

# Producer incentives and plant investments for *Salmonella* control in pork supply chains

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## Abstract

This paper presents a unified analysis of dynamic producer incentive systems for *Salmonella* control in primary production and slaughter plant investments in *Salmonella* control measures. We identify optimal incentive system parameters and cost-effective control strategies for achieving various levels of *Salmonella* prevalence. We compare the performance measures of the combined plant-level control and producer incentive system with results obtained under a producer incentive system only. The combined system allocates control effort among producers and the slaughter plant, resulting in 25–83 per cent lower expected total control cost for a wide range of threshold values.

**Keywords:** dynamic programming, supply chain, food quality, principal–agent

**JEL classification:** L14, Q13, Q18

## 1. Introduction

By far the most frequently reported zoonotic diseases in humans are salmonellosis and campylobacteriosis. In 2006, a total of 160,649 cases of salmonellosis were reported in the EU member states (EFSA, 2007). In accordance with regulation (EC) No. 2160/2003 on the control of *Salmonella* and other zoonotic agents in animals and products of animal origin, EU-level targets shall be established for reducing the prevalence of *Salmonella* in pigs and poultry. The Commission will conduct a cost–benefit analysis of any possible targets for reducing *Salmonella* prevalence in slaughter pigs before they are approved (EFSA, 2008). At present, pork supply chains in most European countries have neither a formal control system spanning the entire chain nor payment differentials based on *Salmonella* contamination.

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King, Backus and van der Gaag (2007), henceforth denoted as KBG, described a dynamic principal–agent model for controlling serological *Salmonella* prevalence in herds (King *et al.*, 2007). They explored optimal incentives and farm control actions for achieving a given serological *Salmonella* herd prevalence. Nielsen *et al.* (2005) analysed the cost effectiveness of an existing Danish *Salmonella* control programme, concluding that further on-farm initiatives could not significantly reduce *Salmonella* prevalence in Danish pork. Only an intensified focus on slaughterhouse measures can further reduce the prevalence of *Salmonella* in pork (Alban and Stärk, 2005). Van der Gaag *et al.* (2004) explored the trade-offs in choosing *Salmonella* control interventions implemented in each chain segment.

This paper extends a model developed by KBG to include the evaluation of plant control measures in a two-stage supply chain comprised of a set of identical producers and a slaughter plant. Our extended analysis considers two different food safety performance measures: serological *Salmonella* prevalence in the pig herd and bacteriological *Salmonella* carcass prevalence, which is a more appropriate plant-level measure. The model identifies the best allocation of plant- and farm-level control associated with an exogenously determined prevalence threshold value. Using cost and performance parameters based on data from the Dutch and Danish pork chains, we determine the cost of increasingly stringent prevalence threshold values. This information will be critical for the benefit–cost analysis required to establish EU-level targets for reducing *Salmonella* prevalence.

## **2. *Salmonella* testing procedures and prevalence levels**

Pork can become contaminated with *Salmonella* in different ways and at different points in the supply chain. 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.

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 more accurate 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 minimising or contributing to cross-contamination. *Salmonella* contamination of carcasses after slaughter is caused by bacteria deposited from previously slaughtered *Salmonella*-infected herds or by resident flora in

the slaughterhouse. Slaughter hygiene, including careful removal of the intestinal tract from the carcass, cleaning and disinfection, can reduce cross-contamination. Slaughter line equipment is the most important contamination source for carcasses from both sero-negative and sero-positive herds. Logistic slaughter, or separate slaughter of sero-negative herds, can decrease the *Salmonella* prevalence of pork after slaughter (Swanenburg *et al.*, 2001).

### 3. Model description

The model developed for this study extends that presented in KBG by adding the possibility of plant control measures that reduce bacteriological *Salmonella* prevalence, selection of a serological prevalence threshold by the plant, and a farm control package with no control measures. The model description here draws on the more detailed description presented by KBG.

The model can be viewed as a three-stage static game played by a principal, the manager of a slaughter plant that has a *Salmonella* control programme, and a homogeneous set of hog producers who manage identical operations but act independently. In the first stage of the game, the slaughter plant manager selects one package from a set of three *Salmonella* plant control measure packages,  $\gamma \in \{\gamma_1, \gamma_2, \gamma_3\}$ , with an associated cost,  $cs(\gamma)$ . He also selects the elements of a parameter vector,  $\alpha$ , for a dynamic incentive system that determines producer quality premiums, testing probabilities, serological prevalence thresholds, penalties, and the incidence of testing costs based on producer-specific production history information. He is risk neutral, and his objective is to maximise the expected value of a plant performance measure. In the second stage of the game, each producer selects an optimal policy for making monthly decisions about the choice of one package from a set of four *Salmonella* control measure packages,  $x_t \in \{x_0, x_1, x_2, x_3\}$ , with an associated cost,  $c(x_t)$ . Each producer maximises expected utility over an infinite planning horizon, subject to the incentive system selected by the plant manager – as defined by the parameter vector,  $\alpha$  – and a participation constraint requiring that expected utility be greater than what could be achieved through delivery to a slaughter plant without a *Salmonella* control programme. Since producers are homogeneous and operate independently, the optimal policy for a representative producer is chosen by them. In the third stage of the game, the principal and the agents realise revenues and costs associated with their respective choices over an infinite sequence of months.

The model is solved by backwards recursion. The representative producer problem, which is cast as an infinite horizon dynamic programming problem, is solved repeatedly for a wide range of feasible incentive system parameter values. Results for the representative producer problem are then used to construct aggregate plant-level performance measures that would occur under alternative incentive system parameter and plant-level control measure choices, and the optimal values of  $\alpha$  and  $\gamma$  are determined. The resulting plant-level choices and the representative producer policy associated with the incentive system parameter vector,  $\alpha$ , constitute a Nash equilibrium.

**Table 1.** Allowable parameter values for the slaughter plant optimisation problem

Parameters	Minimum	Maximum	Step size
$\alpha_0$ – producer quality premium (€/hog)	0.50	4.25	0.05
$\alpha_1$ – maximum $R_t$ (production history indicator level)	1	24	1
$\alpha_2$ – maximum testing probability	0.00	1.00	0.01
$\alpha_3$ – testing probability reduction	0.00	0.20	0.01
$\alpha_4$ – minimum testing probability	0.00	0.50	0.10
$\alpha_5$ – producer share of testing cost	0.00	1.00	1.00
$\alpha_6$ – producer penalty (€/hog)	0.00	4.25	0.10
$\alpha_7$ – serological threshold value (%)	0	40	10
$g(\gamma)$ – plant-level <i>Salmonella</i> control	1	3	1

As in KBG, we assume that each producer makes a single delivery of 200 hogs per month to the slaughter plant. Deliveries are evenly distributed over time, with a constant  $dhogd = 50$  producers making deliveries each day. Producers have identical costs for inputs not related to *Salmonella* control,  $PC = \text{€}90.90$  per hog, and receive an identical base price,  $PH = \text{€}115.00$ , per hog delivered. At slaughter, a sample of the producer’s hogs may be serologically tested for *Salmonella* prevalence. The percentage of positively tested blood samples for 10 of the 200 hogs delivered,  $prev_t \in \{0, 10, 20, \dots, 100\}$ , has a discrete probability distribution,  $h(prev_t|x_t)$ , which is a function of the current *Salmonella* control package.<sup>1</sup>

Of the two incentive system families described in KBG, we use the more efficient cumulative experience system. The incentive system parameter vector has eight elements,  $\alpha_0$  to  $\alpha_7$ . The first seven of these directly correspond with parameters in the KBG analysis. The eighth,  $\alpha_7$ , is the serological threshold level set by the plant. In KBG, this was fixed at 20 per cent, but here it is chosen by the plant. Parameter definitions and allowable values are presented in Table 1.

For this incentive system, the production history indicator level,  $R_t$ , is the number of consecutive months the producer has delivered hogs prior to the current period without having a *Salmonella* prevalence test level exceeding the serological threshold level set by the plant. The probability that hogs will be tested on delivery,  $t(R_t)$ , declines as  $R_t$  increases according to the following relationship:

$$t(R_t) = \max((\alpha_2 e^{-\alpha_3 R_t}), \alpha_4). \tag{1}$$

The evolution of the production history indicator is described by

$$R_{t+1} = \begin{cases} \min((R_{t+1}), \alpha_1) & \text{if Test}_t\text{Fail}(x_t) = 0 \\ 0 & \text{if Test}_t\text{Fail}(x_t) = 1 \end{cases}, \tag{2}$$

<sup>1</sup> We assume the prevalence of *Salmonella* at  $t$  is independent of prevalence at  $t - 1$ .

where  $\text{Test}_t$  is a binary variable equal to 1 if hogs are tested in period  $t$  and 0 otherwise, and  $\text{Fail}(x_t)$  is a binary variable equal to 1 if hogs are tested in period  $t$  and have a prevalence test result above the allowable threshold and 0 otherwise. We assume that the producer pays the expected testing cost, regardless of whether his hogs are actually tested.

The producer's single period return from participation in the *Salmonella* control programme,  $f(x_t, R_t)$ , is defined by

$$f(x_t, R_t) = \alpha_0 - c(x_t) - \alpha_5 t(R_t) \text{TC} - \alpha_6 \text{Test}_t \text{Fail}(x_t), \tag{3}$$

where  $\text{TC} = \text{€}0.10$  is the testing cost per hog. 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 have an additively time-separable constant absolute risk aversion utility function with an infinite planning horizon. From the producer's perspective, the plant's investments in *Salmonella* control measures and the incentive system parameters are exogenously determined and fixed. The producer's dynamic programming problem can be formally stated as:

$$\max_{\{x_t\}_{t=0}^{\infty}} E \left[ \sum_{t=0}^{\infty} \delta^t (-e^{-\lambda f(x_t, R_t)}) \right], \tag{4}$$

subject to

$$R_{t+1} = \begin{cases} \min((R_t + 1), \alpha_1) & \text{if } \text{Test}_t \text{Fail}(x_t) = 0 \\ 0 & \text{if } \text{Test}_t \text{Fail}(x_t) = 1 \end{cases}, \tag{5}$$

$$\frac{\ln(-E[\sum_{t=0}^{\infty} \delta^t (-e^{-\lambda f(x_t, R_t)})])}{(-\lambda)} \geq 0$$

where  $E$  is the expectations operator,  $\delta = 0.9967$  is a monthly discount factor equivalent to a 4 per cent annual rate and  $\lambda = 0.10$  is the producer's constant level of absolute risk aversion. The first constraint is the state equation. The second is a participation constraint stipulating that the certainty equivalent gain from participation in the *Salmonella* control programme must be non-negative.

The slaughter plant manager cannot observe producers' quality control efforts, but he can influence their behaviour through the choice of parameter values for the compensation/testing system. He can also influence plant performance through the choice of a plant-level *Salmonella* control measure package,  $\gamma \in \{\gamma_1, \gamma_2, \gamma_3\}$ . The plant receives an exogenously determined quality premium equivalent to  $\text{QPS} = \text{€}4.25$  per hog from its downstream customers if the mean plant-level bacteriological prevalence of *Salmonella* for hog carcasses produced by the plant on a given day,  $\text{pprev}$ , does not exceed an exogenously determined bacteriological threshold,  $\text{BPREV}^*$ . In

this analysis, BPREV\* is allowed to vary from a high of 5.0 per cent to a low of 0.5 per cent.

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 farm-level control measures used by producers. Therefore, the bacteriological prevalence measure for a group of hogs delivered, bprev, is a random variable with a probability function,  $m(\text{bprev}|\text{prev}_t, \gamma)$ , that is conditional on the producer's serological prevalence level and the plant-level *Salmonella* control package. Procedures for characterising the probability distributions of pprev and bprev are a direct extension of those presented in KBG, with modifications that allow for variation in plant-level control packages (available from the authors on request).

The plant receives no premium when the plant-level bacteriological prevalence exceeds BPREV\*. The expected plant premium is the product of QPS and the probability the plant-level prevalence will be less than or equal to BPREV\*. The plant pays its own *Salmonella* control costs, quality premiums to producers and *Salmonella* testing costs not paid by producers. The plant also receives penalties assessed to producers. Otherwise, the plant's processing margin per hog is fixed.

The manager's performance measure depends on the slaughter plant's ownership structure. KBG considered ownership by non-producer investors and by a producer cooperative, as well as an overall efficiency benchmark in which the manager chooses incentive system parameters to maximise net gains from *Salmonella* control for the entire two-segment chain (CHAIN). In this analysis, we consider only the CHAIN structure, for which the objective is to maximise the plant's expected quality premium minus control and testing costs. Under the other two ownership structures, returns are shifted between the plant and the producers by varying the producer quality premium,  $\alpha_0$ .

Four *Salmonella* control packages are available to producers. Packages 1, 2, and 3 are identical to those defined in KBG. Their respective costs are estimated to be €0.72, €1.14, and €2.92 per hog. Farm control package 0, with no measures and zero costs, is added to enable analysis of higher serological prevalence threshold levels than the 20 per cent serological prevalence threshold considered by KBG. Farm-level serological prevalence probability distributions for the four control packages, i.e.  $h(\text{prev}_t|x_t)$ , are shown in Table 2.<sup>2</sup>

Three plant-level *Salmonella* control packages are considered in this study. Plant control package 1 contains strict hygienic practices at slaughter and processing (cleaning and disinfection) induced 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 to reduce cross-contamination in the slaughterhouse.

<sup>2</sup> KBG did not report the prevalence distribution of control package 0, but developed it together with control packages 1, 2, and 3.

**Table 2.** Expected serological prevalence for *Salmonella* farm control packages

Farm control package	0	1	2	3
Serological prevalence level (%)	Probability			
0	0.01	0.03	0.18	0.72
10	0.02	0.06	0.24	0.17
20	0.04	0.09	0.22	0.06
30	0.07	0.12	0.15	0.03
40	0.09	0.18	0.10	0.02
50	0.15	0.21	0.06	0.00
60	0.22	0.15	0.03	0.00
70	0.17	0.08	0.01	0.00
80	0.11	0.05	0.01	0.00
90	0.08	0.02	0.00	0.00
100	0.04	0.01	0.00	0.00
Expected prevalence level (%)	59.3	45.1	21.6	4.6
Variance of prevalence level	460.41	442.99	311.44	78.84

Logistic slaughter requires testing all pig herds and slaughtering positively tested herds either at the end of the day or at another location.

Cost estimates for the three plant-level control packages are based on figures provided by experts from the VION food company. The cost of monitoring the plant manager’s effort to reduce the average bacteriological prevalence is included in all three plant control packages and so can be normalised to 0. The costs of plant control packages 2 and 3 are estimated to be €0.10 and €0.40 per hog.<sup>3</sup>

Probability distributions describing the relation between serological prevalence and bacteriological prevalence for plant control package 1 are shown in Table 3. 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 study in three Danish abattoirs in which the relation between herd serology and the prevalence of *Salmonella* bacteria measured at the carcass surface is described by a 1.4 percentage point increase in the probability of *Salmonella*-positive carcasses with each 10 percentage point increase in herd serological prevalence (Sorensen *et al.*, 2004). The dispersion of the probability distribution increases when serological prevalence levels increase. It was estimated that monitoring the plant manager’s effort to reduce *Salmonella* results in a 50 per cent reduction of the bacteriological prevalence probabilities in the Danish study (Urlings, 2007). Acidification of slaughter equipment in cleaning and disinfecting procedures

<sup>3</sup> The costs of logistic slaughter of *Salmonella*-free herds are estimated for the Dutch VION food company. 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 per cent increase in transportation costs.

**Table 3.** Bacteriological prevalence probabilities for plant control package  $\gamma_1$

Bacteriological prevalence level	0	10	20	30	40	50	60	70	80	90	100
Serological prevalence level											
0	0.9500	0.0500	0	0	0	0	0	0	0	0	0
10	0.9400	0.0500	0.0100	0	0	0	0	0	0	0	0
20	0.9270	0.0530	0.0150	0.0050	0	0	0	0	0	0	0
30	0.8978	0.0747	0.0200	0.0075	0	0	0	0	0	0	0
40	0.8679	0.0921	0.0250	0.0100	0.0050	0	0	0	0	0	0
50	0.8186	0.1289	0.0300	0.0125	0.0075	0.0025	0	0	0	0	0
60	0.7840	0.1350	0.0350	0.0225	0.0150	0.0075	0.0011	0	0	0	0
70	0.7326	0.1400	0.0600	0.0350	0.0150	0.0075	0.0050	0.0050	0	0	0
80	0.6660	0.1350	0.0950	0.0500	0.0250	0.0150	0.0100	0.0040	0	0	0
90	0.6300	0.1050	0.0900	0.0650	0.0500	0.0300	0.0150	0.0100	0.0050	0	0
100	0.5817	0.0800	0.0800	0.0750	0.0600	0.0500	0.0350	0.0250	0.0133	0	0

under plant control package 2 results in an additional 50 per cent reduction of the probability matrix values, except for the zero bacteriological prevalence level, compared with plant control package 1. This results in higher probabilities for a bacteriological prevalence level of 0 per cent. Adding logistic slaughter of sero-negative pig herds as a control measure under control package 3 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. The probability distribution for package 1 has most of its probability mass at a bacteriological prevalence level of 0 per cent. With higher serological herd prevalence levels, the probability distribution is more dispersed with non-zero probabilities up to bacteriological prevalence levels of 80 per cent.

#### 4. Results

The plant manager's problem of selecting an optimal plant control package and a set of incentive system parameters was solved by embedding the producer problem in a grid search programme that systematically explored the relevant plant control package and incentive parameter space, as defined in Table 1. Nash equilibrium incentive system parameters and key performance measures for the model presented in this paper, henceforth denoted as BK, and for KBG are presented in Table 4. KBG did not calculate bacteriological threshold levels, but the procedures developed in this paper are used to calculate them here. Optimal use of control packages, incentives, and key performance measures are presented for bacteriological threshold values  $\{0.5, 1.0, 1.5, \dots, 5.0\}$  under BK and serological threshold values  $\{40, 35, 30, \dots, 15\}$  under KBG.

Looking first at the results for BK, all expected performance measures are calculated using the plant's optimal *Salmonella* control policy, the producers' optimal *Salmonella* control policies, and the associated steady-state probabilities for each possible production history state. In all cases with non-zero farm control cost, the optimal production history indicator level is 24. This means that the dynamic incentive system performs better than a static incentive system because it economises on testing costs more effectively. The producer always pays all testing costs. Because there is some uncertainty in testing costs under this incentive system, shifting this risk to the producer makes it easier to induce the use of less risky, more effective farm control packages.

The optimal serological threshold takes the highest allowable value for plant threshold ranging from 5.0 to 1.0 per cent, and the lowest allowable value when the plant threshold is 0.5 per cent. This indicates that it is effective to adopt plant control measures before farm control measures. To keep the expected slaughter penalty down, control measures are used to reduce the expected bacteriological prevalence to the range of one to two-thirds of the threshold level.

Starting at a plant threshold of 3.5 per cent, we observe a combination of plant- and farm-level control. The increasing producer quality premium,

**Table 4.** Optimal incentive system parameters and performance measures

	Plant control and producer incentive system (BK)										Producer incentive system (KBG)					
Threshold parameter																
Bacteriological threshold value	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5						
Serological threshold value											40	35	30	25	20	15
Optimal incentive parameter values																
$\alpha_0$ – Producer quality premium	0.20	0.20	0.80	1.1	1.1	1.30	1.35	1.55	1.55	4.05	2.7	3.55	3.55	3.85	3.60	3.95
$\alpha_1$ – Production history indicator level	1–24	1–24	1–24	24	24	24	24	24	24	24	24	24	24	24	24	24
$\alpha_2$ – Maximum testing probability	0.00	0.00	0.00	0.43	0.69	0.71	0.71	0.8	0.8	0.98	0.66	0.72	0.80	1.00	1.00	1.00
$\alpha_3$ – Testing probability reduction	0.00	0.00	0.00	0.11	0.11	0.08	0.04	0.06	0.06	0.02	0.08	0.08	0.05	0.15	0.11	0.10
$\alpha_4$ – Minimum testing probability	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\alpha_5$ – Producer share of testing cost	0–1	0–1	0–1	1	1	1	1	1	1	1	1	1	1	1	1	1
$\alpha_6$ – Producer penalty	0.00	0.00	0.00	2.70	1.80	2.00	2.20	4.00	4.00	3.90	2.10	2.00	2.00	3.20	4.10	2.80
$\alpha_7$ – Serological threshold value	40	40	40	40	40	40	40	40	40	10						

*Salmonella* performance measures (%)

Expected bacteriological prevalence	2.33	2.33	2.33	1.86	1.50	1.08	0.81	0.64	0.64	0.13	2.34	1.91	1.50	1.21	1.05	0.84
Expected serological prevalence	59.3	59.3	59.3	48.85	40.77	31.43	25.52	21.6	21.6	4.6	33.51	28.7	23.55	19.92	15.78	11.01
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
Expected farm control cost	0.000	0.000	0.000	0.316	0.561	0.843	1.021	1.140	1.140	2.920	0.779	0.927	1.081	1.316	1.749	2.252
Expected slaughter plant cost	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.400						
Expected serological testing cost	0.000	0.000	0.000	0.012	0.021	0.035	0.050	0.033	0.033	0.082	0.030	0.039	0.059	0.014	0.026	0.048
Expected slaughter penalty	0.045	0.129	0.317	0.226	0.194	0.101	0.090	0.147	0.944	0.123	0.033	0.032	0.023	0.073	0.107	0.058
Expected control cost for the chain	0.145	0.229	0.417	0.654	0.876	1.079	1.261	1.420	2.217	3.525	0.842	0.998	1.163	1.403	1.882	2.358
Expected monetary gain for the chain	4.106	4.021	3.833	3.597	3.375	3.171	2.989	2.829	2.033	0.725	3.408	3.252	3.087	2.847	2.368	1.892
Expected welfare gain for the chain	4.072	3.988	3.780	3.535	3.318	3.116	2.936	2.764	1.967	0.623	3.350	3.191	3.028	2.779	2.267	1.804

likelihood of testing, and producer penalty provide an adequate incentive for producers to use some control measures. Testing frequencies and/or producer penalties increase as bacteriological prevalence threshold levels decrease in order to induce more stringent farm control packages. High producer quality premiums allow for costly farm control measures when the bacteriological threshold value is low. Finally, at the lowest bacteriological threshold value, the challenge of reliably being below this threshold induces the highest possible levels of control for both the plant and producers. The plant manager adopts plant control package 3 and chooses incentive system parameters that induce producers to adopt farm control package 3. Adopting plant control package 3, with a probability of 100 per cent for a zero bacteriological prevalence when the seroprevalence is 0, calls for adopting farm control package 3, with a high probability of a zero seroprevalence.

The right-hand portion of Table 4 presents comparable results for the KBG model, which does not include plant-level controls. KBG results are presented for producer serological threshold levels ranging from 40 down to 15. Even at a serological threshold of 40 per cent, farmers are induced to use farm control measures under KBG. Testing frequencies and the testing probability reduction parameter values are relatively high to induce farmers' use of costly control packages. Producers' quality premiums are also high to enable farmers to adopt these costly control packages.

The performance information in Table 4 can also be used to identify the most cost-effective system for a wide range of threshold values. Expected plant-level bacteriological prevalence levels ranging between 2.34 and 0.84 per cent can be achieved under the KBG incentive system and no plant-level control measures. This is roughly the same as the range of prevalence levels achieved in the new analysis for plant-level bacteriological thresholds ranging from 5.0 per cent down to 2.0 per cent. The expected total control cost<sup>4</sup> of achieving comparable expected bacteriological threshold levels is much lower under the combined plant-level control and incentive system introduced here. For example, when the bacteriological threshold is 3.0 per cent, the expected bacteriological prevalence level is 1.50 per cent, and the expected control cost for the chain is €0.876. Under the KBG system, an expected bacteriological prevalence of 1.50 is achieved when the farm-level serological threshold is set at 30 per cent. In this case, the expected control cost for the chain is €1.143. Similar comparisons can be made between results for plant-level bacteriological thresholds of 5.0, 3.5, 2.5, and 2.0 and results from the KBG model for corresponding farm-level serological thresholds of 40, 35, 20, and 15. Expected total control costs are 25–83 per cent lower under the combined plant-level control and incentive system introduced here.

The extended incentive system can also realise a much lower expected bacteriological prevalence level, 0.13 per cent for a plant threshold value of 0.5, instead of 0.84 per cent for a serological threshold value of 15. Under both

4 The sum of farm and plant control costs, testing costs, and expected slaughter penalty.

systems, further lowering the threshold value increases the slaughter penalty but does not lower the expected *Salmonella* prevalence.

We investigated the effects of decreases in the costs of serological tests and in the plant quality premium, and an increase and decrease in the representative producer's level of absolute risk aversion. Values of the expected welfare gain for the chain, defined as the sum of the farmer certainty equivalent of gain and the monetary gain for the slaughter plant, remain very similar when the costs of serological tests and the producer's level of absolute risk aversion change. Except for a bacteriological threshold value of 0.5 per cent and a serological threshold value of 15 per cent, the expected welfare gain for the chain decreases by €1.00 when the plant quality premium decreases by €1.00. For a serological threshold of 15 per cent, a lower plant quality premium only allows for less costly farm control measures, resulting in a strong increase in the slaughter plant penalty, and a €1.474 decline in welfare gain for the chain under KBG. For a plant threshold of 0.5 per cent, there is no feasible solution under the extended incentive system when the plant premium falls by €1.00. The extended incentive system can still realise a lower expected bacteriological prevalence level, 0.64 per cent for a plant threshold value of 1.0, instead of 0.93 per cent for a serological threshold value of 15. Changes in these behavioural assumptions and external conditions do not change the dominance of the combined system over KBG.

The plant threshold is determined exogenously in this new analysis. In practice, it could be set either by government or by retailers. Decisions about lowering this threshold should reflect both the value of benefits to consumers associated with lower bacteriological prevalence and the costs incurred by the supply chain to achieve a lower bacteriological prevalence. We are unable to assess the value of benefits to consumers, but our model does provide information on the costs of bacteriological prevalence reduction. When the plant threshold decreases from 5.0 to 2.5 per cent, the expected bacteriological *Salmonella* prevalence decreases by 54 per cent, while expected overall welfare gains for the chain decrease by only 23 per cent. Further reductions are much more costly. Lowering the plant threshold another 2 percentage points, to 0.5 per cent, results in a further 88 per cent decline in expected bacteriological *Salmonella* prevalence but also eliminates 80 per cent of the remaining expected overall welfare gain for the chain. This suggests that setting plant bacteriological thresholds is likely to be a critical issue in future policy debates on EU-wide targets for the reduction of *Salmonella*.

Finally, our analysis assumes that participants in the supply chain receive at least some reward for improved *Salmonella* control. This is reflected in the positive expected welfare gain for the chain in the last row of Table 4, which implies that combined control and risk-bearing costs for farmers and the slaughter plant are less than the €4.25 slaughter plant premium. In a highly competitive environment, however, there could be pressure to shift some or all of this welfare gain to retailers and consumers by lowering the slaughter plant premium. To investigate this possibility, we systematically varied the slaughter plant premium to determine a chain-wide break-even

**Table 5.** Break-even analysis of optimal incentive system parameters and performance measures

Bacteriological threshold value	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5
Minimum slaughter plant price premium QPS (€/hog) <sup>a</sup>	0.180	0.270	0.452	0.709	0.933	1.137	1.322	1.488	2.284	3.630
Optimal incentive parameter values										
$\alpha_0$ – producer quality premium	0.04	0.04	0.04	0.43	0.72	1.00	1.26	1.38	1.38	3.46
$\alpha_1$ – production history indicator level	1–24	1–24	1–24	24	24	24	24	24	24	24
$\alpha_2$ – maximum testing probability	0.00	0.00	0.00	0.54	0.70	0.87	1.00	0.93	0.92	1.00
$\alpha_3$ – testing probability reduction	0.00	0.00	0.00	0.13	0.11	0.09	0.06	0.07	0.07	0.02
$\alpha_4$ – minimum testing probability	0	0	0	0	0	0	0	0	0	0
$\alpha_5$ – producer share of testing cost	0–1	0–1	0–1	1	1	1	1	1	1	1
$\alpha_6$ – producer penalty	0.00	0.00	0.00	2.20	1.76	1.60	1.60	3.85	3.91	3.85
$\alpha_7$ – serological threshold value	40	40	40	40	40	40	40	40	40	10
<i>Salmonella</i> performance measures (%)										
Expected bacteriological prevalence	2.33	2.33	2.33	1.88	1.49	1.12	0.82	0.64	0.64	0.13
Expected serological prevalence	59.3	59.3	59.3	49.13	40.57	32.39	25.57	21.6	21.6	4.6
Overall chain gain (€/hog)										
Slaughter plant price premium	0.180	0.270	0.452	0.709	0.933	1.137	1.322	1.488	2.284	3.630
Expected farm control cost	0.000	0.000	0.000	0.308	0.566	0.814	1.020	1.140	1.140	2.920
Expected slaughter plant cost	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.400
Expected serological testing cost	0.000	0.000	0.000	0.010	0.021	0.038	0.062	0.034	0.034	0.084
Expected slaughter penalty	0.045	0.129	0.317	0.234	0.187	0.131	0.091	0.147	0.944	0.123
Expected control cost for the chain	0.145	0.229	0.417	0.652	0.874	1.083	1.273	1.421	2.218	3.527
Expected monetary gain for the chain	0.036	0.021	0.035	0.057	0.058	0.054	0.049	0.067	0.067	0.103
Expected welfare gain for the chain	0.002	0.008	0.002	0.003	0.009	0.000	0.000	0.003	0.002	0.001

<sup>a</sup>Minimum slaughter plant premium required to induce *Salmonella* control measures for given bacteriological threshold levels.

level for each bacteriological threshold value. In doing this, we identified the minimum slaughter plant premium required to induce the two-segment supply chain to undertake *Salmonella* control actions given a specific bacteriological threshold value.

Results of this break-even analysis are presented in Table 5. As expected, the minimum slaughter plant premium required to induce *Salmonella* control measures declines consistently as the bacteriological threshold increases. Reducing the slaughter plant premium to this break-even level requires higher maximum testing probabilities and downward adjustments in the producer quality premium and producer penalty parameters of the incentive system, but otherwise there are only minor changes from the incentive system parameter reported in Table 4. Expected bacteriological and serological prevalence levels change only slightly, if at all. Therefore, shifting some or all of the rewards for *Salmonella* control from producers and slaughter plants to consumers has little impact on the food safety performance of the supply chain.

## 5. Concluding comments

This paper presents a unified analysis of dynamic producer incentive systems for *Salmonella* control in primary production and slaughter plant investments in *Salmonella* control measures. The analysis clearly indicates the value of including plant control strategies to control *Salmonella*. It also demonstrates the trade-offs between prevalence reduction and related costs. The results demonstrate the power of the cumulative experience incentive system, which induces appropriate farm-level control actions while minimising testing costs, and show that the optimal incentive system parameters and the overall performance measures can vary considerably with the bacteriological threshold level.

Finally, as noted in the discussion of results, valuation of the public health benefits associated with reductions in bacteriological prevalence is outside the scope of this study. Ultimately, the appropriate levels for the bacteriological threshold and slaughter plant premium set by a government agency or by downstream customers can only be determined by balancing the cost estimates provided by this study against those benefits.

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