CrossMark

Journal of Agricultural Science (2016), **154**, 720–731. © Cambridge University Press 2016
doi:10.1017/S0021859616000101

MODELLING ANIMAL SYSTEMS RESEARCH PAPER

A decision support system for the control of Campylobacter in chickens at farm level using data from Denmark

A. B. GARCIA[1]*, A. L. MADSEN[2,3] AND H. VIGRE[1]

[1] *DTU FOOD, Denmark Technical University, Lyngby, Denmark*
[2] *Computer Science Department, Aalborg University, Aalborg, Denmark*
[3] *HUGIN EXPERT, Aalborg, Denmark*

(*Received 30 October 2014; revised 17 November 2015; accepted 1 February 2016; first published online 7 March 2016*)

SUMMARY

The control of *Campylobacter* in poultry is considered a public health priority and some intervention strategies have been implemented in Denmark. Nonetheless, *Campylobacter* infection in poultry can still be considerable particularly during the summer when the most promising *Campylobacter* control strategy seems to be the use of fly screens. The use of cost-effective vaccines against *Campylobacter* is also desirable. In order to control *Campylobacter*, poultry producers need to make crucial decisions under conditions of uncertainty. With the aim of assisting poultry producers in decision making regarding *Campylobacter* control strategies, the objective of the present study was to produce a decision support system that integrated knowledge and used a Bayesian approach to handle uncertainty. This decision support system integrated epidemiological data, microbiological considerations, financial information and potential control strategies (the use of fly screens and hypothetical vaccines). In conclusion, results from model and sensitivity analyses indicated that the financial variables (cost–benefit functions) and the effectiveness of the different control strategies drove the results.

INTRODUCTION

Human campylobacteriosis represents an important public health issue and it has been notifiable in Denmark since 1980. Raw chicken meat is considered one of the most important risk factors for human infections with *Campylobacter* in Denmark (Wingstrand *et al.* 2006). A risk profile for pathogenic *Campylobacter* was conducted in 1998 (Forsythe 2002) and ever since broiler flocks have been tested for *Campylobacter* at slaughter. The first Danish Action plan against *Campylobacter* in broilers was established in 2003 (Christensen *et al.* 2001). A more recent action plan to control *Campylobacter* in broilers and broiler meat was implemented in Denmark in 2008. Between 2001 and 2009, *Campylobacter* prevalence in Danish broiler flocks before slaughter decreased from around 0.4 to about 0.3 (Boysen 2012). A recent report from the European Food Safety Authority stated an average prevalence of 0·192 for *Campylobacter* in Danish broiler flocks (EFSA Panel on Biological Hazards 2011). Nevertheless, *Campylobacter* prevalence in broiler flocks during the summer months in Denmark can be as high as 0·514 (Hald *et al.* 2007). Researchers have reported several risk factors significantly associated with *Campylobacter* infection of broilers in Denmark such as late introduction of whole wheat in the chickens' diet, improper storage of whole wheat, age of birds at slaughter, old broiler houses, number of chimneys on the broiler house, improper rodent control, number of broiler houses on farm and the location of the poultry farm in relation to cattle farms (Heuer *et al.* 2007; Sommer & Heuer 2007; Sommer *et al.* 2013). Chowdhury *et al.* (2012) found that season, increasing age of the birds and several factors related to biosecurity (age of the poultry houses, previous *Campylobacter* positive flocks in the same houses and the number of persons entering the houses) were significantly associated with

* To whom all correspondence should be addressed. Email: anna-garcia10@hotmail.com

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

Campylobacter infection of broilers. Field trials conducted in Denmark showed that the use of fly screens in broiler houses during the summer can reduce the prevalence of *Campylobacter* in Danish broilers (Hald *et al*. 2007; Boysen *et al*. 2011). A recommendation to use fly-nets in all the houses on a farm has been made because transmission of *Campylobacter* from the non-netted houses to the netted houses has been considered probable (Hald *et al*. 2004; EFSA Panel on Biological Hazards 2011). In fact, the use of fly screens on farms may decrease *Campylobacter* prevalence in broilers by 10–30% (Hald *et al*. 2007), which in turn may translate to a significant reduction of human campylobacteriosis cases.

Campylobacter control measures that can reduce the numbers in already infected chickens, such as vaccination strategies, might also be considered. Effective vaccination is highly desirable; however, a cost-efficient vaccination strategy against *Campylobacter* in poultry is not yet commercially available. Garcia *et al*. (2012) conducted investigations into a vaccination strategy against *Campylobacter* in poultry aiming to reduce the numbers of *Campylobacter* in chickens. In addition, decision support tools have been developed to assist poultry producers to make complex decisions under conditions of uncertainty for the control of *Campylobacter* in poultry flocks (Madsen *et al*. 2012; Garcia *et al*. 2013).

The main objective of the present work was to develop a decision support system to assist poultry farmers in the control of *Campylobacter* (at farm level) using data from Denmark. The model presented is constructed as a probabilistic graphical model (PGM) which integrates prior knowledge related to the farm as well as the expected cost-effectiveness of two different *Campylobacter* controls on-farm: hypothetical *Campylobacter* vaccines and/or the use of fly screens. The integration of prior knowledge (prior probabilities) can be used to infer the probabilities of other variables that are not known (posterior probabilities) using a Bayesian approach. The prior probability distributions should integrate knowledge obtained from diverse reliable sources such as epidemiological data, empirical observations and expert knowledge in order to obtain reliable outcomes from the models. Epidemiological data, microbiological considerations, financial information and diverse control strategies have been integrated in the model. The present work aimed to provide the decision support system and solutions derived from the model such as posterior probabilities related to expected *Campylobacter* levels in chickens before and after implementation of controls and a cost–benefit balance for each control strategy considered. Poultry producers can adapt the model to real-life conditions and decide if/when to use fly screens and/or vaccines (if they were commercially available) selecting the most beneficial decision/s in every real-life situation.

MATERIALS AND METHODS

Probabilistic graphical models

The PGM presented in the present paper has been designed using the HUGIN tool, a commercial software package from Hugin Expert (http://www.hugin.com/). Briefly, PGMs include prior knowledge and uncertainties using a number of variables and probabilistic dependence relationships between the variables (Madsen *et al*. 2012; Garcia *et al*. 2013). The PGMs formed by a set of variables have two components: a qualitative and a quantitative part. The qualitative part includes diverse 'nodes' such as variables, decision nodes and utility functions and arcs representing relationships between them (as exemplified in Fig. 1). A chance node (an oval in Fig. 1) represents a random variable, while a decision node (a rectangle in Fig. 1) defines decision alternatives at a specific point in time and a utility node (a diamond in Fig. 1) represents a reward or cost function. The relationships of dependence or independence between the variables included in the models can be represented and the strength of the relationships can be defined using conditional probability distributions (Heckerman *et al*. 1995). The quantitative part of the models includes the mathematical expressions and probability distributions. The results from the models comprise posterior probability distributions (for every strategy) related to expected *Campylobacter* numbers in the flock (in logs) before and after the implementation of the decision(s) and the expected cost–benefit balance associated with each decision.

Prior knowledge related to poultry production management factors

The developed decision support model (Fig. 1) integrates epidemiological data from a study on risk factors potentially associated with Campylobacter infection in Danish broiler flocks (Chowdhury *et al*. 2012). These authors investigated >1700 variables and found the following risk factors to be significantly

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

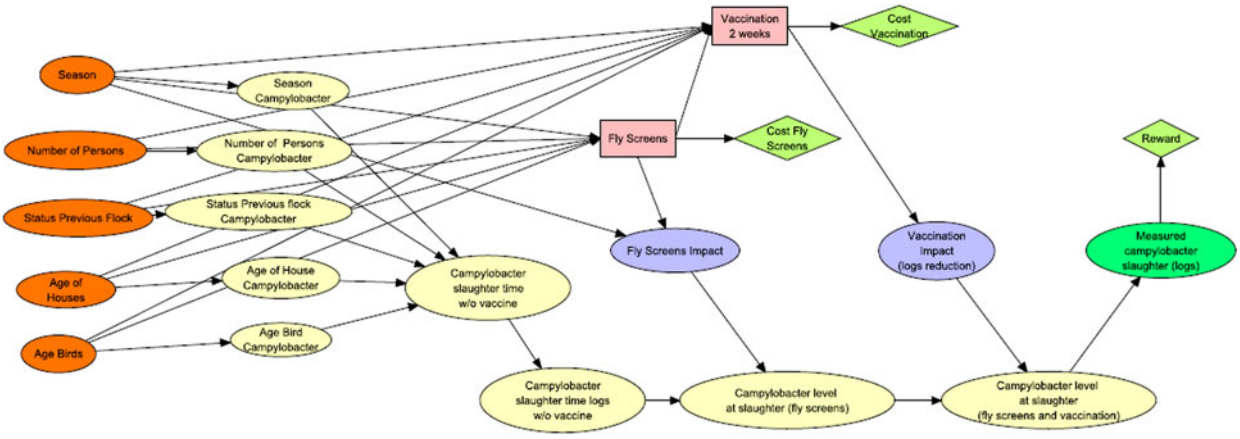


Fig. 1. The Commercial Broilers in Denmark (ComBDK) model designed based on epidemiological and financial data from Denmark.

associated with Campylobacter positive flocks: season, increasing age of the birds, the age of the poultry houses, previous Campylobacter positive flocks in the same houses and the number of persons entering the poultry houses (Chowdhury *et al.* 2012). Odds ratio (OR) values were used to represent the concept of 'increased risk' due to the factor(s) considered in their research. To integrate this information into the PGM, the significant risk factors were included in the model (Fig. 1) and the OR values were transformed to a probability of infection with Campylobacter at varying states of the risk factor (*P(s)*) using the following formula:

$$P(s) = \frac{\exp(\ln(b_p/1 - b_p) + \ln(\mathrm{ORs}))}{1 + \exp(\ln(b_p/1 - b_p) + \ln(\mathrm{ORs}))}$$

where b_p is the baseline Campylobacter flock prevalence and ORs is the odds ratios (Table 1). In addition, Campylobacter introduction in the flock due to the presence of risk factors was assumed to be conditional to a baseline Campylobacter flock prevalence (b_p: lowest level of Campylobacter in broilers close to slaughter time found in the literature) of 0·14 (Chowdhury *et al.* 2012).

The 'Commercial Broilers in Denmark' (ComBDK) model: design and assumptions

The ComBDK model (Fig. 1) was developed to assist poultry producers in Denmark to make decisions regarding *Campylobacter* controls in commercial broilers based on the following assumptions:

(i) A microbiological detection level of *Campylobacter* was considered to be 2 logs colony forming units (CFU)/g or ml of sample while the maximum colonization level was assumed to be 10 logs CFU/g or ml of sample. Thus, in this model, a *Campylobacter* level of 0–2 logs will produce a negative result while a positive result suggests *Campylobacter* numbers present in the samples from 2 to 10 logs. Intervals for bacterial concentration with two log widths (e.g. 0–2 logs, 2–4 logs, 4–6 logs, 6–8 logs and 8–10 logs) were considered.

(ii) The contributions from different risk factors to the level of *Campylobacter* are independent.

(iii) The 'measured *Campylobacter* numbers at slaughter' will depend on the microbiological quantitative methods used and the 'true numbers' of *Campylobacter* in chickens. In the model, a hypothetical nearly perfect quantitative method has been considered.

(iv) The *Campylobacter* controls included in the model are: the use of fly screens and hypothetical *Campylobacter* vaccines A and B. Fly screens are used during the summer but the costs associated with the use of fly screens are always considered (Lawson *et al.* 2009).

In this model, data related to the influence of the risk factors on the expected *Campylobacter* status of the flock were based on a positive (2–10 logs)/negative (0–2 logs) result while data related to the effect of interventions were based on a log-scale because the objective was to develop a control strategy (e.g. vaccination strategy) able to reduce the numbers of *Campylobacter* in commercial broilers. Data must be on the same scale to obtain reliable results from the model. For this reason, a mathematical transformation from positive/

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

Table 1. *Significant risk factors, frequency of occurrence and associated probability of* Campylobacter *introduction in broiler flocks in Denmark (Chowdhury* et al. *2012)*

Risk factor and frequency of occurrence (ref.)	*P*-value	Odds ratio (95% CI)	Probability *Campylobacter* positive*
Season	<0·001		
Summer (0·28)		12·59 (6·79–23·36)	067
Autumn (0·22)		5·27 (2·77–10·02)	0·46
Spring (0·25)		1·33 (0·66–2·67)	0·18
Winter (0·25)†			
Number of persons entering the house	0·009		
>1 person (0·86%)		2·03 (1·19–3·84)	0·25%
1 person (0·14%)†			
Campylobacter infection status (previous flock)	0·002		
Positive (0·22%)		1·80 (1·22–2·63)	0·23
Negative (0·78%)†			
Establishment year of the house	0·002		
Before or during 1990 (0·46%)		1·60 (1·17–2·18)	0·21
After 1990 (0·54%)†			
Age of birds at slaughter	0·04		
>35·5 days (0·46%)		1·33 (1·02–1·76)	0·18
⩽35·5 days (0·54%)†			

* Based on a basic level of Campylobacter of 14% (Chowdhury *et al.* 2012).

† Reference category.

negative to the diverse *Campylobacter* levels (in logs)-scale was performed. Figure 2 illustrates the mathematical transformation used to translate results from a positive/negative format ('*Campylobacter* slaughter time without vaccine') to a log scale format ('*Campylobacter* slaughter time logs without vaccine'). A flat distribution was selected to transform a general expected posterior probability of a *Campylobacter* flock (e.g. 0·72) into a distribution of equal probabilities (0·18) for the different levels of *Campylobacter* considered in the model (Fig. 2).

The effectiveness of *Campylobacter* controls and cost–benefit functions included in the model

The use of a cost-effective vaccine against *Campylobacter* in chickens is desirable; however, no commercial vaccine is presently available. Based on prices of other vaccines used to control diseases in poultry (Dianova 2013), a hypothetical price can be considered to be around 0·15–0·50 Danish Kroners (DKK), equivalent to €0·02–0·07. Two hypothetical vaccines (A and B) were incorporated in the model with different vaccine effectiveness and costs (Table 2). The use of fly screens in poultry houses in order to control *Campylobacter* has been recommended (Hald *et al.* 2004, 2007; Bahrndorff *et al.* 2013). The average cost (including capital costs that cover long-term investments and variable expenses) of implementing fly screens on broiler farms was calculated to be 0·13 DKK/chicken (Lawson *et al.* 2009), equivalent to approximately €0·02, and included in the model (Table 2). The impact of interventions and the cost–benefit functions were based on a log-scale because the objective was to develop a control strategy that could reduce the numbers of *Campylobacter* in already infected chickens. The use of fly screens can reduce the prevalence of *Campylobacter* in broiler flocks significantly; therefore, it was assumed in the model that the effectiveness of fly screens was 0·90 (expected reduction of *Campylobacter* numbers in more than 2 logs).

Two reward systems (Table 3) were designed based on an 'average' gross profit (for Danish farmers producing chickens carrying an 'average' number of *Campylobacter*) considered to be DKK 2·92/chicken (equivalent to €0·39/chicken) based on financial data from 2013 (Farmtal Online 2013). It was assumed that an average broiler chicken from a positive flock in Denmark will carry *Campylobacter* in a concentration of 4–6 logs CFU/g or ml of sample (from the digestive tract). The reward system 1 was

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

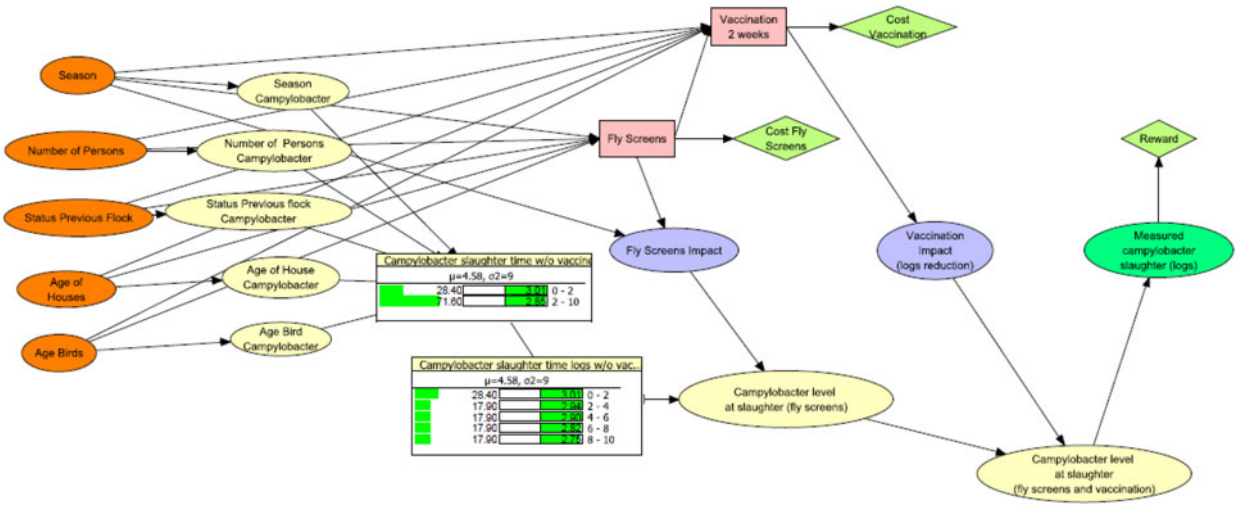


Fig. 2. Illustration showing the part of the model where a mathematical transformation is performed to translate results from a positive/negative format ('*Campylobacter* slaughter time w/o vaccine') to a log scale format ('*Campylobacter* slaughter time logs w/o vaccine').

Table 2. *Costs and effectiveness related to control measures included in the model*

Control measure	Cost (DKK/ chicken)	Cost (€/chicken)	Effectiveness (expected reductions of *Campylobacter* numbers in >2 logs) (%)
Vaccine A	−0·19	−0·03	40
Vaccine B	−0·45	−0·06	80
Fly screens	−0·13	−0·02	90
Vaccine A + fly screens	−0·32	−0·04	95
Vaccine B + fly screens	−0·58	−0·08	100

DKK, Danish Kroners.

designed based on a system implemented in Denmark where poultry producers get an extra payment when the flock is identified as *Campylobacter* negative before slaughter (Marianne Sandberg, personal communication, 2013). In the model, an extra payment (between DKK 0·02 and 0·04) is given to farmers producing chickens carrying *Campylobacter* in numbers <4 logs and a reduced payment (between 0·04 and 0·08 less) is established for farmers producing poultry flocks that carry *Campylobacter* in numbers >6 logs before slaughter (Table 3). A different reward system 2 was designed based on an extra payment of 2·5 times the normal price for chickens testing negative for *Campylobacter* before slaughter in order to test the sensitivity of the reward variable in the model.

Sensitivity analyses

Three different types of sensitivity analyses were performed on the model. Firstly, parameter sensitivity analyses were conducted (using the Hugin Expert software) in order to determine which parameters in the model had the strongest influence on final outcomes (Nielsen & Jensen 2003), for example, the effect of vaccination impact (in logs reduction) on measured *Campylobacter* at slaughter (Fig. 3). Furthermore, the impact of changes in parameters related to the reward system was investigated such as the effect of changes in '*p*' (increased/decreased payment based on numbers of *Campylobacter* in commercial chickens) on the cost–benefit balance (or expected utility) of different control measures (Fig. 4). Secondly, an evidence- (or scenario-) driven sensitivity analysis was performed in order to determine the sensitivity of the decisions considered in the model under diverse evidence scenarios (Jensen 1996). For this purpose, different scenarios (e.g. best/worst case scenarios) and the two different reward systems previously described were used. Thirdly, a sensitivity analysis using a number of control measures including a third hypothetical vaccine C (with an effectiveness level of 0·90 and a cost of DKK 0·26/ chicken equivalent to €0·04 was conducted.

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

Table 3. *Reward systems 1 and 2*

Campylobacter level (logs)	0–2	2–4	4–6	6–8	8–10
Reward system 1					
Gross profit (DKK/chicken)	3·04	2·98	2·92	2·80	2·69
Gross profit (€/chicken)	0·41	0·40	0·39	0·38	0·36
Reward system 2					
Gross profit (DKK/chicken)	7·6	2·98	2·92	2·80	2·69
Gross profit (€/chicken)	1·02	0·40	0·39	0·38	0·36

DKK, Danish Kroners.

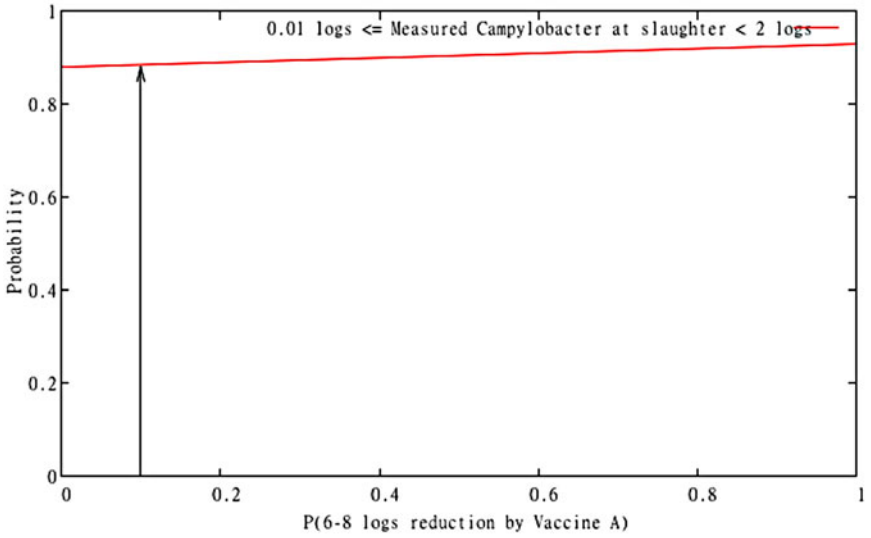


Fig. 3. Results from sensitivity analyses performed to investigate the effect of vaccination impact (in logs reduction when using Vaccine A) on measured *Campylobacter* at slaughter.

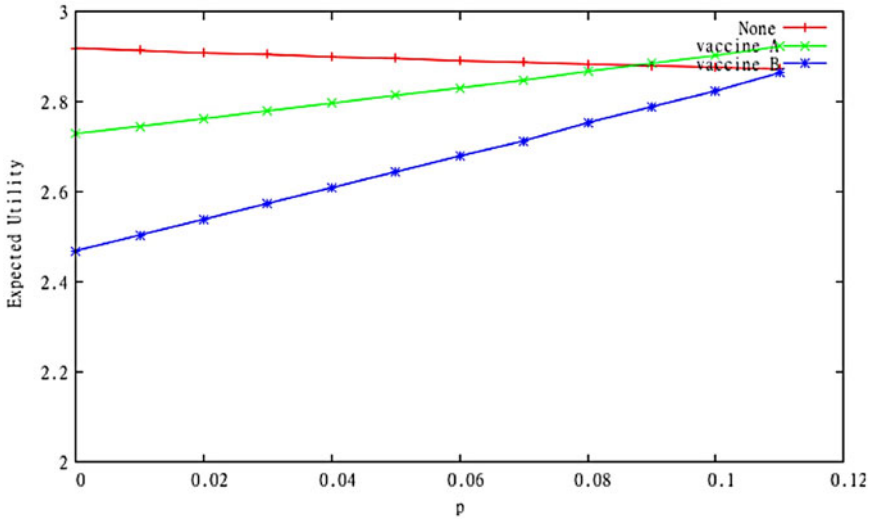


Fig. 4. Results from sensitivity analyses in terms of changes of the expected utility (cost–benefit balance) when selecting some decisions (no controls and using vaccines A or B) as a function of '*p*' (decreased/increased payment considered in reward system 1).

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

RESULTS

Interpretation of results obtained from the Commercial Broilers in Denmark model

A high number of the diverse risk factors' states and combinations or scenarios can be considered in the model and therefore it is up to the user to select the most adequate combination for the real-life problem under investigation. Three combinations are described in Table 4 in order to illustrate the potential outputs of the model in terms of expected posterior probabilities related to *Campylobacter* numbers in chickens and associated expected cost–benefit analyses (or expected utilities) when implementing reward system 1 (Table 5).

Results obtained from the model based on the previously described assumptions suggested that the best solution in financial terms would be to use the fly screens alone in the worst case scenario and not to implement the controls under the assumed conditions in the 'average' and best case scenarios. Nevertheless, the best solution from a public health point of view would be the use of fly screens and vaccine B synergistically. Based on the results from the model, this strategy (fly screens and vaccine B) could significantly decrease the posterior probability related to expected *Campylobacter* positive results in all scenarios (from 072 to 0·29 in the average scenario; from 0·55 to 0·30 in the best scenario and from 0·87 to 0·09 in the worst case-scenario) although the implementation of this strategy would translate into a decrease of expected gross profit (around DKK 0·50/chicken equivalent to €0·07). During the summer, the use of fly screens alone and/or synergistically with vaccines A or B may be able to reduce the posterior probability related to expected *Campylobacter* positive results below the considered 'baseline level of 0·14'. In fact, using fly screens alone during the summer would reduce the posterior probability related to the expected *Campylobacter* positive results from 0·87 to 0·13, resulting also in a small increase of the expected gross profit (based on the cost–benefit balance).

Results from sensitivity analyses

The parameter sensitivity analyses performed showed that the financial variables (cost–benefit functions) and to a lesser extent the effectiveness of the control measures (e.g. vaccination impact) were driving the model's results (Figs 3 and 4). Figure 3 shows how the posterior probability of 'Measured *Campylobacter*' in the range '0·01–2' changes as a function of the probability of vaccine A producing a 6–8 logs reduction. The relationship is a linear function in the parameter (i.e. the impact of vaccine A producing a 6–8 logs reduction) with a constant of 0·88 and a coefficient of 0·05. It is possible to observe that the posterior probability of 'Measured *Campylobacter*' equal to '0·01–2' does not change much. However, this change was more pronounced when using hypothetical vaccines B and C because they were considered to be more effective than vaccine A in reducing *Campylobacter* numbers in infected chickens.

Figure 4 shows how the expected utility (cost–benefit balance) of some decisions (no controls and using vaccines A, B) changes as a function of '*p*' (decreased/increased payment considered in reward system 1): for low values of '*p*', no vaccine produces the highest expected utility. Figure 4 shows that vaccine A produces the highest expected utility (cost–benefit balance) only when '*p*' (increase in payment in reward system 1) is in the order of 0·09 and the value of '*p*' has to be even higher for vaccine B to result in the highest expected utility (cost–benefit balance).

Results from the model when using reward system 2 (based on an extra payment of 2·5 times the normal price for chickens testing *Campylobacter* negative before slaughter) and the diverse control options (including vaccine C) are presented in Table 6.

The results presented in Table 5 (reward system 1) and Table 6 (reward system 2) indicate that the posterior probabilities related to expected *Campylobacter* positive results are the same but the financial results (cost–benefit balances) are very different. As a result of implementing reward system 2, the farmers would potentially obtain higher payments and the differences between implementing diverse controls are more pronounced.

The effectiveness of hypothetical vaccines B and C are very similar but vaccine C is more cost-effective and desirable for this reason. From a public health perspective, the best *Campylobacter* control strategy would be the use of fly screens together with vaccine B or C. However, from an economic or financial point of view, the best solution would depend on the scenario considered, for example, in the average/reference scenario, the best solution would be using fly screens and vaccine C while in the worst case scenario (during the summer) the use of fly screens alone

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

Table 4. *Risk factors and frequency of occurrence in every scenario*

Best scenario	Worst scenario	Average/reference scenario (based on study data)
Winter (1)	Summer (1)	Summer (0·28) Autumn (0·22) Spring (0·25) Winter (0·25)
Age of broilers ⩽35·5 days (1)	Age of broilers >35·5 days (1)	Age of broilers >35·5 days (0·46) ⩽35·5 days (0·54)
Number of persons 1 person (1)	Number of persons >1 person (1)	Number of persons 1 person (0·14) >1 person (0·86)
Campylobacter status of previous flock Negative (1)	*Campylobacter* status of previous flock Positive (1)	*Campylobacter* status of previous flock Positive (0·22) Negative (0·78)
Age of poultry houses After 1990 (1)	Age of poultry houses Before 1990 (1)	Age of poultry houses After 1990 (0·54) Before 1990 (0·46)

would be financially most rewarding. The use of vaccine C alone in the best case scenario would seem to be the most cost-effective strategy based on the results from the model.

DISCUSSION

Poultry producers need to make decisions and sometimes expensive investments to control *Campylobacter* before they even know for sure if the flock will become infected or challenged with *Campylobacter*. For this reason, poultry producers might benefit from the use of decision support systems such as the one presented in the present paper. Furthermore, the integration of increasing amounts of knowledge from diverse sources makes the decision process complex but if done properly, the accuracy of the results will increase and there will be less uncertainty surrounding the decision-making process. Bayesian inference is used when decisions have to be made under conditions of uncertainty and statistical inference is required (Greenland 2006). Nevertheless, there will always be a degree of uncertainty surrounding Bayesian networks and their outputs. In this regard, uncertainty analyses of Bayesian networks may prove useful to provide information in relation to how uncertainties surrounding the parameter probabilities may affect the output/s; such uncertainty analyses of Bayesian networks are under development (Van der Gaag *et al.* 2013).

In order to predict the presence and numbers of *Campylobacter* in poultry flocks, a variety of potential risk factors for the introduction of *Campylobacter* may be considered in predictive models increasing their complexity (Garcia *et al.* 2013). Moreover, the development of a generic global model would be almost utopic because risk factors may vary between geographical regions as well as between production systems (Barrios *et al.* 2006; Guerin *et al.* 2007; Lyngstad *et al.* 2008). For this reason, it seems useful to include risk factors found to be statistically significant for the introduction of *Campylobacter* in poultry flocks under specified conditions. A specific model for the control of *Campylobacter* in poultry based on data from the UK and considering only one control strategy (the use of hypothetical vaccines against *Campylobacter* in poultry) has been previously published (Garcia *et al.* 2013). The model presented in the present paper has been adapted to Danish poultry production conditions and includes more than one control strategy and their combinations. Thereby, in this way it is possible to compare the effect of very different control options (reducing the probability of introduction of *Campylobacter* into the flock by using fly screens *v.* reducing the amount of *Campylobacter* in the gut of the chickens in the flock if the flock is infected using hypothetical vaccines) in the same model. The risk factors incorporated in the model presented in the present paper (ComBDK model) were those found to be significant

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

Table 5. *Results from 'Commercial Broilers in Denmark' model using reward system 1*

Scenarios	Best		Worst		Average/reference based on study data	
Decisions	Posterior probabilities related to expected *Campylobacter* positive results (2–10 logs)	Expected cost–benefit financial balance gross profit DKK/chicken (€/chicken)	Posterior probabilities related to expected *Campylobacter* positive results (2–10 logs)	Expected cost–benefit financial balance gross profit DKK/chicken (€/chicken)	Posterior probabilities related to expected *Campylobacter* positive results (2–10 logs)	Expected cost–benefit financial balance gross profit DKK/chicken (€/chicken)
None	0·55	+2·94 (0·39)	0·87	+2·87 (0·39)	0·72	+2·90 (0·39)
Vaccine A	0·42	+2·78 (0·37)	0·65	+2·74 (0·37)	0·55	+2·76 (0·37)
Vaccine B	0·30	+2·55 (0·34)	0·46	+2·53 (0·34)	0·39	+2·54 (0·34)
Fly screens	0·55	+2·81 (0·38)	0·13	+2·89 (0·39)	0·52	+2·81 (0·38)
Vaccine A + fly screens	0·42	+2·65 (0·36)	0·11	+2·71 (0·36)	0·40	+2·66 (0·36)
Vaccine B + fly screens	0·30	+2·42 (0·32)	0·09	+2·45 (0·33)	0·29	+2·43 (0·32)

DKK, Danish Kroners.

Table 6. *Results from the model when considering reward system 2 and an additional vaccine C*

Scenarios	Best		Worst		Average/reference based on study data	
Decisions	Posterior probabilities related to expected *Campylobacter* positive results (2–10 logs)	Expected cost–benefit financial balance gross profit DKK/chicken (€/chicken)	Posterior probabilities related to expected *Campylobacter* positive results (2–10 logs)	Expected cost–benefit financial balance gross profit DKK/chicken (€/chicken)	Posterior probabilities related to expected *Campylobacter* positive results (2–10 logs)	Expected cost–benefit financial balance gross profit DKK/chicken (€/chicken)
None	0·55	+4·89 (0·66)	0·87	+3·37 (0·45)	0·72	+4·07 (0·55)
Vaccine A	0·42	+5·47 (0·73)	0·65	+4·46 (0·60)	0·55	+4·92 (0·66)
Vaccine B	0·30	+5·87 (0·79)	0·46	+5·29 (0·71)	0·39	+5·56 (0·75)
Fly screens	0·55	+4·76 (0·64)	0·13	+6·76 (0·91)	0·52	+4·90 (0·66)
Vaccine A + fly screens	0·42	+5·34 (0·72)	0·11	+6·68 (0·90)	0·40	+5·44 (0·73)
Vaccine B + fly screens	0·30	+5·74 (0·77)	0·09	+6·51 (0·87)	0·29	+5·80 (0·78)
Vaccine C	0·29	+6·18 (0·83)	0·44	+5·69 (0·76)	0·37	+5·91 (0·79)
Vaccine C + fly screens	0·29	+6·05 (0·81)	0·09	+6·72 (0·90)	0·28	+6·10 (0·82)

DKK, Danish Kroners.

for the presence of *Campylobacter* in Danish broilers in a recent study by Chowdhury *et al*. (2012). Other studies have also found a clear correlation between biosecurity-related risk factors and flock infection with *Campylobacter* (Cardinale *et al*. 2004; Johnsen *et al*. 2006).

One of the objectives of the present paper was to illustrate the increased complexity of the model when including more than one control strategy. More *Campylobacter* controls could be incorporated in the model presented in this paper but the complexity will increase accordingly. For example, hygiene barriers have been suggested as the most important biosecurity measures to produce *Campylobacter*-free chickens (Berndtson *et al*. 1996; Van de Giessen *et al*. 1996; Hald *et al*. 2000; Johnsen *et al*. 2006). In the present model, the use of fly screens was included because their use has been recommended for the control of *Campylobacter* in Danish broiler systems (Hald *et al*. 2004, 2007; EFSA Panel on Biological Hazards 2011; Bahrndorff *et al*. 2013). The effectiveness of the use of fly screens against *Campylobacter* in poultry has been reported in terms of decreased *Campylobacter* prevalence in broiler flocks in Denmark. The experimental use of fly screens during the 2006 summer (June–October) produced a statistically significant decrease from 0·514 to 0·154 of *Campylobacter* positive flocks in comparison with control houses (Hald *et al*. 2007). A recently published study (Bahrndorff *et al*. 2013) reports data related to the long-term effect of the use of fly screens on the prevalence of *Campylobacter* in broiler flocks in Denmark collected over the years 2006–09. Bahrndorff *et al*. (2013) reported a statistically significant decrease in *Campylobacter* prevalence from 0·414 in 2003–05 (before the use of fly screens) to 0·103 in 2006–09. The use of fly screens was tested on poultry farms in Iceland during the summer of 2008 and significant reductions on *Campylobacter* prevalence were observed (Lowman *et al*. 2009). Results from the experimental studies previously mentioned relate to average *Campylobacter* prevalence values obtained from diverse farms and flocks and therefore different farming conditions. Comparison of the results related to the use of fly screens on broiler farms previously reported (Hald *et al*. 2007; Lowman *et al*. 2009; Bahrndorff *et al*. 2013) with the results from the ComBDK model presented here are not straightforward. Results from the ComBDK model are based on one flock level and the expected posterior probability related to a *Campylobacter* positive result for that flock under specific conditions. Even more, a 'nearly perfect' quantitative microbiological test has been incorporated in the model and consequently results related to the expected probability of a *Campylobacter* positive result might be higher than the actual result if a quantitative *Campylobacter* test was performed in that particular flock (considering that the detection limit of most microbiological test are around 2 logs).

The model presented in the present paper has been designed for specific poultry farming conditions in Denmark; however, since the poultry industry is becoming more and more integrated and standardized it is possible that the model could be applied to farming conditions in other areas of the world. Nevertheless, the model (qualitative and/or quantitative parts) should be adjusted to other situations in order to design useful tailor-made models (Garcia *et al*. 2013). The flexibility of the model allows the user to test diverse controls, different farming conditions, microbiological protocols and cost–benefit systems. Sensitivity analyses performed indicated that the factors that influenced the results to a greater extent were the financial variables (cost–benefit functions) and the effectiveness of the *Campylobacter* control strategies. The assessment of the effectiveness of control strategies might prove challenging in some cases e.g. the assessment of vaccine effectiveness (Garcia *et al*. 2012). The effectiveness of fly screens was assumed to be 0·90 but they were only used during the summer. The financial impact of the implementation of disease control strategies needs to be considered in disease control programmes.

In conclusion, the financial results obtained seemed to be highly dependent on the reward systems and the scenarios considered. From a public health perspective, the best *Campylobacter* control strategy will be the use of fly screens alone or synergistically with hypothetical vaccines B or C. In some occasions, the financial results obtained from the model indicated that the expected financial gains might be too small to justify the implementation of controls. Nevertheless, this type of information might prove very valuable and it is likely that producers will find this decision making tool more beneficial at times when the consequences from implementing alternative decisions for the control of *Campylobacter* are not so obvious. In contrast, when considering the most cost-efficient choices (e.g. reward system 2 and the use of vaccine C) significant reductions in

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

expected *Campylobacter* levels and substantial expected financial gains were obtained. Clearly, cost-effective control measures will be preferred by poultry producers and a reward system that can translate on an attractive cost–benefit balance will be a good incentive for producers to implement *Campylobacter* control strategies in poultry production. The implementation of cost-effective control strategies during primary poultry production will potentially translate into a decrease of *Campylobacter* prevalence in chickens, a reduction of *Campylobacter* numbers in poultry products and in turn, a potential decrease of human campylobacteriosis cases. From a public health perspective, a *Campylobacter* prevalence level of 0·10 in broilers could potentially result in a reduction of human cases by nearly 50% (Nauta *et al*. 2009; EFSA Panel on Biological Hazards 2011).

This work was supported by The Danish Council for Strategic Research project CamVac (contract 09-067131).

REFERENCES

Bahrndorff, S., Rangstrup-Christensen, L., Nordentoft, S. & Hald, B. (2013). Foodborne disease prevention and broiler chickens with reduced Campylobacter infection. *Emerging Infectious Diseases* **19**, 425–430.

Barrios, P. R., Reiersen, J., Lowman, R., Bisaillon, J. R., Michel, P., Fridriksdóttir, V., Gunnarsson, E., Stern, N., Berke, O., McEwen, S. & Martin, W. (2006). Risk factors for Campylobacter spp. colonization in broiler flocks in Iceland. *Preventive Veterinary Medicine* **74**, 264–278.

Berndtson, E., Emanuelson, U., Engvall, A. & Danielsson-Tham, M. L. (1996). A 1-year epidemiological study of campylobacters in 18 Swedish chicken farms. *Preventive Veterinary Medicine* **26**, 167–185.

Boysen, L. (2012). Campylobacter *in Denmark*. Ph.D. Thesis, Denmark Technical University, Denmark.

Boysen, L., Vigre, H. & Rosenquist, H. (2011). Seasonal influence on the prevalence of thermotolerant Campylobacter in retail broiler meat in Denmark. *Food Microbiology* **28**, 1028–1032.

Cardinale, E., Tall, F., Gueye, E. F., Cisse, M. & Salvat, G. (2004). Risk factors for Campylobacter spp. infection in Senegalese broiler-chicken flocks. *Preventive Veterinary Medicine* **64**, 15–25.

Chowdhury, S., Sandberg, M., Themudo, G. E. & Ersbøll, A. K. (2012). Risk factors for Campylobacter infection in Danish broiler chickens. *Poultry Science* **91**, 2701–2709.

Christensen, B. B., Sommer, H. M., Rosenquist, H. & Nielsen, N. L. (2001). *Risk Assessment of* Campylobacter jejuni *in Chicken Products*. Glostrup, Denmark: The Danish Veterinary and Food Administration.

Dianova (2013). *Salmonella*. Aarhus, Denmark: Dianova. Available from: http://www.dianova.dk/Consultancies/Salmonella.aspx (verified 9 December 2015).

EFSA Panel on Biological Hazards (Biohaz) (2011). Scientific opinion on Campylobacter in broiler meat production: control options and performance objectives and/or targets at different stages of the food chain. *EFSA Journal* **9**, 2105. doi: 10.2903/j.efsa.2011.2105.

Farmtal Online (2013). *Agricultural Database Managed by the Danish Knowledge Centre for Agriculture (VFL)*. Available from: https://farmtalonline.dlbr.dk/Navigation/NavigationTree.aspx?Farmtal=221 (verified 19 July 2013).

Forsythe, S. J. (2002). Application of microbiological risk assessment. In *The Microbiological Risk Assessment of Food* (Ed. S. J. Forsythe), pp. 113–173. Oxford, UK: Blackwell Publishing.

Garcia, A. B., Bahrndorff, S., Hald, B., Hoorfar, J., Madsen, M. & Vigre, H. (2012). Design and data analysis of experimental trials to test vaccine candidates against zoonotic pathogens in animals: the case of a clinical trial against Campylobacter in broilers. *Expert Review of Vaccines* **11**, 1179–1188.

Garcia, A. B., Madsen, A. L. & Vigre, H. (2013). Integration of epidemiological evidence in a decision support model for the control of Campylobacter in poultry production. *Agriculture* **3**, 516–535.

Greenland, S. (2006). Bayesian perspectives for epidemiological research: I. Foundations and basic methods. *International Journal of Epidemiology* **35**, 765–775.

Guerin, M. T., Martin, W., Reiersen, J., Berke, O., McEwen, S. A., Bisaillon, J. R. & Lowman, R. (2007). House-level risk factors associated with the colonization of broiler flocks with Campylobacter spp. in Iceland, 2001–2004. *BMC Veterinary Research* **3**, 30. doi: 10.1186/1746-6148-3-30.

Hald, B., Wedderkopp, A. & Madsen, M. (2000). Thermophilic Campylobacter spp. in Danish broiler production: a cross-sectional survey and a retrospective analysis of risk factors for occurrence in broiler flocks. *Avian Pathology* **29**, 123–131.

Hald, B., Skovgard, H., Bang, D. D., Pedersen, K., Dybdahl, J., Jespersen, J. B. & Madsen, M. (2004). Flies and Campylobacter infection of broiler flocks. *Emerging Infectious Diseases* **10**, 1490–1492.

Hald, B., Sommer, H. M. & Skovgard, H. (2007). Use of fly screens to reduce Campylobacter spp. introduction in broiler houses. *Emerging Infectious Diseases* **13**, 1951–1953.

Heckerman, D., Mamdani, A. & Wellman, M. P. (1995). Real-World Applications of Bayesian Networks. *Communications of the ACM* **38**, 24–26.

Heuer, O. E., Sommer, H. M., Wong, D. L. F., Patrick, M. E., Wainø, M., Wedderkopp, A. & Madsen, M. (2007). Risk factors for the occurrence of campylobacter in Danish broiler flocks (poster presentation). *Zoonoses and Public Health* **54**(Suppl. 1), 138.

Jensen, F. V. (1996). *An Introduction to Bayesian Networks*, Vol. **210**. London: UCL Press.

Johnsen, G., Kruse, H. & Hofshagen, M. (2006). Genetic diversity and description of transmission routes for

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press

Campylobacter on broiler farms by amplified-fragment length polymorphism. *Journal of Applied Microbiology* **101**, 1130–1139.

Lawson, L. G., Jensen, J. D. & Lund, M. (2009). *Cost of Interventions against Campylobacter in the Danish Broiler Supply Chain*. Report no. 201. Copenhagen: Institute of Food and Resource Economics.

Lowman, R., Reiersen, J., Jónsson, T., Gunnarsson, E., Bisaillon, J. R. & Daoadottir, S. (2009). Iceland: 2008 pilot year fly netting ventilation inlets of 35 broiler houses to reduce flyborne transmission of *Campylobacter spp.* to flocks. In *Abstracts of the 15th International Workshop on Campylobacter, Helicobacter and Related Organisms (CHRO), Sep 2–5*, Niigata, Japan. Abstract 210, p. 140. Niigata, Japan: CHRO.

Lyngstad, T. M., Jonsson, M. E., Hofshagen, M. & Heier, B. T. (2008). Risk factors associated with the presence of Campylobacter species in Norwegian broiler flocks. *Poultry Science* **87**, 1987–1994.

Madsen, A. L., Karlsen, M., Barker, G. C., Garcia, A. B., Hoorfar, J. & Jensen, F. (2012). *An Architecture for Web Deployment of Decision Support Systems Based on Probabilistic Graphical Models with Applications*. Technical Report TR-12-001. Aalborg, Denmark: Department of Computer Science, Aalborg University.

Nauta, M., Hill, A., Rosenquist, H., Brynestad, S., Fetsch, A., Van Der Logt, P., Fazil, A., Christensen, B., Katsma, E., Borck, B. & Havelaar, A. (2009). A comparison of risk assessments on Campylobacter in broiler meat. *International Journal of Food Microbiology* **129**, 107–123.

Nielsen, T. D. & Jensen, F. V. (2003). Sensitivity analysis in influence diagrams. *IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans* **33**, 223–234.

Sommer, H. M. & Heuer, O. E. (2007). Statistical analysis of a risk factor study on the occurrence of Campylobacter in Danish broiler flocks. *Zoonoses and Public Health* **54** (Suppl. 1), 143–144.

Sommer, H. M., Heuer, O. E., Sørensen, A. I. & Madsen, M. (2013). Analysis of factors important for the occurrence of Campylobacter in Danish broiler flocks. *Preventive Veterinary Medicine* **111**, 100–111.

Van De Giessen, A. W., Bloemberg, B. P. M., Ritmeester, W. S. & Tilburg, J. J. H. C. (1996). Epidemiological study on risk factors and risk reducing measures for Campylobacter infections in Dutch broiler flocks. *Epidemiology and Infection* **117**, 245–250.

Van Der Gaag, L. C., Kuijper, R., Van Geffen, Y. M. & Vermeulen, J. L. (2013). Towards uncertainty analysis of Bayesian Networks. In *Proceedings of the 25th Benelux Conference on Artificial Intelligence* (Eds K. Hindriks, M. de Weerdt, B. van Riemsdijk & M. Warnier), pp. 223–230. Delft, The Netherlands: BNAIC.

Wingstrand, A., Neimann, J., Engberg, J., Nielsen, E. M., Gerner-Smidt, P., Wegener, H. C. & Mølbak, K. (2006). Fresh chicken as main risk factor for campylobacteriosis, Denmark. *Emerging Infectious Diseases* **12**, 280–285.

https://doi.org/10.1017/S0021859616000101 Published online by Cambridge University Press