Impact of testing accuracy on incentive mechanisms: optimal control actions for *Mycobacterium avium* in the pork supply chain

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Abstract

Impact of diagnostic testing accuracy on optimal incentive parameter values to induce food safety control measures was determined. Agency theory was applied to *Mycobacterium avium* in pigs. Economic consequences of sensitivity and specificity combined with penalties for increased risk deliveries and food safety failure costs were analysed with a principal agent model. Results showed that high sensitivity and low specificity increase control measure use. More intense control packages could lead to increased type-II-errors. In case of full traceability failure costs in stead of penalty steer producer behaviour. Sensitivity, specificity, penalty, and failure costs are relevant in optimizing incentives to induce control measures.

Key words: testing accuracy, food safety incentives, *Mycobacterium avium*

1. Introduction

Food safety legislation world wide increasingly shifts food safety responsibility and associated financial risks towards individual companies. For companies, insufficient private control of food safety hazards can lead to costly product recalls, to damaged relationships between supplier and customer with subsequent trade implications, and to liability costs. To mitigate these risks food safety control becomes increasingly important. Food producing companies in the EU use quality control systems based on Hazard Analysis of Critical Control Points (HACCP), as laid down in Regulation EU/178/2002 (General Food Law). HACCP is used to control specific food safety hazards in the company. If, however, control of specific hazards is located in the production process of suppliers, buyers have to manage food safety risks through control of critical food safety attributes of the raw materials. To assure absence of non-visual hazards, such as microbiological and chemical contamination, raw material control includes verification of critical food safety attributes with diagnostic tests. Diagnostic tests are part of a so called food safety control system that includes all actions of the company to control food safety. To induce suppliers to improve raw material safety, control systems can include financial incentive mechanisms as bonuses on products classified without increased risk (Hueth and Ligon, 2002), penalties on products classified with increased risk (King et al., 2007), and failure costs as recall costs, reputation damage costs, and liability costs (Pouliot and Sumner, 2007). Whether failure costs are attributable to a buyer or supplier depends on the extent to which ex post traceability is possible from no traceability, via partial traceability to a buyer, to full traceability to all individual suppliers (Hobbs, 2004).

Financial incentive mechanisms use the results of diagnostic tests to classify raw materials in levels of food safety risk. Classification depends on the sampling inspection policy (sample size, acceptance number) and on the accuracy of the diagnostic test. Test accuracy is defined by sensitivity and specificity. Sensitivity is probability of correctly qualifying a product with increased risk. Specificity is probability of correctly qualifying a product without increased risk. Starbird (2005) has shown that the settings of the sampling inspection parameters can influence supplier incentives for use of improved food safety technologies. Furthermore, test accuracy can be used in the design of contracts that segregate low and high quality producers (Starbird, 2007). But, can improved accuracy of a new test influence supplier control actions through an incentive mechanism? This paper aims to analyze how testing accuracy influences optimal parameter values of an incentive system that induces suppliers to use food safety control actions.

A new test for detection of *Mycobacterium avium* (*Ma*) at slaughter is currently being developed to further decrease the number of false negative and false positive diagnosis of *Ma* infections. Traditional meat inspection procedures in the EU include incision and visual inspection of sub-maxillary and mesenteric lymph nodes of all pigs at slaughter for presence of granulomatous lesions caused by classical tuberculosis and chronic *Ma* infections. Infection of pigs at later age can result in a too short period between infection and slaughter to develop these specific lesions (Wisselink et al., 2006), and other pathogens as *Rhodococcus Equi* can cause these specific lesions (Komijn et al., 2007).

Human *Ma* infections cause disseminated disease in AIDS patients (Falkinham 3rd, 1996), lymph node disease in children (Haverkamp et al., 2004), lung disease in middle aged and elderly people (Dailloux et al., 2006). Humans and pigs share similar strains of *Ma*, which suggests that infected pork could be a source of human infections or that both man and pig get infected by a common source (Tirkkonen et al., 2007). Critical control points for *Ma* are located at farm level, where infection of pork is initiated. To reduce the risks of *Ma* contamination in its products, a slaughterhouse can dispose of the increased risk parts of pigs infected with *Ma*, and it can use preventive actions through inducing *Ma* control at farm level.

To analyze how test accuracy influences supplier incentives to take control measures we modeled a possible future control system for *Ma*. The model is based on the operational system used by a large pig slaughter company in the Netherlands. This system is based on risk assessment at individual herd level and uses a serodiagnostic test as suggested by Ellerbroek (2007). Serodiagnostic tests determine whether *Ma* antibodies are present in the blood. Bacteriological tests determine whether *Ma* bacteria are present in a tissue sample from a carcass. Serologically infected pigs do not have to be bacteriologically infected. Serological prevalence levels will normally be higher than bacteriological prevalence levels. We assumed that serological positive pigs can result in bacteriological contamination of meat and that contaminated meat can cause food safety problems. Although the serodiagnostic test is currently under development and not yet validated, expert knowledge about the accuracy and serological infection levels was available. In the model the blood of specific number of pigs of each delivery was analysed at slaughter. The control system used results from current and several previous deliveries to determine a producer's *Ma* risk level. The *Ma* risk level determined the values of incentive parameters applicable to the producer. Penalties on deliveries classified with increased risk and food safety failure costs were included in the system to assess impact of testing accuracy on producer incentives to control *Ma* infections.

2. Materials and method

A dynamic principal agent model of a slaughterhouse and its supplying producers has been developed. The model deals with asymmetric information between the slaughterhouse manager and producers, because the slaughterhouse manager cannot observe the production process of each producer. Under insufficient control producers might be tempted to take less *Ma* control actions than slaughterhouses require. The model is dynamic, because the incentive system includes test results from several successive deliveries. The model can be viewed as a two-stage static game with the slaughterhouse as the principal and the producer as the agent.

To solve the slaughterhouse's decision problem of selecting an optimal penalty we used the method proposed by King et al. (2007). The producer's dynamic optimization problem of selecting optimal *Ma* control measures was embedded in a grid search program systematically exploring the parameter space of sensitivity, specificity, and penalty. The producer's dynamic optimization problem was defined as a Markov chain with infinite horizon. States were discrete, because each state was a combination of producer *Ma* risk levels. The program used policy iteration to identify an optimal steady-state control package for each possible risk level history. A steady state probability matrix existed, because all states were recurrent, aperiodic, and communicated with each other (Winston, 1991). This matrix was used along with the optimal policy to calculate expected *Ma* prevalence, producer costs, slaughterhouse costs, chain costs, and type-II-error. MATLAB routines developed by Miranda and Fackler (2002) were used to solve the producer's problem for a given set of sensitivity, specificity, and penalty.

2.1 General outline of the model

Figure 1 gives the general outline of the model. In stage 1, the producer model, a dynamic optimization model was used to determine *Ma* control measures that minimize producer costs for each combination of sensitivity, specificity and penalty. Other input parameters in the producer model included the sampling system, traceability, failure and control package costs, and control package effectiveness. Output included optimal control packages, *Ma* prevalence levels, and type-II-errors. In stage 2, the slaughterhouse model, a grid search was used over sensitivity, specificity, and penalty parameter values to determine the optimal penalty for the slaughterhouse. Input and output from the producer model was used as input in the slaughterhouse model. Input was complemented with additional processing costs and testing costs. Output included optimal penalty, optimal *Ma* control packages, related *Ma* prevalence and type-II-errors, producer costs, slaughterhouse costs, and chain costs. Chain costs were sum of producer costs and slaughterhouse costs.

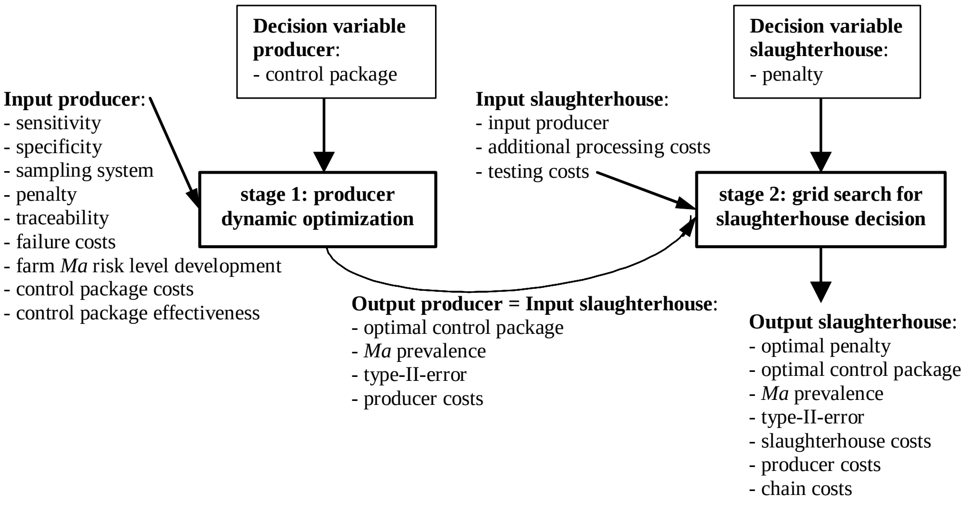

Figure 1: General outline of the model

2.2 Model specification

The producer's decision problem in (1) is to choose a *Ma* control package, a specific combination of *Ma* control measures, in each period t that minimizes expected discounted costs over an infinite horizon. This results in steady state probabilities $(cp_1^*,...,cp_k^*)$ of *Ma* control package cp_i being optimal for producers. In each period t producers incur penalty costs *pen* on pigs in a delivery classified with increased risk, control package costs ccp_i, and part α of expected failure costs *fc*. The penalty depends on the probability p_i^s that a delivery is classified without increased risk Failure costs depend on the probability p_i^{is} that a delivery is incorrectly classified without increased risk or type-II-error.

$$(cp_1^*,...,cp_k^*) = \underset{cp_{1,t},...,cp_{k,t}}{\operatorname{argmin}}[E\sum_{t=0}^{\infty}\{\delta^t\sum_{i=1}^{k}(N\cdot((1-p_i^s)\cdot pen+ccp_i)+\alpha\cdot p_i^{is}\cdot fc)\cdot cp_{i,t}\}] \tag{1}$$

where:

α = fraction of failure costs *fc* slaughterhouse passes on to the producer;
ccp_i = control package costs in euro per pig;
$cp_{i,t}$ = control package *i* in period *t*;
cp_i^* = steady state probability of control package *i* being optimal for the producer;
δ = monthly discount factor;
E = expectations parameter;
fc = food safety failure costs in euro per delivery;
i = index for *Ma* control packages;
k = number of *Ma* control packages;
N = number of pigs in a delivery;
p_i^s = probability that a delivery of producer *i* is classified without increased risk;
p_i^{is} = probability that a delivery of producer *i* is incorrectly classified without increased risk or type-II-error;
pen = penalty in euro per pig in a delivery classified with increased risk;
t = index for period.

General relationships for the evolution of producer *Ma* risk level RL_t and related aspects are described in (2a), (2b) and (2c). Specific parameter settings used in the model are given in (6a), (6b) and 6(c). Evolution of *Ma* risk level depends on *Ma* risk levels in $\hat{t}$ previous periods and number of pigs in the sample classified with increased risk in the current delivery TR_t (2a). Sample size (2b) and penalties (2c) depend on the *Ma* risk level in period *t*.

$$RL_{t+1} = f_1(RL_t,...,RL_{t-\hat{t}},TR_t) \quad \hat{t}\in\{0,1,2,...\} \qquad \forall t \tag{2a}$$

$$n = f_2(RL_t) \qquad \forall t \tag{2b}$$

$$pen = f_3(RL_t) \qquad \forall t \tag{2c}$$

where:

f_1 = function that gives farm *Ma* risk level development;
f_2 = function that relates sample size to farm *Ma* risk level;
f_3 = function that relates penalty to farm *Ma* risk level;
n = number of pigs in a sample;
RL_t = farm *Ma* risk level in period *t*;
$\hat{t}$ = index for number of previous periods considered to determine a farm's *Ma* risk level;
TR_t = *Ma* test result in period *t*.

The relationship between each control package $cp_{i,t}$ and *Ma* prevalence distribution in a herd is given in (3a), (3b), and (3c). Producers choose one control package $cp_{i,t}$ in each period *t* (3a), where $cp_{i,t}$ is an integer variable (3b). The probability q_i that a random uncontrolled risk factor is contaminated with *Ma* raises the infection probability above a background infection level, which is a generally present *Ma* prevalence level that can not be controlled with control measures. It is assumed to equal the average of the expected prevalence probability distribution $\hat{h}_k(m)$ of the most intense control package cp_k, with m the prevalence level. Assuming that control packages in period t are independent of control packages in previous periods, that control packages have a direct impact when implemented, and that contamination probabilities of risk factors are independent, expected prevalence distribution $\hat{h}_i(m)$ is given in (3c).

$$\sum_{i=1}^{k} cp_{i,t} = 1 \qquad \forall t \tag{3a}$$

$$cp_{i,t} \in \{0,1\} \qquad \forall i = 1,...,k, \forall t \tag{3b}$$

$$\hat{h}_i(m) = q_i \cdot h_i(m) + (1 - q_i) \cdot h_k(m) \qquad \forall i = 1,...,k \tag{3c}$$

where:

$h_i(m)$ = probability of *Ma* prevalence level m when uncontrolled risk factors under control package i are contaminated with *Ma*;

$\hat{h}_i(m)$ = expected probability of *Ma* prevalence level m under control package i;

m = *Ma* prevalence level in number of pigs in a delivery with *Ma* infection;

q_i = probability of uncontrolled risk factors in control package i to be *Ma* contaminated.

The probabilities that a delivery is correctly or incorrectly classified without increased risk are given in (4a), (4b), and (4c). Probability $p(n, N, d, m, se, sp)$ that d or less pigs in a sample are classified without increased risk is based on the hypergeometric distribution (Cameron and Baldock, 1998) and depends on sensitivity se and specificity sp (4a). For x tested positives j are true positives and $x – j$ are false positives. For y pigs with *Ma* infection in the sample, the number of true positives has a binomial distribution with parameters y and se, and number of false positives has a binomial distribution with parameters $n–y$ and $1–sp$. Considering all possible number of pigs classified with increased risk probability p_i^s that a delivery is classified without increased risk for each control package i is given in (4b). A delivery is classified with increased risk when there are more than M pigs with *Ma* infection in the delivery. Probability p_i^{is} that a delivery is incorrectly classified without increased risk for each control package i is given in (4c).

$$p(n,N,d,m,se,sp) = \sum_{x=0}^{d} \left[\sum_{y=0}^{\min\{n,m\}} \left[\frac{\binom{m}{y}\binom{N-m}{n-y}}{\binom{N}{n}} \sum_{j=0}^{\min\{x,y\}} \left[\binom{y}{j} se^j (1-se)^{y-j} \binom{n-y}{x-j} (1-sp)^{x-j} sp^{n-x-y+j} \right] \right] \right] \tag{4a}$$

$$p_i^s = \sum_{m=0}^{N} p(n,N,d,m,se,sp) \cdot \hat{h}_i(m) \qquad \forall i = 1,...,k \tag{4b}$$

$$p_i^{is} = \sum_{m>M}^{N} p(n,N,d,m,se,sp) \cdot \hat{h}_i(m) \qquad \forall i = 1,...,k \tag{4c}$$

where:

d = maximum number of pigs in a sample classified with increased risk to classify the whole delivery without increased risk;

j = number of pigs in a sample correctly classified with increased risk;
M = minimum number of pigs with *Ma* infection in a delivery to define the delivery with increased risk;
$p(n, N, d, m, se, sp)$ = probability of d or less pigs classified with increased risk when a sample n from a delivery N contains m pigs with *Ma* infection using a test with sensitivity se and specificity sp;
se = test sensitivity;
sp = test specificity;
x = number of pigs in a sample tested with increased risk;
y = number of pigs with *Ma* infection in a sample.

The decision problem of the slaughterhouse manager is to set a penalty *pen* on pigs in deliveries classified with increased risk. This problem depends on the ownership structure for the slaughterhouse (King et al., 2007). For a non-producer investor owned slaughterhouse, the manager minimizes slaughterhouse costs. For a producer cooperative, the manager minimizes producer costs. For an integration the manager minimizes chain costs. Slaughterhouse costs given in (5) consist of testing costs, additional processing costs, and failure costs at the steady state probabilities $(cp_1^*, ..., cp_k^*)$, corrected for penalty revenue from producers. The slaughterhouse incurs testing costs of *tc* per tested pig. With probability (1 – p_i^s) it has additional processing cost *apc* for pigs in a delivery classified with increased risk, because their head and gastro-intestinal tract are unfit for consumption and have to be disposed of safely. Furthermore, the slaughterhouse has part (1 – α) of failure costs with probability p_i^{is}.

$$\sum_{i=1}^{k} (N \cdot (1 - p_i^s) \cdot (apc - pen) + (1 - \alpha) \cdot p_i^{is} \cdot fc + n \cdot tc) \cdot cp_i^* \tag{5}$$

where:
apc = additional processing costs in euro per pig in a delivery classified with increased risk;
tc = testing costs in euro per tested pig.

3. Model parameters and assumptions

The optimal steady-state control packages for producers were calculated for sensitivity 0.50, 0.70 and 0.90, and for specificity 0.95, 0.97 and 0.99. Sensitivity and specificity of the new serological test are expected to lie in this range. The values of sensitivity and specificity were combined with penalty values €0, €2, €4, €6, €8 and €10 per pig in a delivery classified with increased risk. We analysed three cases of traceability. First, in case of no traceability (fc = 0) neither slaughterhouse manager nor producers were confronted with failure costs (Table 2 and 3). Second, in case of partial traceability ($fc > 0$, $\alpha = 0$) the slaughterhouse manager was confronted with failure costs, but he did not know which producer was the cause (Table 2 and 3). Third, in case of full traceability ($fc > 0$, $\alpha = 1$) the slaughterhouse manager could trace individual producers and passed failure costs on to them (Table 4).

In each period t a producer was categorised in one of six *Ma* risk levels $RL_t \in \{1, \ldots, 6\}$. Levels 1 and 2 were levels with the highest risk, levels 4 and 6 levels with medium risk, and levels 3 and 5 levels with the lowest risk. The *Ma* risk level RL_{t+1} depended on the risk levels from up to and including 7 previous periods (6a). If a farm had risk level 2 in t current test results TR_t and risk levels from the previous two periods were considered to determine the farms risk level in t+1. If a farm had risk level 3 in t current test results TR_t and risk levels from the previous seven periods were considered to determine the farms risk level in t+1. For other risk levels current test results TR_t and the previous risk level were considered to determine the risk level in t+1. The sample size depended on the risk level as given in (6b). A low sample size of 2 or 6 is sufficient because the control system aims to identify chronic *Ma* infections on herd level. The penalty depended on the risk level as given in (6c). For this system the producer's dynamic optimization problem was a Markov chain with 2,008 states. Each state was a possible combination of *Ma* risk levels in 8 consecutive periods.

$$RL_{t+1} = f_1(RL_t,...,RL_{t\text{-}7},TR_t) = \begin{cases} 1 \text{ if } (RL_t \in \{1,2,4,6\} \text{ and } TR_t \geq 1) \text{ or } (RL_t \in \{3,5\} \text{ and } TR_t \geq 2) \\ 2 \text{ if } (RL_t = 1 \text{ and } TR_t = 0) \text{ or } (RL_{t-1} \neq 2 \text{ and } RL_t = 2 \text{ and } TR_t = 0) \\ 3 \text{ if } (RL_{t-1} = RL_t = 2 \text{ and } TR_t = 0) \text{ or} \\ \qquad (RL_t = 3 \text{ and } TR_t = 0 \text{ and } \exists \hat{t} \in \{1,...,7\} \text{ with } RL_{t\text{-}\hat{t}} \neq 3) \qquad\qquad \forall t \\ 4 \text{ if } RL_t = 3 \text{ and } TR_t = 1 \\ 5 \text{ if } (RL_t \in \{5,6\} \text{ and } TR_t = 0) \text{ or } (RL_{t\text{-}7} = ... = RL_t = 3 \text{ and } TR_t = 0) \\ 6 \text{ if } RL_t = 5 \text{ and } TR_t = 1 \end{cases} \tag{6a}$$

$$n = f_2(RL_t) = \begin{cases} 2 \text{ if } RL_t \in \{3,5\} \\ 6 \text{ if } RL_t \in \{1,2,4,6\} \end{cases} \qquad \forall t \tag{6b}$$

$$pen_{RL} = f_3(RL_t) = \begin{cases} pen & \text{if } RL_t \in \{1,2\} \\ 0.5 \cdot pen & \text{if } RL_t \in \{3,4\} \\ 0 & \text{if } RL_t \in \{5,6\} \end{cases} \qquad \forall t \tag{6c}$$

We modelled pig producers with monthly deliveries of each 100 pigs. The monthly discount factor δ was assumed to be 0.9967, implying an annual interest rate of 4.0%. Estimated testing costs *tc* were €8 per test (V.M.C. Rijsman, personal communication, 2007). Additional processing costs *apc* were €0.92 per pig in a delivery classified with increased risk, based on foregone revenues of a head of €0.06 (3 kg at €0.02 per kg), foregone revenues of a gastro-intestinal tract of €0.50 per tract, and rendering costs for head and tract of €0.36 (head 3 kg and tract 6 kg at €0.04 per kg) (L. Heres, personal communication, 2007).

A general value of food safety failure costs *fc* that includes recall costs, reputation damage, and liability costs was sufficient to analyze how failure costs influence producer incentives. Expected jury award to consumers for court cases on food borne illness in the USA was used as failure costs per delivery. Expected award was $41,888, which meant €41,446 in 2006, with a range of $0 to $2,368,858 (Buzby et al., 2001).

Four *Ma* control packages (i = 1, 2, 3, 4) were defined that consisted of combinations of bird control, small terrestrial mammal control, invertebrate control, use of uncontaminated bedding materials, water quality control, and use of uncontaminated feed supplements (Table 1). Data were gathered using literature and were discussed with two leading experts of *Ma* infections in pigs in the Netherlands and the Czech Republic. Probability distribution of prevalence levels of each control package were based on Engel et al. (1978), Fischer et al. (2000), Fischer et al. (2001), Mátlová et al. (2005), Mátlová et al. (2003), Mátlová et al. (2004a), Mátlová et al. (2004b), and Pavlík et al. (2007). Average prevalence levels were highest for control package 1 (46.0%) and lowest for control package 4 (0.1%). Costs for bird, small terrestrial mammal, and invertebrate control, and for water control were based on King et al. (2007). Costs for feed supplements were €1.50 per pig, calculated as the additional costs of pigs fed a supplement mix (€5.12 per pig: 2.5 kg of supplement mix at €135 per 100 kg and 2.5 kg of weaner feed at €70 per 100 kg) above costs of pigs provided pig-compost (€3.62 per pig: 2.5 kg of pig-compost at €75 per 100 kg and 2.5 kg of weaner feed at €70 per 100 kg). Costs of uncontaminated bedding material were those of commercially available bedding materials. Contamination probability that a random uncontrolled risk factor was contaminated with *Ma* was based on Mátlová et al. (2003). Expected prevalence for each control package is the average prevalence multiplied by the contamination probability. Expected prevalence was highest for control package 1 (13.8%) and lowest for control package 4 (0.1%).

Table 1 also provides impact of sensitivity and specificity on the probability p_i^s of a delivery being classified without increased risk and on the type-II-error p_i^{is} at the average prevalence of each control package *i* and at sample size 6. A higher sensitivity or a lower specificity led to lower p_i^s and p_i^{is}. A lower expected prevalence resulted in a higher p_i^s. For control package 1 with average prevalence of 46.0% probability that a delivery of 100 pigs contained infected pigs was 95% and probability of infected pigs in the sample was 98%. This resulted in p_1^{is} between 0.096 and 0.245. For control package 2 probability that a delivery contained infected pigs was 95%, but probability of infected pigs in the sample was 63% for average prevalence of 15.8%. This resulted in p_2^{is} between 0.321 and 0.567. Although control package 2 had lower average prevalence than control package 1, p_2^{is} was larger than p_1^{is}, because of a high probability of not having infected pigs in the sample. For control package 3 probability that a delivery contained infected pigs was 95% and probability of infected pigs in the sample was 0% for average prevalence of 0.3%. This resulted in p_3^{is} between 0.028 and 0.040. Although the probability of not having infected pigs in the sample was high for control package 3, probability that a delivery contained infected pigs was so small, that p_3^{is} was smaller than p_2^{is} and p_1^{is}. For control package 4 probability that a delivery contained infected pigs was 99% resulting in p_4^{is} smaller than p_3^{is}.

Table 1: *Mycobacterium avium* control packages with control package costs, probability distribution of serological prevalence levels at slaughter, contamination probability, probability p_i^s of a delivery classified without increased risk, and type-II-error p_i^{is}

	control package			
	1	**2**	**3**	**4**
Bird, terrestrial mammal, and invertebrate control (€0.07/pig)		X	X	X
Use of uncontaminated bedding materials (€0.15/pig)			X	X
Water quality control (€0.20/pig)			X	X
Use of uncontaminated feed and feed supplements (€1.50/pig)				X
Control package costs (€/pig)	0.00	0.07	0.42	1.92
Prevalence probabilities at slaughter [a]				
0% prevalence	5.0	5.0	95.0	99.0
5% prevalence	5.0	25.0	5.0	1.0
10% prevalence	5.0	20.0	0.0	0.0
15% prevalence	5.0	20.0	0.0	0.0
20% prevalence	5.0	10.0	0.0	0.0

25% prevalence	10.0	10.0	0.0	0.0
50% prevalence	30.0	10.0	0.0	0.0
70% prevalence	30.0	0.0	0.0	0.0
100% prevalence	5.0	0.0	0.0	0.0
Average prevalence	46.0	15.8	0.3	0.1
Contamination probability	0.30	0.17	0.04	0
Expected prevalence	13.8	2.7	0.1	0.1

sensitivity / specificity	p_1^{s} [b]	p_1^{is} [b]	p_2^{s} [b]	p_2^{is} [b]	p_3^{s} [b]	p_3^{is} [b]	p_4^{s} [b]	p_4^{is} [b]
0.50 / 0.95	0.237	0.200	0.488	0.451	0.730	0.032	0.734	0.006
0.50 / 0.97	0.263	0.221	0.548	0.506	0.827	0.036	0.832	0.007
0.50 / 0.99	0.292	0.245	0.614	0.567	0.935	0.040	0.940	0.008
0.70 / 0.95	0.169	0.132	0.416	0.379	0.728	0.030	0.734	0.006
0.70 / 0.97	0.190	0.148	0.469	0.427	0.825	0.034	0.831	0.007
0.70 / 0.99	0.213	0.166	0.527	0.480	0.932	0.038	0.940	0.008
0.90 / 0.95	0.133	0.096	0.358	0.321	0.726	0.028	0.733	0.006
0.90 / 0.97	0.150	0.109	0.405	0.363	0.823	0.031	0.831	0.006
0.90 / 0.99	0.170	0.122	0.457	0.410	0.930	0.035	0.939	0.007

[a] Serological ELISA at Optical Density cut-off value of 20 Percentage Positives.

[b] With $N = 100$, $n = 6$, $M = 0$, and $d = 0$.

4. Results

Impact of penalty on the optimal steady state probability of each control package, expected *Ma* prevalence, type-II-error, producer costs, slaughterhouse costs, and chain costs without traceability for sensitivity 0.50, 0.70, and 0.90 and specificity 0.95 is given in Table 2. Producer and slaughterhouse manager decisions were based on the economic consequences of the penalty. For sensitivity 0.50 optimal penalty value for producers was €0. Then control package 1 was optimal, resulting in expected *Ma* prevalence of 14.3% and type-II-error of 0.073. Producer costs were €0 per pig and both slaughterhouse costs and chain costs €0.68. In contrast, for sensitivity 0.50 optimal penalty value for the slaughterhouse was €10, because the penalty revenue was highest. Then control package 2 was optimal for 74% of producers and control package 3 for 26% of producers. The expected *Ma* prevalence was 2.0% and the type-II-error was 0.078. Use of control package 2 led to a higher type-II-error compared to the use of control package 1. Slaughterhouse costs were –€0.20[1] per pig, producer costs €0.82, and chain costs €0.62. For sensitivity 0.50 chain costs were minimal at penalty €2. Then control package 2 was optimal for producers, resulting in an expected Ma prevalence of 2.7% and a type-II-error of 0.084. Chain costs were €0.50 per pig, with producer costs €0.26 and slaughterhouse costs €0.24. Optimal penalty values for producer, slaughterhouse, and chain did not change with a higher sensitivity of 0.70 or 0.90. At higher sensitivity, however, producers increased use of more intense control packages, because more pigs were classified with increase risk resulting in lower expected prevalence and lower type-II-errors. At higher sensitivity producer and chain costs were higher, and slaughterhouse costs were similar.

In case of partial traceability optimal control packages, expected *Ma* prevalence and type-II-errors were the same as in case of no traceability for all levels of sensitivity and penalty (Table 2). With partial traceability slaughterhouse decision also included failure costs, the economic consequences of the type-II-error. This increased slaughterhouse costs between

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[1] Costs include the revenue from the penalty. Negative costs indicate positive benefits.

€22.72 and €48.44 per pig compared to case no traceability depending on sensitivity and penalty parameter values. In case of partial traceability at sensitivity 0.50, 0.70, and 0.90 optimal penalty value for producers was €0 per pig and optimal penalty value for the slaughterhouse was €10 per pig. Producer costs were lower at higher levels of sensitivity through the lower type-II-errors. At sensitivity 0.50 and 0.70 chain costs were minimal at penalty €10 per pig. However, at sensitivity 0.90, chain costs were minimal at penalty €0. Low failure costs and low producer costs compensated for additional production costs of the slaughterhouse originating from the high expected *Ma* prevalence.

Impact of penalty on optimal steady state probability of each control package, expected *Ma* prevalence, type-II-error, producer costs, slaughterhouse costs, and chain costs without traceability for specificity 0.95, 0.97, and 0.99 and sensitivity 0.70 is given in Table 3. Producer and slaughterhouse manager decisions were based on the economic consequences of the penalty. For specificity 0.95 optimal penalty value for producers was €0. Then control package 1 was optimal, resulting in expected *Ma* prevalence of 14.3% and type-II-error of 0.048. Producer costs were €0 per pig and both slaughterhouse costs and chain costs €0.68. In contrast, for specificity 0.95 optimal penalty value for the slaughterhouse was €10, because the penalty revenue was highest. Then control package 2 was optimal for 50% of producers and control package 3 for 50% of producers. This resulted in an expected *Ma* prevalence of 1.4% and a type-II-error of 0.054. Use of control package 2 led to a higher type-II-error compared to the use of control package 1. Slaughterhouse costs were –€0.20 per pig, producer costs €0.82, and chain costs €0.62. For sensitivity 0.95 chain costs were minimal at penalty €2. Then control package 2 was optimal for producers, resulting in an expected Ma prevalence of 2.7% and a type-II-error of 0.084. Chain costs were €0.50 per pig, with producer costs €0.26 and slaughterhouse costs €0.24. Optimal penalty values for producers and slaughterhouse did not change with a higher specificity of 0.97 or 0.99. For specificity 0.97 chain costs were minimal for penalty €2 per pig, but at specificity 0.99 for penalty €4. At higher specificity, however, producers decreased use of more intense control packages, because less pigs were classified with increase risk. This resulted in higher expected prevalence and higher type-II-errors. Slaughterhouse costs were higher for higher specificity at penalty €0, because less pigs were classified with increased risk and additional processing costs were lower. At penalty €2 slaughterhouse costs did not differ much between levels of specificity. At penalty €4 or higher slaughterhouse costs were lower for higher specificity because the penalty revenue from pigs classified with increased risk were higher than additional processing costs. Producer costs and chain costs were lower at higher specificity.

In case of partial traceability optimal control packages, expected *Ma* prevalence and type-II-errors were the same as in case of no traceability for all levels of specificity and penalty (Table 3). With partial traceability slaughterhouse decision also included the failure costs. This increased slaughterhouse costs between €25.84 and €53.42 per pig compared to case no traceability depending on sensitivity and penalty parameter values. In case of partial traceability at specificity 0.95, 0.97, and 0.99 producer costs were minimal at penalty €0 per pig. For specificity 0.95 optimal penalty for slaughterhouse and chain was €10. However, for specificity 0.97 and 0.99 optimal penalty for slaughterhouse and chain was €0, because use of control package 2 at penalties of €2 and higher led to high failure costs.

In case of full traceability, when the failure costs were included in the producer decision, sensitivity, specificity and penalty had no influence on producer incentives to take *Ma* control measures (Table 4). Control package 3 was optimal for all combinations. Penalty and sensitivity had no impact on the type-II-error, but the type-II-error was lower at lower specificity. Producer costs were higher at lower sensitivity, higher specificity, and higher penalty. Producer costs were €400 to €4.50 per pig lower compared to the cases no traceability and partial traceability. Producer costs were minimal at sensitivity 0.90, specificity 0.95 and penalty €0. Slaughterhouse costs were minimal at sensitivity 0.50, specificity 0.95 and penalty €10. Sensitivity had little influence on slaughterhouse costs. At penalty €0 slaughterhouse costs were higher compared to case no traceability, because less pigs were classified with increased risk. At penalty €10 slaughterhouse costs were lower because the lower expected *Ma* prevalence decreased penalty revenue.

5. Sensitivity analysis

In a sensitivity analysis the impact of alternative values of failure costs, contamination probabilities, and control package costs was analyzed. In case of no traceability and partial traceability failure costs had no impact on producer decision to take *Ma* control measures. In case of full traceability optimal solution at failure costs €5,000 and €100,000 was that as in Table 4. At failure costs €1,000 or lower the optimal solution shifted towards that of no traceability, with a combination of control package 1 and 3 being optimal. At failure costs €10 the optimal solution resembled that of no traceability. If the slaughterhouse and producers shared failure costs ($fc > 0$, $\alpha = 0.5$), slaughterhouse costs, producer costs, and chain were minimal at sensitivity 0.90 and specificity 0.95.

Contamination probabilities of 1.00 led to increased use of more intense control packages, higher producer costs (from €0.00 to €0.24 per pig depending on sensitivity and specificity), and lower slaughterhouse costs (from €0.02 to €0.72 per pig) compared to Table 1. Higher sensitivity, lower specificity, and higher penalty led to use of more intense control packages and higher producer costs. Contamination probabilities of 1.00 further increased type-II-errors if control package 2 was used. At penalty €0 lower sensitivity and higher specificity led to higher slaughterhouse costs, because additional production costs of pigs classified with increased risk were larger than the penalty. At penalty €2 to €10 lower sensitivity and higher specificity led to lower slaughterhouse costs.

Control package 4 was never optimal, because producer revenues from lower *Ma* prevalence and lower type-II-errors did not outweigh additional control package costs. Expected *Ma* prevalence of 0.1% of control package 4 was equal to that of control package 3, while costs of control package 4 (€1.92) were €1.50 higher than those of control package 3 (€0.42). Control package costs can differ amongst producers. Producers with good management skills can provide weaner feed to pigs in small amounts in hygienically clean circumstances to prevent weaner diarrhoea. For these farmers estimated costs were €3.50 per pig (5 kg weaner feed at €70 per 100 kg), indicating no additional control package costs above providing pig-compost. If control package 4 had costs of €0.42, control package 4 was used in stead of control package 3. Probability of use of control packages 1 and 2 did not change. Lower average *Ma* prevalence of control package 4 compared to control package 3 led to a lower expected *Ma* prevalence and a lower type-II-error. Lower expected prevalence led to less pigs classified with increased risk and a lower producer penalty, and resulted in lower producer costs and higher slaughterhouse costs.

Table 2: Impact of penalty on optimal control packages, expected *Ma* prevalence, type-II-errors, producer costs, slaughterhouse costs and chain costs in case of no traceability and in case of partial traceability with sensitivity 0.50, 0.70, 0.90, and specificity 0.95

sensitivity	0.50	0.50	0.50	0.50	0.50	0.50	0.70	0.70	0.70	0.70	0.70	0.70	0.90	0.90	0.90	0.90	0.90	0.90
penalty (€/pig)	0	2	4	6	8	10	0	2	4	6	8	10	0	2	4	6	8	10
Prevalence performance																		
steady state probability of [a]:																		
-control package 1	1.00	0	0	0	0	0	1.00	0	0	0	0	0	1.00	0	0	0	0	0
-control package 2	0	1.00	0.94	0.83	0.76	0.74	0	1.00	0.82	0.74	0.67	0.50	0	1.00	0.81	0.65	0.48	0.48
-control package 3	0	0	0.06	0.17	0.24	0.26	0	0	0.18	0.26	0.33	0.50	0	0	0.19	0.35	0.52	0.52
expected *Ma* prevalence	14.3	2.7	2.6	2.3	2.1	2.0	14.3	2.7	2.2	2.0	1.8	1.4	14.3	2.7	2.2	1.8	1.3	1.3
type-II-error	0.073	0.097	0.093	0.084	0.079	0.078	0.048	0.084	0.073	0.068	0.064	0.054	0.035	0.072	0.063	0.056	0.046	0.046
Economic performance																		
no traceability																		
-producer costs (€/pig)	0.00	0.23	0.39	0.52	0.64	0.76	0.00	0.26	0.43	0.57	0.70	0.82	0.00	0.29	0.47	0.61	0.74	0.86
-slaughterhouse costs (€/pig) [b]	0.62	0.25	0.10	0.00	-0.11	-0.22	0.68	0.24	0.11	-0.01	-0.12	-0.20	0.73	0.23	0.09	-0.02	-0.10	-0.22
-chain costs (€/pig)	0.62	0.48	0.49	0.52	0.53	0.54	0.68	0.50	0.54	0.56	0.58	0.62	0.73	0.52	0.56	0.59	0.64	0.64
partial traceability																		
-producer costs (€/pig)	0.00	0.23	0.39	0.52	0.64	0.76	0.00	0.26	0.43	0.57	0.70	0.82	0.00	0.29	0.47	0.61	0.74	0.86
-slaughterhouse costs (€/pig) [b]	45.56	49.09	46.68	42.36	40.18	39.05	31.95	44.38	38.43	36.44	33.05	25.64	23.45	40.12	34.78	29.90	22.84	22.72
-chain costs (€/pig)	45.56	49.32	47.07	42.88	40.82	39.81	31.95	44.64	38.86	37.01	33.75	26.46	23.45	40.41	35.25	30.51	23.58	23.58

[a] control package 4 was never optimal.

[b] costs corrected for penalty revenue received from pig producers (negative costs indicate positive benefits).

Table 3: Impact of penalty on optimal control packages, expected *Ma* prevalence, type-II-errors, producer costs, slaughterhouse costs and chain costs in case of no traceability and in case of partial traceability with specificity 0.95, 0.97, 0.99, and sensitivity 0.70

specificity	0.95	0.95	0.95	0.95	0.95	0.95	0.97	0.97	0.97	0.97	0.97	0.97	0.99	0.99	0.99	0.99	0.99	0.99
penalty (€/pig)	0	2	4	6	8	10	0	2	4	6	8	10	0	2	4	6	8	10
Prevalence performance																		
steady state probability of [a]																		
-control package 1	1.00	0	0	0	0	0	1.00	0	0	0	0	0	1.00	0	0	0	0	0
-control package 2	0	1.00	0.82	0.74	0.67	0.50	0	1.00	0.91	0.85	0.85	0.80	0	1.00	0.99	0.98	0.93	0.93
-control package 3	0	0	0.18	0.26	0.33	0.50	0	0	0.09	0.15	0.15	0.20	0	0	0.01	0.02	0.07	0.07
expected *Ma* prevalence	14.3	2.7	2.2	2.0	1.8	1.4	14.3	2.7	2.5	2.3	2.3	2.2	14.3	2.7	2.7	2.7	2.5	2.5
type-II-error	0.048	0.084	0.073	0.068	0.064	0.054	0.057	0.099	0.093	0.089	0.089	0.086	0.068	0.116	0.115	0.114	0.111	0.111
Economic performance																		
no traceability																		
-producer costs (€/pig)	0.00	0.26	0.43	0.57	0.70	0.82	0.00	0.14	0.21	0.25	0.30	0.34	0.00	0.09	0.10	0.11	0.12	0.13
-slaughterhouse costs (€/pig) [b]	0.68	0.24	0.11	-0.01	-0.12	-0.20	0.58	0.25	0.20	0.17	0.13	0.10	0.48	0.23	0.21	0.21	0.21	0.20
-chain costs (€/pig)	0.68	0.50	0.54	0.56	0.58	0.62	0.58	0.39	0.41	0.42	0.43	0.44	0.48	0.32	0.31	0.32	0.33	0.33
partial traceability																		
-producer costs (€/pig)	0.00	0.26	0.43	0.57	0.70	0.82	0.00	0.14	0.21	0.25	0.30	0.34	0.00	0.09	0.10	0.11	0.12	0.13
-slaughterhouse costs (€/pig) [b]	31.95	44.38	38.43	36.44	33.05	25.64	37.78	49.50	46.41	44.22	44.18	41.88	43.60	53.65	53.29	52.89	50.78	50.78
-chain costs (€/pig)	31.95	44.64	38.86	37.01	33.75	26.46	37.78	49.64	46.62	44.47	44.48	42.22	43.60	53.74	53.39	53.00	50.90	50.91

[a] control package 4 was never optimal.

[b] costs corrected for penalty revenue received from pig producers (negative costs indicate positive benefits).

Table 4: Impact of penalty on type-II-errors, producer costs, slaughterhouse costs and chain costs in case of full traceability with sensitivity 0.50, 0.70, 0.90 and specificity 0.95, 0.97, 0.99[a].

sensitivity	specificity	penalty[c] (€/pig)	type-II-error	producer costs (€/pig)	slaughterhouse costs[b] (€/pig)	chain costs (€/pig)
0.50	0.95	0	0.008	4.34	0.35	4.69
0.50	0.95	10	0.008	4.81	-0.12	4.69
0.70	0.95	0	0.008	4.22	0.35	4.57
0.70	0.95	10	0.008	4.70	-0.13	4.57
0.90	0.95	0	0.008	4.11	0.35	4.46
0.90	0.95	10	0.008	4.59	-0.13	4.46
0.50	0.97	0	0.010	4.64	0.25	4.89
0.50	0.97	10	0.010	4.75	0.15	4.90
0.70	0.97	0	0.009	4.54	0.26	4.80
0.70	0.97	10	0.009	4.65	0.15	4.80
0.90	0.97	0	0.009	4.43	0.26	4.69
0.90	0.97	10	0.009	4.55	0.15	4.70
0.50	0.99	0	0.011	4.89	0.19	5.08
0.50	0.99	10	0.011	4.89	0.18	5.07
0.70	0.99	0	0.010	4.79	0.19	4.98
0.70	0.99	10	0.010	4.79	0.18	4.97
0.90	0.99	0	0.010	4.69	0.19	4.88
0.90	0.99	10	0.010	4.70	0.18	4.88

[a] Control package 3 with expected *Ma* prevalence 0.1% was optimal for all combinations.

[b] Costs corrected for penalty revenue (negative costs indicate positive benefits).

[c] Results for penalty parameter values €2 to €8 are available from the authors upon request.

6. Discussion

This paper analyzed the influence of sensitivity and specificity on pig producer incentives to control *Ma* infections in a control system with a penalty on pigs classified with increased risk and with failure costs using a principal-agent model. Analyses with this model indicate a tight relation between sensitivity, specificity, penalty, type-II-errors, and prevalence probability distribution of control packages in the provision of *Ma* free pig meat. Results showed that higher sensitivity, lower specificity, higher penalty, and failure costs induced use of more intense *Ma* control packages.

Results depend on input parameter values. We assumed that serological infections led to bacteriological infections of meat and that each infected pig could cause food safety problems of which failure costs could be attributed to the supply chain. We expect low failure costs to be the most likely for *Ma* in pigs. The probability that failure costs are attributable to the supply chain is small, because the long incubation period of human *Ma* infections complicates traceability to the source of such infections. Notwithstanding, this paper provides insight into the mechanism of how failure costs influence producer incentives.

This research used partial analysis on *Ma*. Almost all control actions are also effective in reducing other pathogens or improving production results. Thus, the costs to reduce prevalence should be divided over more pathogens. This research did not include benefits from other pathogens and improved production results. Including these benefits in the producer decision increases producer incentives to use control measures. Dutch pig farms mainly use control measures as described by control package 3 and 4. Possibilities to decrease costs, however, may tempt them to lower their attention for *Ma* control, leading to reduced effectiveness of the control packages and to increased risk of *Ma* infections in pigs.

We did not use a participation constraint, because we intended to analyze how testing accuracy influences optimal parameter values of an incentive system. In practice producers can switch slaughterhouses if costs increased too much. Thus, slaughterhouses can only set a penalty up to a specific level. This level depends on the individual participation constraint of each producer. Extending the model with a participation constraint would limit the optimal penalty to a maximum value. It would not change the influence of testing accuracy.

7. Conclusions

A dynamic principal agent model of deliveries of pig producers to a slaughterhouse has been developed. The model assesses the influence of test sensitivity and specificity on pig producer incentives to control *Mycobacterium avium*. It included a penalty on pigs in deliveries classified with increased risk set by the slaughterhouse and food safety failure costs. Test sensitivity and specificity influence producer incentives through probabilities of correctly and incorrectly classifying a delivery without increased risks on producer, slaughterhouse, and chain costs. Results showed that without traceability sensitivity and specificity did not influence optimal penalty values for producer and slaughterhouse. Notwithstanding, higher sensitivity and lower specificity increased incentives for producers to take *Ma* control measures resulting in lower expected *Ma* prevalence. Producer costs were minimal at a low penalty, slaughterhouse costs at a high penalty, and chain costs at an intermediate penalty, with the lowest total costs at the intermediate penalty. However, more intense control packages could lead to increased type-II-errors with consequential failure costs. In case of partial traceability the slaughterhouse manager used a penalty that avoided use of a control package with a high type-II-error. Sensitivity and specificity influenced optimal penalty values in minimizing chain costs. In case of full traceability and high failure costs the main goal was to minimize failure costs. Sensitivity and specificity did not influence optimal penalty values. Results at low failure costs resembled those of without traceability.

Chain control can lower total *Ma* control costs compared to minimizing producer costs or slaughterhouse costs. Sensitivity and specificity in combination with a penalty on high risk products influence producer incentives for *Ma* control. Including failure costs in the incentive system can increase producer incentives for *Ma* control. Effectiveness of a food safety control system aiming to minimize *Ma* prevalence in pig meat products depends on the type-II-error. Traceability is essential to increase food safety above the level provided with penalties.

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