *Salmonella* control in pork production. The paper draws extensively on King, Backus, and van der Gaag (2007), but the reader is encouraged to consult that paper for more details.

We develop a dynamic principal-agent model that allows for explicit consideration of the producer's performance history in controlling *Salmonella*. Using cost estimates and technical parameters based on Dutch data, we use the model to evaluate two dynamic incentive systems for quality assurance. Each system is described by a set of parameters that can take a wide range of possible values, and our analysis identifies optimal parameter values for each system. Both systems include penalties for delivery of hogs with a high *Salmonella* prevalence level and both systems rely on sampling strategies in testing for product quality. In this way they extend previous work by adding consideration of production history. The first system captures the essential features of the system currently implemented in Denmark and includes the Danish system as a special case. The second is a reasonable alternative to the Danish system that uses production history based random testing to economise on testing costs. It includes static systems with and without random testing as special cases. We also assess the impact of ownership structure on overall chain performance, considering slaughter plant ownership by a producer cooperative and by investors who are not pork producers.

2. Model Description

The dynamic principal-agent model developed for this study identifies Nash equilibrium incentive system parameters and associated farm-level *Salmonella* control policies for a two- segment supply chain that includes producers and a slaughter plant. We consider two of many possible incentive system designs, with each design having many possible parameter configurations.

We assume there is a homogeneous group of hog producers, each of whom is treated as an agent in the model. Each producer delivers a fixed number of hogs 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, *QPP*, 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 finite set of *Salmonella* control measure packages, $x_t \in \{x_1, x_2, \ldots, x_m\}$, with an associated cost, $c(x_t)$, that increases with the intensity of the control measures. We only consider reversible control measures that can differ from one month to another. More effective *Salmonella* control packages are more costly. At slaughter, a sample of the producer's hogs may be serologically tested for *Salmonella* prevalence, $prev_t \in \{0, 10, 20, \ldots, 100\}$. The cost of testing per hog, *TC*, may be borne by the producer or by the slaughter plant, depending on the structure of the incentive system.

The probability distribution of prevalence levels is a function of the *Salmonella* control package and is denoted by the discrete probability function $h(prev_t|x_t)$. If hogs are tested, the test results become part of the producer's production history, which is summarised by one element from a finite set of production history indicator levels, $R_t \in \{R_1, R_2, \ldots, R_n\}$. The incentive system in place – defined by a vector of parameters, α – determines how prevalence test results affect the evolution of the production history indicator level, the probability that a producer's hogs will be tested, and penalties for *Salmonella* prevalence levels that exceed thresholds set by the slaughter plant.

Producers are assumed to be risk averse with an infinite planning horizon. Preferences are represented by an additively time-separable constant absolute risk aversion utility function, and the model does not allow for saving. Producers consider the plant's incentive system to be exogenously determined and fixed. Each period, the producer chooses a *Salmonella* control package and realises a net gain from participation in the *Salmonella* control programme 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. 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. The optimal solution 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 programme 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 does not restrict *Salmonella* prevalence.

The manager of the slaughter plant is treated as the principal in this model. He cannot directly observe producers' quality control efforts, but he can influence their behaviour through the design of the compensation/testing system. Specifically, he can choose the structure of the incentive system and the values of parameters in the vector, α, that determine the producer quality premium, testing probabilities, penalties, the incidence of testing costs, and the evolution of production history indicator levels. Because it has a *Salmonella* control programme, the slaughter plant receives an exogenously determined quality premium equivalent to *QPS* per hog from its downstream customers if the plant level prevalence of *Salmonella* in hogs delivered by all producers is less than or equal to an exogenously determined threshold, $PREV^*$. The plant receives no premium when the plant level prevalence in hogs delivered exceeds $PREV^*$. The plant pays 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 that optimises his relevant performance measure, subject to producers' optimal behaviour 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 programme must be greater than or equal to zero. Note that, under the assumption of homogeneous producers, the production history indicator state probability information that is part of the optimal solution for the producer model can be used to determine the distribution of *Salmonella* prevalence for all the hogs delivered to the slaughter plant and the expected value of penalties to be assessed on the slaughter plant by its customers.

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 maximises the plant's expected gain from participation in a *Salmonella* control programme, which is defined as the expected premium received from downstream customers plus expected penalties paid to the plant by producers minus producer quality premiums and *Salmonella* testing costs paid by the plant. Under the COOP structure, the manager maximises 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 maximise net gains from *Salmonella* control for the entire two-segment chain (CHAIN). In this case, the objective is to maximise the plant's expected quality premium minus control and testing costs.

Given the behavioural 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 he chooses under a particular incentive system design and ownership structure, the incentive system parameters and the producer's associated optimal *Salmonella* control policy 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 their optimal solutions.

2.1 Moving Average System

The first of the two compensation/testing systems considered in this analysis – denoted the 'moving average' system – has the structure of the current Danish *Salmonella* control system. Under this system, each producer's hogs are tested each month, with the per-hog cost of testing, *TC*, being borne by either the producer or the slaughter plant. The producer's production history indicator level, $\mathbf{R}_t^M$, is represented by a vector whose two elements are the two most recent prevalence test results. The *Salmonella* prevalence category level for period t, L_t, is based on MA_t, a weighted moving average of the current and two most recent prevalence test results. Note that MA_t is a random variable, since the current prevalence level, $prev_t$, is a random variable, with a probability function, $h(prev_t|x_t)$, that is conditional on the control level. This, in turn, makes L_t a random variable. The prevalence penalty per hog paid by the producer, pen_t, is based on the current *Salmonella* prevalence level.

All producers participating in the plant's *Salmonella* control programme receive the quality premium, *QPP*. This is chosen by the plant as a parameter of the incentive system and is designated α_0^M. A final parameter in this system is $\alpha_6^M \in [0,1]$, the share of the testing cost borne by the producer. The current return per hog under the moving average system, $f^M(x_t, R_t^M)$, is defined by the following expression:

$$f^M(x_t, R_t^M) = \alpha_0^M - c(x_t) - \alpha_6^M TC - pen_t \tag{1}$$

Under this system, the producer's choice of control package, x_t, influences the probability distribution of current returns not only through control costs but also through its impact on the probability of being required to pay a prevalence penalty that is determined by current and prior test results. The current control package also influences future returns through its effect on the production history indicator level. The producer's dynamic programming problem under this system can be formally stated as:

$$\max_{\{x_t\}_{t=0}^{\infty}} E[\sum_{t=0}^{\infty} \delta^t (-e^{-\lambda f^M(x_t, R_t^M)})] \quad \text{subject to} \quad \begin{aligned} R_{1,t+1}^M &= prev_t \\ R_{2,t+1}^M &= R_{1,t}^M \end{aligned} \tag{2}$$

where *E* is the expectations operator, *δ* is the monthly discount factor, and *λ* is the producer's constant level of absolute risk aversion. The fact that the current prevalence test result, $prev_t$, is a random variable known only after the *Salmonella* control package has been chosen introduces uncertainty into this problem.

2.2 Cumulative Experience System

Under the second of the two compensation/testing system designs considered in this analysis – denoted the "cumulative experience" system – the producer's production history indicator level, R_t^C, is a scalar defined as the number of consecutive months (up to a maximum of $\alpha_1^C \in \{0, 1, 2, \ldots, 24\}$)

he has delivered hogs prior to the current period without having a *salmonella* prevalence test level exceeding the plant's *Salmonella* threshold level, *PREV**. The probability that the producer's hogs will be tested on delivery, $t(R_t^C)$, declines as R_t^C increases according to the following relationship:

$$t(R_t^C) = \max((\alpha_2^C e^{-\alpha_3^C R_t^C}), \alpha_4^C) \ , \tag{3}$$

where α_2^C is the maximum probability of being tested, α_3^C is a testing probability reduction parameter, and α_4^C is the minimum probability of being tested. The evolution of the production history indicator is described by the following expression:

$$\mathrm{R}_{t+1}^C = \begin{cases} \min((R_t^C + 1), \alpha_1^C) & \text{if } Test_t Fail(x_t) = 0 \\ 0 & \text{if } Test_t Fail(x_t) = 1 \end{cases} \tag{4}$$

where $Test_t$ is a binary variable equal to one if the producer's hogs are tested in period t and zero otherwise, and $Fail(x_t)$ is a binary variable equal to one if the producer's hogs are tested in period *t* and have a prevalence test result above the allowable threshold and zero otherwise. R_{t+1}^C 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, $s(x_t)$, is calculated for each control package by summing values of the prevalence probability function, $h(prev_t|x_t)$, over prevalence levels less than or equal to the *Salmonella* threshold, *PREV**. This incentive system has three additional parameters: α_0^C is the quality premium per hog paid to producers who participate in the plant's *Salmonella* control program, α_5^C is the size of the penalty per hog for a prevalence test result that exceeds the plant's *Salmonella* threshold level, and $\alpha_6^C \in [0,1]$ is the share of the expected testing cost paid by the producer. The current return per hog under the cumulative reputation system is defined by:

$$f^C(x_t, R_t^C) = \alpha_0^C - c(x_t) - \alpha_5^C Test_t Fail(x_t) - \alpha_6^C t(R_t^C) TC \tag{5}$$

The producer pays his expected testing cost, regardless of whether his hogs are actually tested. As in the moving average system, the producer's choice of a *Salmonella* control package, 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 dynamic programming problem can be formally stated as:

$$\max_{\{x_t\}_{t=0}^{\infty}} E[\sum_{t=0}^{\infty} \delta^t (-e^{-\lambda f^C(x_t, R_t^C)})] \quad \text{subject to} \quad R_{t+1}^C = \begin{cases} \min[(R_t^C + 1), \alpha_1^C] & \text{if } Test_t Fail(x_t) = 0 \\ 0 & \text{if } Test_t Fail(x_t) = 1 \end{cases} \tag{6}$$

where *E, δ* and *λ* are as defined for the moving average system.

The cumulative experience system can provide strong incentives for a producer to use intensive *Salmonella* control measures in order to build a favourable production history. At the same time, a producer's experience under this system is sensitive to uncertainties regarding control measure efficacy and the accuracy of testing.

3. Model Parameters and solution Procedures

Model parameters for this analysis are based on current conditions for hog finishing operations in the Netherlands. Only reversible measures are included in the three control packages considered in this analysis. These three packages all contain basic control measures. 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.

Prevalence probability distributions for the three farm control packages ($h(prev_t|x_t)$ are elicited based on *Salmonella* expert opinions. These prevalence distributions are used to determine elements of the state transition matrices required to solve the producer's dynamic programming problem.

General purpose MATLAB routines developed by Miranda and Fackler (2002) were adapted to solve the producer's stochastic discrete time/discrete state infinite horizon dynamic programming problem for a given set of parameters under each of the two incentive systems. The program uses policy iteration to identify an optimal steady state 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 producer operating under the optimal policy.

In order to solve the slaughter plant manager's problem of selecting an optimal set of incentive parameters, the producer problem was embedded in a grid search program that systematically explored the relevant incentive parameter space. The optimal parameters for the manager problem combined with the optimal producer control policy for those parameters, define a Nash equilibrium, since both the producer and the slaughter plant are responding optimally the other party's choices.

4. Results

Nash equilibrium incentive system parameters and performance measures for the two incentive systems under each of the three ownership structures are calculated using the producer's optimal *Salmonella* control policies and the associated steady state probabilities for each possible production history state. Under the moving average incentive system, Nash equilibrium parameters differ across ownership structures. With the exception of the producer quality premium and the producer share of testing costs, optimal incentive system parameters are remarkably similar across ownership structures under the cumulative experience system. Changes in the producer quality premium and testing cost share simply transfer returns between producers and the slaughter plant. Producers pay testing costs under IOF ownership, while the plant pays all testing costs under COOP and CHAIN ownership. Because there is some uncertainty over testing costs under this 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 magnitude of the optimal producer quality premium exhibits large changes across ownership structures. This premium is a mechanism for shifting gains between producers and the slaughter plant without affecting risk. It is low under IOF ownership and high under COOP ownership.

The expected welfare gains for the cumulative experience system are higher than corresponding gains under the moving average system for each of the three ownership structures, and differences in gains across ownership structures are very small. The preference for the cumulative experience system is due largely to lower testing costs. A random testing regime makes it possible to reduce testing costs without sacrificing product quality. Relative rankings of the two systems are insensitive to changes in key behavioural assumptions and external conditions, though optimal incentive system parameters can be quite sensitive to these changes. Analysis based on this model demonstrates the value of considering performance history when producers make repeated deliveries, and this analysis yields useful insights into the relative performance of two production history-based incentive systems.

References

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Table. Parameters and Performance Measures for Optimal Incentive Systems (λ = 0.10 and dhogd = 50)

Moving Average System				**Cumulative Experience System**			
Parameters	**IOF**	**COOP**	**CHAIN**	**Parameters**	**IOF**	**COOP**	**CHAIN**
α_0^M – Producer quality premium	2.55	4.25	3.40	α_0^C – Producer quality premium	2.00	4.25	3.60
α_1^M – Weight on current test result	0.33	0.40	0.30	α_1^C – Maximum R_t^C	24	24	24
α_2^M –Level 1 upper prevalence bound	15	25	10	α_2^C – Maximum testing probability	0.98	1.00	1.00
α_3^M –Level 2 upper prevalence bound	20	35	45	α_3^C – Testing probability reduction	0.11	0.11	0.11
α_4^M – Level 2 penalty	0.20	1.15	2.20	α_4^C – Minimum testing probability	0.00	0.00	0.00
α_5^M – Level 3 penalty	2.70	10.05	3.40	α_5^C – Producer penalty	4.20	4.15	4.10
α_6^M – Producer share of testing cost	1.00	0.00	0.00	α_6^C – Producer share of testing cost	1.00	0.00	0.00
Performance Measures				**Performance Measures**			
Expected prevalence	15.691	15.88	15.91	Expected prevalence	15.89	15.78	15.78
- producer quality premium	2.550	4.250	3.400	- producer quality premium	2.000	4.250	3.000
- expected control cost	1.759	1.739	1.735	- expected control cost	1.738	1.749	1.749
- expected testing cost	0.100	0.000	0.000	- expected testing cost	0.025	0.000	0.000
- expected penalty to plant	0.602	0.220	1.273	- expected penalty to plant	0.133	0.135	0.133
- expected total cost	2.460	1.959	3.008	- expected total cost	1.896	1.884	1.882
- expected monetary gain	0.090	2.291	0.392	- expected monetary gain	0.104	2.367	1.720
Farmer certainty equivalent of gain	0.000	2.137	0.329	*Farmer certainty equivalent of gain*	0.003	2.267	1.620
- slaughter plant price premium	4.250	4.250	4.250	- slaughter plant price premium	4.250	4.250	4.250
- quality premium paid to producers	2.550	4.250	3.400	- quality premium paid to producers	2.000	4.250	3.600
- expected penalty from producers	0.602	0.220	1.273	- expected penalty from producers	0.133	0.135	0.133
- expected testing cost	0.000	0.100	0.100	- expected testing cost	0.000	0.026	0.026
- expected slaughter penalty	0.095	0.120	0.126	- expected slaughter penalty	0.122	0.107	0.107
Expected monetary slaughter gain	2.206	0.000	1.897	*Expected monetary slaughter gain*	2.261	0.002	0.650
Expected welfare gain for the chain	2.207	2.138	2.226	*Expected welfare gain for the chain*	2.264	2.269	2.269