

# 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

50 product without increased risk. Starbird (2005) has shown that the settings of the sampling  
51 inspection parameters can influence supplier incentives for use of improved food safety  
52 technologies. Furthermore, test accuracy can be used in the design of contracts that segregate  
53 low and high quality producers (Starbird, 2007). But, can improved accuracy of a new test  
54 influence supplier control actions through an incentive mechanism? This paper aims to  
55 analyze how testing accuracy influences optimal parameter values of an incentive system that  
56 induces suppliers to use food safety control actions.

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

65 Human *Ma* infections cause disseminated disease in AIDS patients (Falkinham 3rd,  
66 1996), lymph node disease in children (Haverkamp et al., 2004), lung disease in middle aged  
67 and elderly people (Dailloux et al., 2006). Humans and pigs share similar strains of *Ma*,  
68 which suggests that infected pork could be a source of human infections or that both man and  
69 pig get infected by a common source (Tirkkonen et al., 2007). Critical control points for *Ma*  
70 are located at farm level, where infection of pork is initiated. To reduce the risks of *Ma*  
71 contamination in its products, a slaughterhouse can dispose of the increased risk parts of pigs  
72 infected with *Ma*, and it can use preventive actions through inducing *Ma* control at farm level.

73 To analyze how test accuracy influences supplier incentives to take control measures  
74 we modeled a possible future control system for *Ma*. The model is based on the operational  
75 system used by a large pig slaughter company in the Netherlands. This system is based on risk  
76 assessment at individual herd level and uses a serodiagnostic test as suggested by Ellerbroek  
77 (2007). Serodiagnostic tests determine whether *Ma* antibodies are present in the blood.  
78 Bacteriological tests determine whether *Ma* bacteria are present in a tissue sample from a  
79 carcass. Serologically infected pigs do not have to be bacteriologically infected. Serological  
80 prevalence levels will normally be higher than bacteriological prevalence levels. We assumed  
81 that serological positive pigs can result in bacteriological contamination of meat and that  
82 contaminated meat can cause food safety problems. Although the serodiagnostic test is  
83 currently under development and not yet validated, expert knowledge about the accuracy and  
84 serological infection levels was available. In the model the blood of specific number of pigs  
85 of each delivery was analysed at slaughter. The control system used results from current and  
86 several previous deliveries to determine a producer's *Ma* risk level. The *Ma* risk level  
87 determined the values of incentive parameters applicable to the producer. Penalties on  
88 deliveries classified with increased risk and food safety failure costs were included in the  
89 system to assess impact of testing accuracy on producer incentives to control *Ma* infections.

90

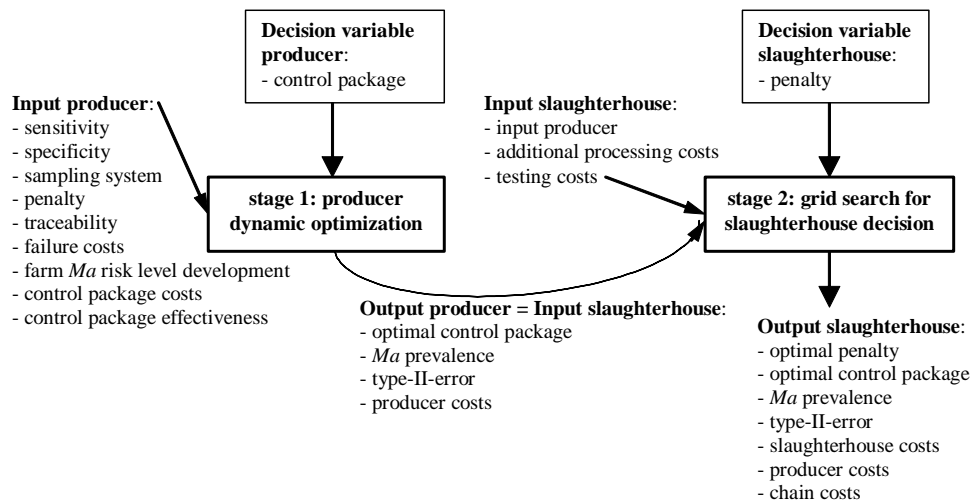
## 91 **2. Materials and method**

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

99 To solve the slaughterhouse's decision problem of selecting an optimal penalty we  
 100 used the method proposed by King et al. (2007). The producer's dynamic optimization  
 101 problem of selecting optimal *Ma* control measures was embedded in a grid search program  
 102 systematically exploring the parameter space of sensitivity, specificity, and penalty. The  
 103 producer's dynamic optimization problem was defined as a Markov chain with infinite  
 104 horizon. States were discrete, because each state was a combination of producer *Ma* risk  
 105 levels. The program used policy iteration to identify an optimal steady-state control package  
 106 for each possible risk level history. A steady state probability matrix existed, because all  
 107 states were recurrent, aperiodic, and communicated with each other (Winston, 1991). This  
 108 matrix was used along with the optimal policy to calculate expected *Ma* prevalence, producer  
 109 costs, slaughterhouse costs, chain costs, and type-II-error. MATLAB routines developed by  
 110 Miranda and Fackler (2002) were used to solve the producer's problem for a given set of  
 111 sensitivity, specificity, and penalty.  
 112

### 113 2.1 General outline of the model

114 Figure 1 gives the general outline of the model. In stage 1, the producer model, a  
 115 dynamic optimization model was used to determine *Ma* control measures that minimize  
 116 producer costs for each combination of sensitivity, specificity and penalty. Other input  
 117 parameters in the producer model included the sampling system, traceability, failure and  
 118 control package costs, and control package effectiveness. Output included optimal control  
 119 packages, *Ma* prevalence levels, and type-II-errors. In stage 2, the slaughterhouse model, a  
 120 grid search was used over sensitivity, specificity, and penalty parameter values to determine  
 121 the optimal penalty for the slaughterhouse. Input and output from the producer model was  
 122 used as input in the slaughterhouse model. Input was complemented with additional  
 123 processing costs and testing costs. Output included optimal penalty, optimal *Ma* control  
 124 packages, related *Ma* prevalence and type-II-errors, producer costs, slaughterhouse costs, and  
 125 chain costs. Chain costs were sum of producer costs and slaughterhouse costs.  
 126



127  
 128 **Figure 1: General outline of the model**

### 129 2.2 Model specification

131 The producer's decision problem in (1) is to choose a *Ma* control package, a specific  
 132 combination of *Ma* control measures, in each period  $t$  that minimizes expected discounted  
 133 costs over an infinite horizon. This results in steady state probabilities  $(cp_1^*, \dots, cp_k^*)$  of *Ma*  
 134 control package  $cp_i$  being optimal for producers. In each period  $t$  producers incur penalty

135 costs  $pen$  on pigs in a delivery classified with increased risk, control package costs  $ccp_i$ , and  
 136 part  $\alpha$  of expected failure costs  $fc$ . The penalty depends on the probability  $p_i^s$  that a delivery  
 137 is classified without increased risk Failure costs depend on the probability  $p_i^{is}$  that a delivery  
 138 is incorrectly classified without increased risk or type-II-error.  
 139

$$140 \quad (cp_1^*, \dots, cp_k^*) = \operatorname{argmin}_{cp_{1,t}, \dots, cp_{k,t}} [E \sum_{t=0}^{\infty} \{ \delta^t \sum_{i=1}^k (N \cdot ((1 - p_i^s) \cdot pen + ccp_i) + \alpha \cdot p_i^{is} \cdot fc) \cdot cp_{i,t} \}] \quad (1)$$

141 where:

- 142  $\alpha =$  fraction of failure costs  $fc$  slaughterhouse passes on to the producer;  
 143  $ccp_i =$  control package costs in euro per pig;  
 144  $cp_{i,t} =$  control package  $i$  in period  $t$ ;  
 145  $cp_i^* =$  steady state probability of control package  $i$  being optimal for the producer;  
 146  $\delta =$  monthly discount factor;  
 147  $E =$  expectations parameter;  
 148  $fc =$  food safety failure costs in euro per delivery;  
 149  $i =$  index for  $Ma$  control packages;  
 150  $k =$  number of  $Ma$  control packages;  
 151  $N =$  number of pigs in a delivery;  
 152  $p_i^s =$  probability that a delivery of producer  $i$  is classified without increased risk;  
 153  $p_i^{is} =$  probability that a delivery of producer  $i$  is incorrectly classified without increased  
 154 risk or type-II-error;  
 155  $pen =$  penalty in euro per pig in a delivery classified with increased risk;  
 156  $t =$  index for period.  
 157

158 General relationships for the evolution of producer  $Ma$  risk level  $RL_t$  and related  
 159 aspects are described in (2a), (2b) and (2c). Specific parameter settings used in the model are  
 160 given in (6a), (6b) and 6(c). Evolution of  $Ma$  risk level depends on  $Ma$  risk levels in  $\hat{t}$   
 161 previous periods and number of pigs in the sample classified with increased risk in the current  
 162 delivery  $TR_t$  (2a). Sample size (2b) and penalties (2c) depend on the  $Ma$  risk level in period  $t$ .  
 163

$$164 \quad RL_{t+1} = f_1(RL_t, \dots, RL_{\hat{t}}, TR_t) \quad \hat{t} \in \{0, 1, 2, \dots\} \quad \forall t \quad (2a)$$

$$165 \quad n = f_2(RL_t) \quad \forall t \quad (2b)$$

$$166 \quad pen = f_3(RL_t) \quad \forall t \quad (2c)$$

167 where:

- 168  $f_1 =$  function that gives farm  $Ma$  risk level development;  
 169  $f_2 =$  function that relates sample size to farm  $Ma$  risk level;  
 170  $f_3 =$  function that relates penalty to farm  $Ma$  risk level;  
 171  $n =$  number of pigs in a sample;  
 172  $RL_t =$  farm  $Ma$  risk level in period  $t$ ;  
 173  $\hat{t} =$  index for number of previous periods considered to determine a farm's  $Ma$  risk level;  
 174  $TR_t =$   $Ma$  test result in period  $t$ .  
 175

176 The relationship between each control package  $cp_{i,t}$  and  $Ma$  prevalence distribution in  
 177 a herd is given in (3a), (3b), and (3c). Producers choose one control package  $cp_{i,t}$  in each  
 178 period  $t$  (3a), where  $cp_{i,t}$  is an integer variable (3b). The probability  $q_i$  that a random

179 uncontrolled risk factor is contaminated with *Ma* raises the infection probability above a  
 180 background infection level, which is a generally present *Ma* prevalence level that can not be  
 181 controlled with control measures. It is assumed to equal the average of the expected  
 182 prevalence probability distribution  $\hat{h}_k(m)$  of the most intense control package  $cp_k$ , with  $m$  the  
 183 prevalence level. Assuming that control packages in period  $t$  are independent of control  
 184 packages in previous periods, that control packages have a direct impact when implemented,  
 185 and that contamination probabilities of risk factors are independent, expected prevalence  
 186 distribution  $\hat{h}_i(m)$  is given in (3c).  
 187

$$188 \quad \sum_{i=1}^k cp_{i,t} = 1 \quad \forall t \quad (3a)$$

$$189 \quad cp_{i,t} \in \{0,1\} \quad \forall i = 1, \dots, k, \forall t \quad (3b)$$

$$190 \quad \hat{h}_i(m) = q_i \cdot h_i(m) + (1 - q_i) \cdot h_k(m) \quad \forall i = 1, \dots, k \quad (3c)$$

191 where:

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

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

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

196  $q_i$  = probability of uncontrolled risk factors in control package  $i$  to be *Ma* contaminated.  
 197

198 The probabilities that a delivery is correctly or incorrectly classified without increased  
 199 risk are given in (4a), (4b), and (4c). Probability  $p(n, N, d, m, se, sp)$  that  $d$  or less pigs in a  
 200 sample are classified without increased risk is based on the hypergeometric distribution  
 201 (Cameron and Baldock, 1998) and depends on sensitivity  $se$  and specificity  $sp$  (4a). For  $x$   
 202 tested positives  $j$  are true positives and  $x - j$  are false positives. For  $y$  pigs with *Ma* infection in  
 203 the sample, the number of true positives has a binomial distribution with parameters  $y$  and  $se$ ,  
 204 and number of false positives has a binomial distribution with parameters  $n - y$  and  $1 - sp$ .  
 205 Considering all possible number of pigs classified with increased risk probability  $p_i^s$  that a  
 206 delivery is classified without increased risk for each control package  $i$  is given in (4b). A  
 207 delivery is classified with increased risk when there are more than  $M$  pigs with *Ma* infection  
 208 in the delivery. Probability  $p_i^{is}$  that a delivery is incorrectly classified without increased risk  
 209 for each control package  $i$  is given in (4c).  
 210

$$211 \quad p(n, N, d, m, se, sp) = \sum_{x=0}^d \left[ \sum_{y=0}^{\min\{n,m\}} \left[ \frac{\binom{m}{y} \binom{N-m}{n-y}}{\binom{N}{n}} \sum_{j=0}^{\min\{x,y\}} \left[ \binom{y}{j} se^j (1-se)^{y-j} \binom{n-y}{x-j} (1-sp)^{x-j} sp^{n-x-y+j} \right] \right] \right] \quad (4a)$$

$$212 \quad p_i^s = \sum_{m=0}^N p(n, N, d, m, se, sp) \cdot \hat{h}_i(m) \quad \forall i = 1, \dots, k \quad (4b)$$

$$213 \quad p_i^{is} = \sum_{m>M}^N p(n, N, d, m, se, sp) \cdot \hat{h}_i(m) \quad \forall i = 1, \dots, k \quad (4c)$$

214 where:

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

217  $j =$  number of pigs in a sample correctly classified with increased risk;  
 218  $M =$  minimum number of pigs with *Ma* infection in a delivery to define the delivery with  
 219 increased risk;  
 220  $p(n, N, d, m, se, sp) =$  probability of  $d$  or less pigs classified with increased risk when a sample  
 221  $n$  from a delivery  $N$  contains  $m$  pigs with *Ma* infection using a test with sensitivity  $se$   
 222 and specificity  $sp$ ;  
 223  $se =$  test sensitivity;  
 224  $sp =$  test specificity;  
 225  $x =$  number of pigs in a sample tested with increased risk;  
 226  $y =$  number of pigs with *Ma* infection in a sample.  
 227

228 The decision problem of the slaughterhouse manager is to set a penalty  $pen$  on pigs in  
 229 deliveries classified with increased risk. This problem depends on the ownership structure for  
 230 the slaughterhouse (King et al., 2007). For a non-producer investor owned slaughterhouse, the  
 231 manager minimizes slaughterhouse costs. For a producer cooperative, the manager minimizes  
 232 producer costs. For an integration the manager minimizes chain costs. Slaughterhouse costs  
 233 given in (5) consist of testing costs, additional processing costs, and failure costs at the steady  
 234 state probabilities  $(cp_1^*, \dots, cp_k^*)$ , corrected for penalty revenue from producers. The  
 235 slaughterhouse incurs testing costs of  $tc$  per tested pig. With probability  $(1 - p_i^s)$  it has  
 236 additional processing cost  $apc$  for pigs in a delivery classified with increased risk, because  
 237 their head and gastro-intestinal tract are unfit for consumption and have to be disposed of  
 238 safely. Furthermore, the slaughterhouse has part  $(1 - \alpha)$  of failure costs with probability  $p_i^{is}$ .  
 239

$$240 \sum_{i=1}^k (N \cdot (1 - p_i^s) \cdot (apc - pen) + (1 - \alpha) \cdot p_i^{is} \cdot fc + n \cdot tc) \cdot cp_i^* \quad (5)$$

241 where:

242  $apc =$  additional processing costs in euro per pig in a delivery classified with increased risk;

243  $tc =$  testing costs in euro per tested pig.  
 244

### 245 3. Model parameters and assumptions

246 The optimal steady-state control packages for producers were calculated for sensitivity  
 247 0.50, 0.70 and 0.90, and for specificity 0.95, 0.97 and 0.99. Sensitivity and specificity of the  
 248 new serological test are expected to lie in this range. The values of sensitivity and specificity  
 249 were combined with penalty values €0, €2, €4, €6,8€ and €10 per pig in a delivery classified  
 250 with increased risk. We analysed three cases of traceability. First, in case of no traceability ( $fc$   
 251  $= 0$ ) neither slaughterhouse manager nor producers were confronted with failure costs (Table  
 252 2 and 3). Second, in case of partial traceability ( $fc > 0$ ,  $\alpha = 0$ ) the slaughterhouse manager was  
 253 confronted with failure costs, but he did not know which producer was the cause (Table 2 and  
 254 3). Third, in case of full traceability ( $fc > 0$ ,  $\alpha = 1$ ) the slaughterhouse manager could trace  
 255 individual producers and passed failure costs on to them (Table 4).

256 In each period  $t$  a producer was categorised in one of six *Ma* risk levels  $RL_t \in \{1, \dots,$   
 257  $6\}$ . Levels 1 and 2 were levels with the highest risk, levels 4 and 6 levels with medium risk,  
 258 and levels 3 and 5 levels with the lowest risk. The *Ma* risk level  $RL_{t+1}$  depended on the risk  
 259 levels from up to and including 7 previous periods (6a). If a farm had risk level 2 in  $t$  current  
 260 test results  $TR_t$  and risk levels from the previous two periods were considered to determine the  
 261 farms risk level in  $t+1$ . If a farm had risk level 3 in  $t$  current test results  $TR_t$  and risk levels  
 262 from the previous seven periods were considered to determine the farms risk level in  $t+1$ . For

263 other risk levels current test results  $TR_t$  and the previous risk level were considered to  
 264 determine the risk level in  $t+1$ . The sample size depended on the risk level as given in (6b). A  
 265 low sample size of 2 or 6 is sufficient because the control system aims to identify chronic *Ma*  
 266 infections on herd level. The penalty depended on the risk level as given in (6c). For this  
 267 system the producer's dynamic optimization problem was a Markov chain with 2,008 states.  
 268 Each state was a possible combination of *Ma* risk levels in 8 consecutive periods.  
 269

$$\begin{aligned}
 & RL_{t+1} = f_1(RL_t, \dots, RL_{t-7}, TR_t) = \\
 & \left\{ \begin{array}{l}
 1 \text{ if } (RL_t \in \{1,2,4,6\} \text{ and } TR_t \geq 1) \text{ or } (RL_t \in \{3,5\} \text{ and } TR_t \geq 2) \\
 2 \text{ if } (RL_t = 1 \text{ and } TR_t = 0) \text{ or } (RL_{t-1} \neq 2 \text{ and } RL_t = 2 \text{ and } TR_t = 0) \\
 3 \text{ if } (RL_{t-1} = RL_t = 2 \text{ and } TR_t = 0) \text{ or} \\
 \quad (RL_t = 3 \text{ and } TR_t = 0 \text{ and } \exists \hat{t} \in \{1, \dots, 7\} \text{ with } RL_{t,\hat{t}} \neq 3) \\
 4 \text{ if } RL_t = 3 \text{ and } TR_t = 1 \\
 5 \text{ if } (RL_t \in \{5,6\} \text{ and } TR_t = 0) \text{ or } (RL_{t-7} = \dots = RL_t = 3 \text{ and } TR_t = 0) \\
 6 \text{ if } RL_t = 5 \text{ and } TR_t = 1
 \end{array} \right. \quad \forall t \quad (6a)
 \end{aligned}$$

$$271 \quad n = f_2(RL_t) = \begin{cases} 2 & \text{if } RL_t \in \{3,5\} \\ 6 & \text{if } RL_t \in \{1,2,4,6\} \end{cases} \quad \forall t \quad (6b)$$

$$272 \quad pen_{RL} = f_3(RL_t) = \begin{cases} pen & \text{if } RL_t \in \{1,2\} \\ 0.5 \cdot pen & \text{if } RL_t \in \{3,4\} \\ 0 & \text{if } RL_t \in \{5,6\} \end{cases} \quad \forall t \quad (6c)$$

273  
 274 We modelled pig producers with monthly deliveries of each 100 pigs. The monthly  
 275 discount factor  $\delta$  was assumed to be 0.9967, implying an annual interest rate of 4.0%.  
 276 Estimated testing costs  $tc$  were €8 per test (V.M.C. Rijsman, personal communication, 2007).  
 277 Additional processing costs  $apc$  were €0.92 per pig in a delivery classified with increased  
 278 risk, based on foregone revenues of a head of €0.06(3 kg at €0.02 per kg), foregone revenues  
 279 of a gastro-intestinal tract of €0.50 per tract, and rendering costs for head and tract of €0.36  
 280 (head 3 kg and tract 6 kg at €0.04 per kg) (L. Heres, personal communication, 2007).

281 A general value of food safety failure costs  $fc$  that includes recall costs, reputation  
 282 damage, and liability costs was sufficient to analyze how failure costs influence producer  
 283 incentives. Expected jury award to consumers for court cases on food borne illness in the  
 284 USA was used as failure costs per delivery. Expected award was \$41,888, which meant  
 285 €41,446 in 2006, with a range of \$0 to \$2,368,858 (Buzby et al., 2001).

286 Four *Ma* control packages ( $i = 1, 2, 3, 4$ ) were defined that consisted of combinations  
 287 of bird control, small terrestrial mammal control, invertebrate control, use of uncontaminated  
 288 bedding materials, water quality control, and use of uncontaminated feed supplements (Table  
 289 1). Data were gathered using literature and were discussed with two leading experts of *Ma*  
 290 infections in pigs in the Netherlands and the Czech Republic. Probability distribution of  
 291 prevalence levels of each control package were based on Engel et al. (1978), Fischer et al.  
 292 (2000), Fischer et al. (2001), Mátlová et al. (2005), Mátlová et al. (2003), Mátlová et al.  
 293 (2004a), Mátlová et al. (2004b), and Pavlík et al. (2007). Average prevalence levels were  
 294 highest for control package 1 (46.0%) and lowest for control package 4 (0.1%). Costs for bird,  
 295 small terrestrial mammal, and invertebrate control, and for water control were based on King  
 296 et al. (2007). Costs for feed supplements were €1.50 per pig, calculated as the additional costs

297 of pigs fed a supplement mix (€5.12 per pig: 2.5 kg of supplement mix at €135 per 100 kg and  
 298 2.5 kg of weaner feed at €70 per 100 kg) above costs of pigs provided pig-compost (€3.62 per  
 299 pig: 2.5 kg of pig-compost at €75 per 100 kg and 25 kg of weaner feed at €70 per 100 kg).  
 300 Costs of uncontaminated bedding material were those of commercially available bedding  
 301 materials. Contamination probability that a random uncontrolled risk factor was contaminated  
 302 with *Ma* was based on Mátlová et al. (2003). Expected prevalence for each control package is  
 303 the average prevalence multiplied by the contamination probability. Expected prevalence was  
 304 highest for control package 1 (13.8%) and lowest for control package 4 (0.1%).

305 Table 1 also provides impact of sensitivity and specificity on the probability  $p_i^s$  of a  
 306 delivery being classified without increased risk and on the type-II-error  $p_i^{is}$  at the average  
 307 prevalence of each control package  $i$  and at sample size 6. A higher sensitivity or a lower  
 308 specificity led to lower  $p_i^s$  and  $p_i^{is}$ . A lower expected prevalence resulted in a higher  $p_i^s$ . For  
 309 control package 1 with average prevalence of 46.0% probability that a delivery of 100 pigs  
 310 contained infected pigs was 95% and probability of infected pigs in the sample was 98%. This  
 311 resulted in  $p_1^{is}$  between 0.096 and 0.245. For control package 2 probability that a delivery  
 312 contained infected pigs was 95%, but probability of infected pigs in the sample was 63% for  
 313 average prevalence of 15.8%. This resulted in  $p_2^{is}$  between 0.321 and 0.567. Although control  
 314 package 2 had lower average prevalence than control package 1,  $p_2^{is}$  was larger than  $p_1^{is}$ ,  
 315 because of a high probability of not having infected pigs in the sample. For control package 3  
 316 probability that a delivery contained infected pigs was 95% and probability of infected pigs in  
 317 the sample was 0% for average prevalence of 0.3%. This resulted in  $p_3^{is}$  between 0.028 and  
 318 0.040. Although the probability of not having infected pigs in the sample was high for control  
 319 package 3, probability that a delivery contained infected pigs was so small, that  $p_3^{is}$  was  
 320 smaller than  $p_2^{is}$  and  $p_1^{is}$ . For control package 4 probability that a delivery contained infected  
 321 pigs was 99% resulting in  $p_4^{is}$  smaller than  $p_3^{is}$ .

322  
 323 **Table 1: *Mycobacterium avium* control packages with control package costs, probability**  
 324 **distribution of serological prevalence levels at slaughter, contamination probability,**  
 325 **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 <sup>a</sup>				
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

326 <sup>a</sup> Serological ELISA at Optical Density cut-off value of 20 Percentage Positives.

327 <sup>b</sup> With  $N = 100$ ,  $n = 6$ ,  $M = 0$ , and  $d = 0$ .

328

#### 329 4. Results

330 Impact of penalty on the optimal steady state probability of each control package,  
 331 expected  $Ma$  prevalence, type-II-error, producer costs, slaughterhouse costs, and chain costs  
 332 without traceability for sensitivity 0.50, 0.70, and 0.90 and specificity 0.95 is given in Table  
 333 2. Producer and slaughterhouse manager decisions were based on the economic consequences  
 334 of the penalty. For sensitivity 0.50 optimal penalty value for producers was €0. Then control  
 335 package 1 was optimal, resulting in expected  $Ma$  prevalence of 14.3% and type-II-error of  
 336 0.073. Producer costs were €0 per pig and both slaughterhouse costs and chain costs €0.68. In  
 337 contrast, for sensitivity 0.50 optimal penalty value for the slaughterhouse was €10, because  
 338 the penalty revenue was highest. Then control package 2 was optimal for 74% of producers  
 339 and control package 3 for 26% of producers. The expected  $Ma$  prevalence was 2.0% and the  
 340 type-II-error was 0.078. Use of control package 2 led to a higher type-II-error compared to the  
 341 use of control package 1. Slaughterhouse costs were –€0.20 per pig, producer costs €0.82,  
 342 and chain costs €0.62. For sensitivity 0.50 chain costs were minimal at penalty €2. Then  
 343 control package 2 was optimal for producers, resulting in an expected  $Ma$  prevalence of 2.7%  
 344 and a type-II-error of 0.084. Chain costs were €0.50 per pig, with producer costs €0.26 and  
 345 slaughterhouse costs €0.24. Optimal penalty values for producer, slaughterhouse, and chain  
 346 did not change with a higher sensitivity of 0.70 or 0.90. At higher sensitivity, however,  
 347 producers increased use of more intense control packages, because more pigs were classified  
 348 with increase risk resulting in lower expected prevalence and lower type-II-errors. At higher  
 349 sensitivity producer and chain costs were higher, and slaughterhouse costs were similar.

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

<sup>1</sup> Costs include the revenue from the penalty. Negative costs indicate positive benefits.

354 €22.72 and €48.44 per pig compared to case no traceability depending on sensitivity and  
355 penalty parameter values. In case of partial traceability at sensitivity 0.50, 0.70, and 0.90  
356 optimal penalty value for producers was €0 per pig and optimal penalty value for the  
357 slaughterhouse was €10 per pig. Producer costs were lower at higher levels of sensitivity  
358 through the lower type-II-errors. At sensitivity 0.50 and 0.70 chain costs were minimal at  
359 penalty €10 per pig. However, at sensitivity 0.90, chain costs were minimal at penalty €0.  
360 Low failure costs and low producer costs compensated for additional production costs of the  
361 slaughterhouse originating from the high expected *Ma* prevalence.

362 Impact of penalty on optimal steady state probability of each control package,  
363 expected *Ma* prevalence, type-II-error, producer costs, slaughterhouse costs, and chain costs  
364 without traceability for specificity 0.95, 0.97, and 0.99 and sensitivity 0.70 is given in Table  
365 3. Producer and slaughterhouse manager decisions were based on the economic consequences  
366 of the penalty. For specificity 0.95 optimal penalty value for producers was €0. Then control  
367 package 1 was optimal, resulting in expected *Ma* prevalence of 14.3% and type-II-error of  
368 0.048. Producer costs were €0 per pig and both slaughterhouse costs and chain costs €0.68. In  
369 contrast, for specificity 0.95 optimal penalty value for the slaughterhouse was €10, because  
370 the penalty revenue was highest. Then control package 2 was optimal for 50% of producers  
371 and control package 3 for 50% of producers. This resulted in an expected *Ma* prevalence of  
372 1.4% and a type-II-error of 0.054. Use of control package 2 led to a higher type-II-error  
373 compared to the use of control package 1. Slaughterhouse costs were –€0.20 per pig, producer  
374 costs €0.82, and chain costs €0.62. For sensitivity 0.95 chain costs were minimal at penalty  
375 €2. Then control package 2 was optimal for producers, resulting in an expected *Ma*  
376 prevalence of 2.7% and a type-II-error of 0.084. Chain costs were €0.50 per pig, with  
377 producer costs €0.26 and slaughterhouse costs €0.24. Optimal penalty values for producers  
378 and slaughterhouse did not change with a higher specificity of 0.97 or 0.99. For specificity  
379 0.97 chain costs were minimal for penalty €2 per pig, but at specificity 0.99 for penalty €4. At  
380 higher specificity, however, producers decreased use of more intense control packages,  
381 because less pigs were classified with increase risk. This resulted in higher expected  
382 prevalence and higher type-II-errors. Slaughterhouse costs were higher for higher specificity  
383 at penalty €0, because less pigs were classified with increased risk and additional processing  
384 costs were lower. At penalty €2 slaughterhouse costs did not differ much between levels of  
385 specificity. At penalty €4 or higher slaughterhouse costs were lower for higher specificity  
386 because the penalty revenue from pigs classified with increased risk were higher than  
387 additional processing costs. Producer costs and chain costs were lower at higher specificity.

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

397 In case of full traceability, when the failure costs were included in the producer  
398 decision, sensitivity, specificity and penalty had no influence on producer incentives to take  
399 *Ma* control measures (Table 4). Control package 3 was optimal for all combinations. Penalty  
400 and sensitivity had no impact on the type-II-error, but the type-II-error was lower at lower  
401 specificity. Producer costs were higher at lower sensitivity, higher specificity, and higher  
402 penalty. Producer costs were €400 to €4.50 per pig lower compared to the cases no

403 traceability and partial traceability. Producer costs were minimal at sensitivity 0.90,  
404 specificity 0.95 and penalty €0. Slaughterhouse costs were minimal at sensitivity 0.50,  
405 specificity 0.95 and penalty €10. Sensitivity had little influence on slaughterhouse costs. At  
406 penalty €0 slaughterhouse costs were higher compared to case no traceability, because less  
407 pigs were classified with increased risk. At penalty €10 slaughterhouse costs were lower  
408 because the lower expected *Ma* prevalence decreased penalty revenue.  
409

## 410 **5. Sensitivity analysis**

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

420 Contamination probabilities of 1.00 led to increased use of more intense control  
421 packages, higher producer costs (from €0.00 to €0.2 per pig depending on sensitivity and  
422 specificity), and lower slaughterhouse costs (from €0.02 to €0.72 per pig) compared to Table  
423 1. Higher sensitivity, lower specificity, and higher penalty led to use of more intense control  
424 packages and higher producer costs. Contamination probabilities of 1.00 further increased  
425 type-II-errors if control package 2 was used. At penalty €0 lower sensitivity and higher  
426 specificity led to higher slaughterhouse costs, because additional production costs of pigs  
427 classified with increased risk were larger than the penalty. At penalty €2 to €10 lower  
428 sensitivity and higher specificity led to lower slaughterhouse costs.

429 Control package 4 was never optimal, because producer revenues from lower *Ma*  
430 prevalence and lower type-II-errors did not outweigh additional control package costs.  
431 Expected *Ma* prevalence of 0.1% of control package 4 was equal to that of control package 3,  
432 while costs of control package 4 (€1.92) were €1.50 higher than those of control package 3  
433 (€0.42). Control package costs can differ amongst producers. Producers with good  
434 management skills can provide weaner feed to pigs in small amounts in hygienically clean  
435 circumstances to prevent weaner diarrhoea. For these farmers estimated costs were €3.50 per  
436 pig (5 kg weaner feed at €70 per 100 kg), indicating no additional control package costs above  
437 providing pig-compost. If control package 4 had costs of €0.42, control package 4 was used in  
438 stead of control package 3. Probability of use of control packages 1 and 2 did not change.  
439 Lower average *Ma* prevalence of control package 4 compared to control package 3 led to a  
440 lower expected *Ma* prevalence and a lower type-II-error. Lower expected prevalence led to  
441 less pigs classified with increased risk and a lower producer penalty, and resulted in lower  
442 producer costs and higher slaughterhouse costs.  
443

444 **Table 2: Impact of penalty on optimal control packages, expected *Ma* prevalence, type-II-errors, producer costs, slaughterhouse costs**  
 445 **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
<b>Prevalence performance</b>																		
steady state probability of <sup>a</sup> :																		
-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 <i>Ma</i> 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
<b>Economic performance</b>																		
<i>no traceability</i>																		
-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) <sup>b</sup>	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
<i>partial traceability</i>																		
-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) <sup>b</sup>	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

446 <sup>a</sup> control package 4 was never optimal.

447 <sup>b</sup> costs corrected for penalty revenue received from pig producers (negative costs indicate positive benefits).

448

449 **Table 3: Impact of penalty on optimal control packages, expected *Ma* prevalence, type-II-errors, producer costs, slaughterhouse costs**  
 450 **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
<b>Prevalence performance</b>																		
steady state probability of <sup>a</sup>																		
-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 <i>Ma</i> 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
<b>Economic performance</b>																		
<i>no traceability</i>																		
-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) <sup>b</sup>	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
<i>partial traceability</i>																		
-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) <sup>b</sup>	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

451 <sup>a</sup> control package 4 was never optimal.

452 <sup>b</sup> costs corrected for penalty revenue received from pig producers (negative costs indicate positive benefits).

453 **Table 4: Impact of penalty on type-II-errors, producer costs, slaughterhouse costs and**  
 454 **chain costs in case of full traceability with sensitivity 0.50, 0.70, 0.90 and specificity 0.95,**  
 455 **0.97, 0.99<sup>a</sup>.**

sensitivity	specificity	penalty <sup>c</sup> (€/pig)	type-II-error	producer costs (€/pig)	slaughterhouse costs <sup>b</sup> (€/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

456 <sup>a</sup> Control package 3 with expected *Ma* prevalence 0.1% was optimal for all combinations.

457 <sup>b</sup> Costs corrected for penalty revenue (negative costs indicate positive benefits).

458 <sup>c</sup> Results for penalty parameter values €2 to €8 are available from the authors upon request.

459

## 460 6. Discussion

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

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

475 This research used partial analysis on *Ma*. Almost all control actions are also effective  
 476 in reducing other pathogens or improving production results. Thus, the costs to reduce  
 477 prevalence should be divided over more pathogens. This research did not include benefits  
 478 from other pathogens and improved production results. Including these benefits in the  
 479 producer decision increases producer incentives to use control measures. Dutch pig farms  
 480 mainly use control measures as described by control package 3 and 4. Possibilities to decrease

481 costs, however, may tempt them to lower their attention for *Ma* control, leading to reduced  
482 effectiveness of the control packages and to increased risk of *Ma* infections in pigs.

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

489

## 490 **7. Conclusions**

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

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

515

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